CHALMERS

Evaluation of Positioning Systems for Laparoscopic Simulators

Master's Thesis in Biomedical Engineering

ANDERS HANSSON

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Department of Signals and Systems
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CHALMERS UNIVERSITY OF TECHNOLOGY
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ABSTRACT

Traditional surgical training is carried out in real surgical environment with a real patient. This may pose a certain risk for the patient, but by introducing a surgical training simulator these risks can be reduced. A training simulator must live up to a certain quality in a way that the skills gained from the training with a simulator can be applied in a real surgery. This Master Thesis will be focusing on laparoscopic simulators and was carried out for the company Surgical Science, headquarter in Gothenburg. Surgical Science is developing a software environment for laparoscopic simulators and has imported the hardware instruments from other companies. But, due to a patent, which concerned the hardware instruments, it is now an option for Surgical Science to develop their own hardware instruments.

The purpose of this thesis was to investigate and examine different position systems which can be used to determine the position of a laparoscopic instrument. The thesis includes two parts. The first part is a survey of the different position systems such as linear and rotary encoders, camera systems and inertial systems. The second part includes a hands on investigation of the winning concept from part one. The winning concept was a laser sensor, which is mainly used in computer mice, due to its price and performance. Programming code and necessary equipment have been developed to test the sensor. The tests showed sufficient result and therefore a laser sensor can be applied for positioning of a laparoscopic instrument. It is however recommended to test the sensor together with Surgical Science's software before making a complete tool based on laser sensors.

Contents

Acknowledgements

The result of this Master Thesis is not only a work by us authors. Without people who have helped and supported us during this project wouldn't the final result been achieved. First we would like to thank Anders Larsson at Surgical Science for his commitment, valuable ideas and soldering skills. Also a big thanks to Senior Lecture Ants Silberberg at department Signals and Systems at Chalmers Technical University for his guidance and finding necessary equipment. Lastly, but not least, we would also like to give our greetings to Hans Odelius at Physical department at Chalmers who took a lot of his time to help us create the prototype.

Thank you all,

Anders Hansson and Anders Hedén

Gothenburg, September 2011

Sweden

Abbreviations and Nomenclature

CMOS – Is a technology for constructing integrated circuits. Two characteristics for CMOS are low noise level and low static power consumption. This result in less waste heat is produced than other IC technologies, like TTL and NMOS logic. Another major reason why CMOS is much applied is the large amount of logic circuits which can be build on a single chip.

Counts per inch (CPI) – Amount of counts in one inch. One inch is equal to 25.4 mm.

Dots per inch (DPI) – Almost the same as CPI but DPI is used to describe resolution for images and screens.

Inch per second (*IPS*) – A measurement unit for speed expressed as inches/seconds.

Integrated Circuits (ICs) – ICs are electronic devices where the components are manufactured together.

Digital Signal Processing/Digital Signal Processor (DSP) – Digital Signal Processing is processing of signals by sequences of numbers and symbols. A sampled analogue signal is an example of a digital signal. Digital Signal Processor is a specialised processor to handle digital signals. Includes often filters and methods to calculate Fast Fourier Transforms and other signal related algorithms.

EAGLE - EAGLE is a software where the user is able to create PCB schematics and to construct instructions for manufacturing it later on.

Frames per second (Fps) – The amount frames, or pictures, that is read during a second.

Hall technique – Hall technique are technical solutions based on the Hall Effect. The Hall Effect is a phenomenon which occurs when charged particles flows in a conductor in a magnetic field. The charged particles will be influenced by a force which makes these particles be “pushed” to one side of the conductor. The voltage difference between the two sides of the conductor can then be measured with a Hall Effect sensor.

LabVIEW - LabVIEW stands for Laboratory Virtual Instrumentation Engineering Workbench and is software to make it easier to visually display measurements and control hardware. It is a graphical programming language where components are placed rather than written.

Printed Circuit Board (PCB) – PCB is a board with pathways for conducting electrical signals. Hence, it is used to connect and support electronic devices.

Pulse Width Modulation (PWM) – A method to control the power voltage to an electric device. By pulsing the power with a high frequency can e.g. a motor be regulated.

Power supply rails – Refers to a single provided voltage supplied by some power supply unit. The name is usually used in electronics.

Quadrature output – A common method to calculate the position for an encoder. By using two outputs, e.g. A and B, with 90° phase shift it is possible to the measure the position and direction of the sensor.

Surface Mounted Component (SMC) – Small electrical components which are mounted directly onto a PCB.

Through Hole Technology (THT) – The size of the electrical components are larger than SMC. THT can easily be assembled on a breadboard by pushing the component's pin through a breadboard hole.

Two complement – A binary arithmetic method. The byte can represent both negative and positive value, where the MSB represent the sign of the byte. So instead of 2^8 representing 0 - 255, 2^8 represents -127 to 128.

1 Introduction

SIMULATORS, from the latin word *si´mulo* ‘affect’, ‘pretend’ (Nationalencyklopedin, 2011), is an old method, over 5000 years old (McLeroy, 2008), and have a wide range of application areas. The core of a simulator is the model, which is as an approximation of the real-world (John A. Sokolowski, 2009). Hence, simulation can be explained as an operation imitating a real-world event. Historically has simulation frequently been used in military applications, e.g. during the Roman Empire where the legion´s used sand stables and small models of armies to simulate battles (McLeroy, 2008) and in the 18th century contributed simulators to the Prussia´s army success on the battlefield (John A. Sokolowski, 2009). Nowadays simulation is used in many more domains than just in the military e.g. in the health, the industry and the transportation sector to name a few. However, what different kinds of simulators have in common is that they are used for training, experimenting and analysis.

One of many positive effects of using simulators in the health sector is the reduced surgical training on actual patients, which may pose a certain risk. Simulators are therefore an excellent tool to train and educate students. However, simulators may not always live up to the real-world scenarios, which will reduce its usefulness. The development of more authentic simulators are therefore of great interest. In this thesis the focus will be on simulators used for laparoscopic surgeries. Laparoscopy is a surgical procedure which is performed in the abdomen or pelvis (Lindström, 2010). The special made laparoscopy instruments are inserted through the skin via holes, making the instruments moveable in four degrees. A video camera is also inserted into the surgical area to give the surgeon the necessary information about the interior conditions and the instruments positions, see Figure 1.1.

Figure 1.1 *A laparoscopy performed in the abdomen. The in-vivo condition is shown on a screen* (Wikipedia, 2005).

Hence, laparoscopy is a complicated performance due to the small working area for the instruments and the fact that the surgeon only has the visibility of the instruments via a display. A training tool for this procedure is therefore of great interest, both for surgeons and patients.

As stated before a simulator should imitate the world in such a way that the performer could use the skills gained from working with a simulator on a real-world event. There are a wide range of different laparoscopic simulators on the market which are approaching this problem in different ways. Some simulators are only hardware based, in that sense that no electronic components such as computers and sensors are used, see Figure 1.2 (Shun, 2005), other simulators use a combination of physical model of a patient´s body form and it’s interior combined with a virtual reality environment, see Figure 1.2 (Ryan, 2010).

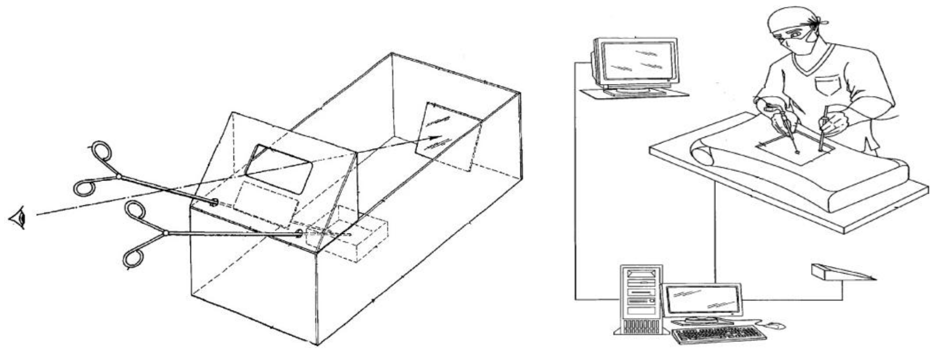


Figure 1.2 *The first picture shows a laparoscopic simulator which is based completely of hardware components. The feeling of not be able to see the operation area is done by two mirrors which reflects the area back to the operator. The second picture illustrates a simulator system from Haptica. The operator is working on a model of a patient and cameras are placed inside the body form to track the movements of the instruments. The interior of the body form is then shown as a virtual reality environment on a display.*

In this report will the focus be on a system from the company Surgical Science (Science, 2011), which are developing and selling laparoscopic simulators. The simulator contains hardware from G-Coder Systems AB (G-Coder Systems AB, 2009) and Surgical Science’s virtual reality environment, see Figure 1.3.

Figure 1.3 *Simball4D, which is the system Surgical Science is currently using. The position of the instrument is determined by encoding a pattern on the ball which the instrument is attached to.*

But, due to different circumstances, see next chapter, Surgical Science has decided to investigate if a hardware system of their own could be designed.

1.1 Background

Surgical Science is a company which is developing digital training software for laparoscopic surgery (Surgical Science, 2011). The software is called LapSim® and gives the possibility to work in virtual human cavity with the help of special built hardware instruments. These instruments are similar to the surgical instruments used in real laparoscopic surgery. Until recently Surgical Science has been focusing on developing software, and has imported the hardware instruments from other companies. However, due to a patent, that concerned the instruments, has expired, it is now an option for Surgical Science to develop their own instruments. These instruments should be more users friendly and fit Surgical Science needs better.

The problem is how to develop a low-cost, flexible and robust instrument with the latest standards that includes both connectivity and measurement. The instrument is supposed to be a cheaper alternative to the existing solutions, and therefore more hospitals and universities have the option to take part of Surgical Science’s system.

This report will cover the field of selecting components, and whole systems, which can be used to determine the position of a laparoscopic simulator tool. Components such as optical encoders, accelerometers and linear sensors will be covered. Whole systems refer to e.g. a camera system which is tracking the instruments while a computer is calculating the position of the instruments. A laparoscopic simulator developed by Immersion (Immersion Coporation, 2011) will be used as a reference model of how a typical laparoscopic simulator can look like, see Figure 1.4 (Xu, 2010). Surgical Science´s current system from G-Coder, simball 4D joystick (G-Coder Systems AB, 2009), will be used to compare the performance of the suggested solutions with the current simulator system.

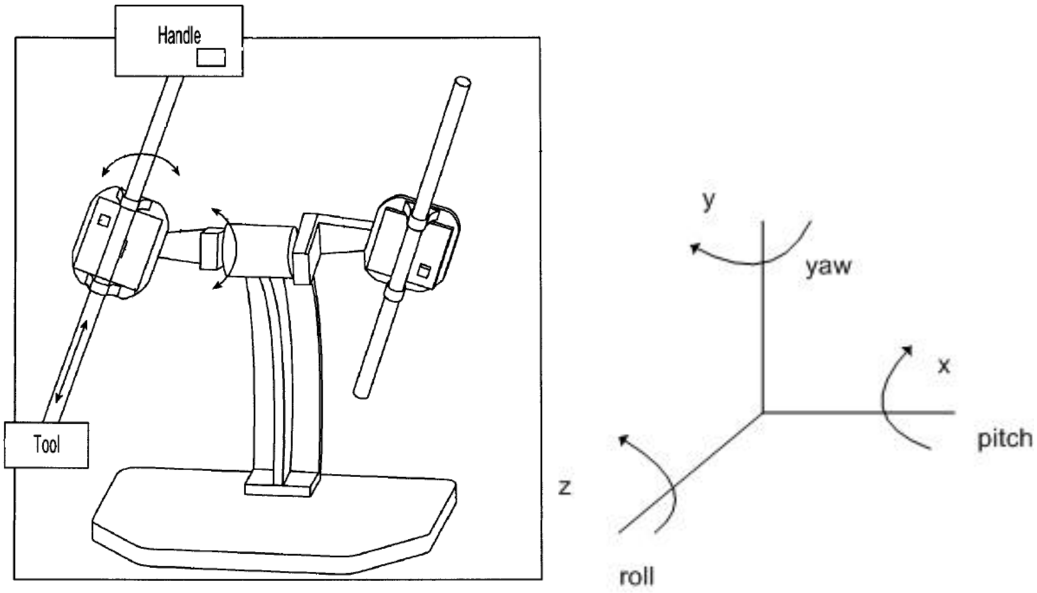


Figure 1.4 *A laparoscopic simulation tool from Immersion. Two instruments are coupled to a robust machine body and have four degrees of freedom (DOF). The possible movements are as the arrows shows; movement along the rod, rotation of the rod, pitch and jaw movement.*

1.2 Purpose

The purpose of this thesis is to determine and to compare solutions for measuring the position of a laparoscopic simulation instrument. The solutions will be compared with each other to find out which solutions best fits the requirements provided by Surgical Science, see Appendix A. Validation of Laser sensor ADNS – 7550 will also be performed to measure its usefulness as a position sensor for a laparoscopic simulation tool.

1.3 Delimitations

The project will not include the aesthetic design of the product. Hence, this report will not deal with how a solution will be assembled to the instrument. However, the report will cover for what kind of movement a specified solution will be most suited to measure, for example the jaw and pitch movement or the rotation of the rod.

Furthermore, this project will not focus on the design and assembly of a final commercial product. Solutions will therefore be developed without any regard concerning cost. However, in the result the cost of a solution will have an impact on its applicability.

2 Method

The main part of this project is to find a solution for a new instrument, and with a lower cost than the existing tool, which Surgical Science is using today. The instrument should also be robust and easy to handle and follow other detailed requirements stated by Surgical Science, these requirements can all be found in appendix C. When developing a new system there should be certain phases to follow and for achieving new solutions the market has been analysed and also the technology concerning the area.

The project as mentioned above is divided into phases to reach the goal: research phase, selection phase, decide winning solution, create prototype and final phase with a working prototype.

2.1 Research phase

This phase include interviews with Surgical Science to determine the goals the project and to specify the requirements of the system. To get a better understanding of how a laparoscopic instrument works, real-time surgery videos have been studied to understand how a simulation instrument should be developed. Other simulations developed by company competitors on the market have also been studied. Surgical Science is not alone within the field of laparoscopic simulation software and there are some patents of other competitors that preventing Surgical Science in the approach of developing a new simulation instrument when it comes to the aspects of design and functionality.

There were also literature studies as well as observations included in this phase to give a better understanding on how laparoscopic surgeries are practiced in hospitals and the focus was mainly on how the equipment works in real time surgery. The development of the instrument should also be adapted for further implementations such as haptic technologies.

2.2 Selection phase

This phase includes the start of development of the instrument and includes mainly concept generations and technologies to select from. The start of this phase was briefly to gather some basic sketches and concept of how the instrument can look like. As said in the delimitations this project is not about constructing a complete system, instead the focus should be on possible technologies and how they could be implemented in the sketches and how it could look like in a complete product.

This phase started with a lot of brainstorming concerning what technologies should be researched and used for the prototype. Each technology has been researched with a brief understanding on how the technology works and its advantages and disadvantages compared to the requirements in the specification list.

2.3 Winning solution

When all solutions from the selection phase have been viewed and weighted with each other according to the specification list, a winning solution was selected which is the mouse sensor from Avago Technology ADNS-7550. This was ordered from a supplier of electronic devices together with more in depth information concerning the ADNS-7550. This phase also included laboratory work on how to make the mouse sensor work and what else needed to be ordered to get the sensor working.

A microcontroller is needed to control the sensor, and some major micro controller manufacturers were compared and finally the Arduino board with an Atmel microcontroller was selected. The programming and usage of this board is rather easy and the specification fulfils the requirements to control the sensor.

2.4 Prototype

First a simple model was constructed with minimal complexity to measure the accuracy of the sensor but also to see how well the sensor actually worked. The sensor was soldered to a printed circuit board, PCB, and from the PCB connected to a breadboard.

The second prototype, a full PCB was constructed with all component implemented directly on the PCB card. Better test could be performed. With this card all the parts was SMC components and the card could be made really small. Three sensors were included with this prototype to see how well a microcontroller could control three sensor at the same time and how it inflicted the accuracy of each sensor.

The test itself consisted of different surfaces to see how the sensor responds to them and to determine which of the surfaces should be used in a final system. With this at hand and the accuracy determined a sensor was mounted in one of Surgical Science older instruments to test how it could be implemented and how it responds to a fixed position where the surface moves instead of the sensor. This phase were consisted of many problems concerning the sensor and its datasheet, because of missing information concerning configuration of the sensor. The problems remain to be solved with the help of Avago support.

3 Solutions

To be able to compare the different solutions the following parameters have been investigated:

- *Resolution.* This is a measurement of how exact a position can be located. It is usually measured in millimetre per millimetre, DPI or degrees.
- *Accuracy.* The range in which a system gives the accurate position, hence how much the error varies. This is expressed as RMS.
- *Sample rate.* How often a system is checking for data, most commonly expressed as frequency or frames per second.
- *Update rate.* The rate a system is sending data to another component, for example to a host computer, most commonly expressed as frequency.
- *Latency.* This is the time between the actual movement of the instrument and the report of the new position to the host computer. It is measured in milli seconds.
- *Out data.* What kind of data which are sent to the host computer.
- *Cost.* How much the system cost.

Since no system is another alike there are parameters which are not direct comparable but will have an impact of how suitable a system is for the task. These parameters will also be taken into account and affect the result.

The first chapter, Components, will describe different components which can be combined to a complete measurement system. The next chapter, Complete Systems, will concern measurement devices that are complete concepts, such as video tracking and motion capture systems.

3.1 Components

This chapter will be divided into sections which correspond to what kind of movements the component is able to measure. Furthermore, LED and laser based sensors can be applied to measure both linear and rotary movements. These two solutions are therefore only described in the chapter about linear movements.

3.1.1 Linear movement

Linear movement refers to when the rod is moving along its length axis, see Figure 1.4.

3.1.1.1 Linear Strip and compatible encoders

A linear strip is a film which are letting light pass through it at specified places. To make a linear strip functional an encoder has to be attached to the strip.

3.1.1.1.1 LIN Transmissive Linear Strip (LIN-500-10-N)

LIN Transmissive Linear Strip is a linear strip from US-digital (US-digital, 2011), see Figure 3.1. There are two encoders recommended by US-digital, EM1 and HEDS, which are also described in this chapter.

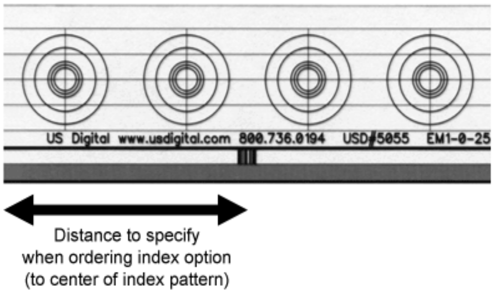


Figure 3.1 *The linear strip consists of an index pattern with a specified distance between each pattern.*

LIN-500-10-N is the linear strip model with highest DPI from US-digital and was in this thesis was chosen to be 10 inches long, due to the specification about insertion length.

Table 3.1 *LIN-500-10-N specification list*

Resolution	500 DPI
Accuracy	Not given
Sample rate	Not given
Update rate	Not given
Latency	Not given
Out data	Not given
Cost/unit	42 $
Length of the strip	10 inch = 254 mm

3.1.1.1.2 EM1 encoder (EM1-0-500)

3.1.1.1.3

EM1 encoder is an optical encoder module from US-digital (US-digital, 2011). It is designed to be used with a codewheel or a linear strip, such as the LIN Transmissive Strip. It consists of a LED source and a monolithic detector IC, see Figure 3.2 for alignment of the encoder and the linear strip.

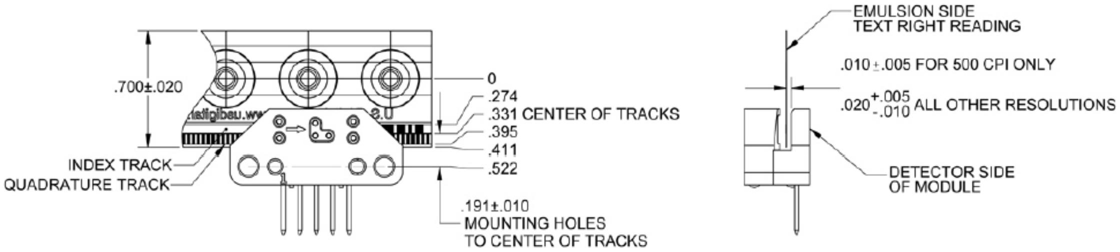


Figure 3.2 *The linear strip is placed between the source and the encoder, no external wires are required.*

The encoder is also TTL-compatible and has a built-in index channel. The output is also quadrature which makes the system more capable of handling errors and it's easier to determine the position (Moore, 2009).

Table 3.2 *EM1-0-500 encoder specification list*

Resolution	500 DPI
Accuracy	Not given
Sample rate	300 kHz
Update rate	Not given
Latency	Not given
Out data	Quadrature output with index pulse
Cost/unit	39,14 $

3.1.1.1.4 HEDS encoder (HEDS-9200-360)

HEDS is another encoder from US-digital which can be used for either codewheel or a linear strip (US-digital, 2011). As the EM1 encoder HEDS also consists of a LED source and a monolithic detector IC. The main difference between HEDS and EM1 is that HEDS is not able to read up to 500 DPI. However, the highest resolution for HEDS is 360 DPI, which may be sufficient. Another thing that differs is that EM1 has no external wires which can disturb when mounting. The assembling is done in a similar way as for EM1.

Table 3.3 *HEDS-9200-3600 encoder specification list*

Resolution	360 DPI
Accuracy	Not given
Sample rate	100 kHz
Update rate	Not given
Latency	Not given
Out data	Quadrature output with no index pulse
Cost/unit	32,31 $

3.1.1.2 LED and LASER based sensors

Sensors built with LED technology use reflected light to measure the change in position by acquiring sequential surface images, even called frames, and processes these frames with a Digital Signal Processor (DSP). The frames are then used to determine direction and the magnitude of movement (Avago Technologies, 2009).

LED sensors are able to work on rough surfaces with good accuracy. LED can also operate on gloomy surfaces or glass surfaces but with worse or almost no accuracy.

Sensors built on Laser technology functions almost like LED based sensors. But instead of an LED, a laser is used to acquire movement and directions changes. The laser sensors which are covered in this thesis apply Vertical Cavity Surface Emitting Laser (VCSEL) (Avago Technologies, 2010). The laser is directed to the surfaces of the material and then reflected back to the sensors. Inside the sensor there are processors, like a DSP, that mathematically determines the directions and magnitude of the movement (Avago Technologies, 2010). Laser based sensors works on most surfaces and is more accurate compared to LED based sensors.

3.1.1.2.1 High-Performance Optical Mouse Sensor (ADNS-3080)

ADNS-3080 is a sensor which is primarily used in optical mice (Avago Technologies, 2009). The sensor is a 20 pin DIP sensor based on LED technology, Figure 3.3. As most of the sensors from Avago it uses the SPI(Serial Peripheral Interference) to communicate with the host.

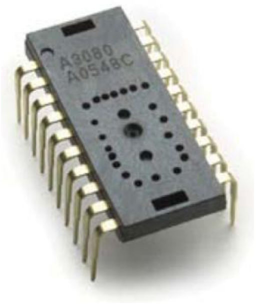


Figure 3.3 *ADNS-3080, an LED based sensor from Avago Technologies.*

Table 3.4 *ADNS-3080 specification list*

Resolution	Up to 1600 DPI
Accuracy	Not given
Sample rate	Different modes but up to 6400 frames/second
Update rate	Not given
Latency	Not given
Speed	Max 40 ips and max 15 g
Out data	Δlx and Δly
Cost/unit	~1 €
Internal oscillator	Yes

3.1.1.2.2 Enhanced Professional Gaming LaserStream™ Sensor (ADNS-6090)

ADNS-6090 is a Laser sensor from Avago Technologies (Avago Technologies, 2010). ADNS-6090 is mainly used in computer mice.

Table 3.5 *ADNS-6090 specification list*

Resolution	Up to 3000 DPI
Accuracy	Not given
Sample rate	Different modes but up to 7200 frames/second
Update rate	Not given
Latency	Not given
Speed (ips)	Max 65 ips and max 20 g
Out data	Δlx, Δly and Δlxy in pixels
Cost/unit	~3 €
Internal oscillator	Yes

3.1.1.2.3 Integrated molded lead-frame DIP Sensor (ADNS-7550)

ADNS-7550 is another Laser based sensor from Avago Technologies (Avago Technologies, 2010).

Table 3.6 *ADNS-7550 specification list*

Resolution	Up to 2000 DPI
Accuracy	Not given
Sample rate	1 MHz (recommended setting)
Update rate	1 MHz
Latency	Not given
Speed	Max 30 ips and max 8 g
Out data	Δlx, Δly and Δlxy in pixels
Cost/unit	~3 €
Internal oscillator	Yes

3.1.1.3 Magnetic based sensors

3.1.1.3.1 ID1101L Dual Channel Linear Encoder Kit

ID1101L dual channel liner encoder kit is a sensor system from Posic (Posic, 2010). The kit consists of an encoder and a linear scale, see Figure 3.4.

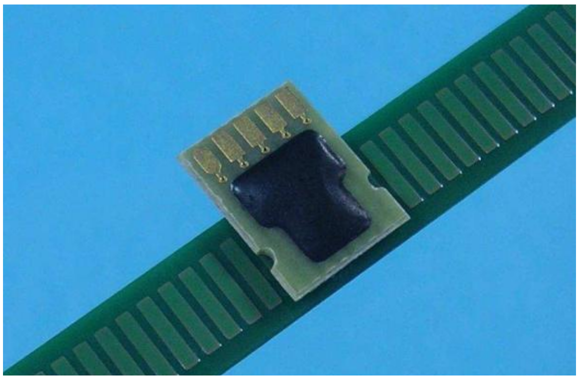


Figure 3.4 *The encoder is placed over a liner scale. The scale and the encoder are both 0.9 mm thick.*

The sensor is a differential transformer consisting of a primary and secondary coil and an electrically conducting object (Posic, 2008). For this sensor the conducting object is the linear scale which may be placed on the rod of the training tool, and the encoder is the primary and secondary coils, see Figure 3.5. However, the conducting object could also be a codewheel or a gear.

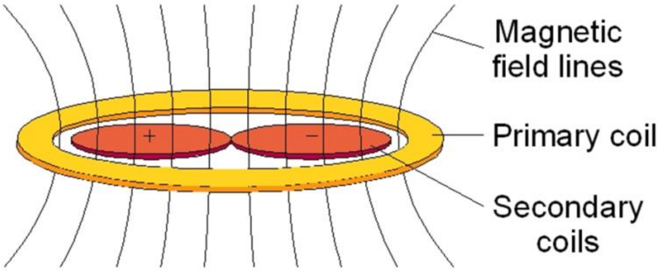


Figure 3.5 *A differential transformer consists of a primary coil and at least of one pair of secondary coils.*

The principle of the system is that the primary coil creates an alternating magnetic field of the AC source, see Figure 3.6, which induces a voltage in the secondary coils due to the Faraday´s law, equation 3.1.

Furthermore, when the conducting object is moving along the coils the output voltage will change with the placement of the object (Zumbahlen, 2008).

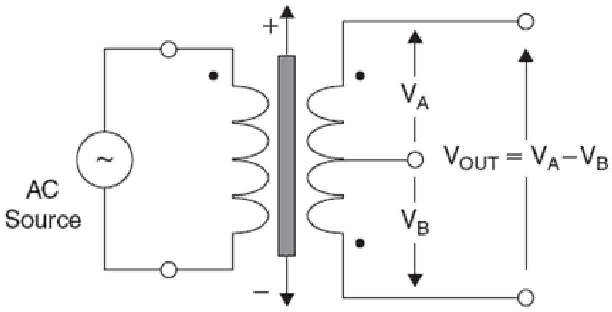


Figure 3.6 *The primary coil is to the left of the conducting object and the secondary coils are the two to the right. The output voltage is the difference between the secondary coils voltage´s.*

The conductive object can either be ferromagnetic or electrically conducting. This will have an impact on how the output varies with the displacement of the conductive object, see Figure 3.7. If the encoder would have the structure as in Figure 3.5, only one coil pair, the signal would be one sinusoid.

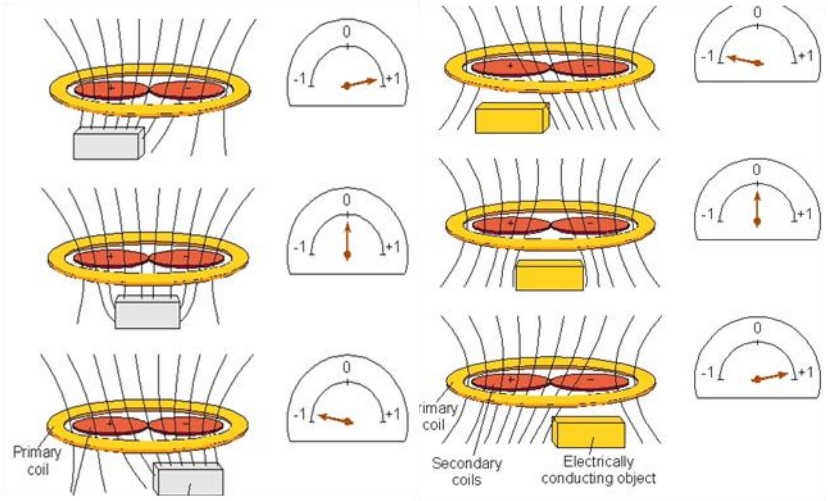


Figure 3.7 *The first figure describes how the output voltage corresponds to a ferromagnetic object. The magnetic field moves towards the object, while it is the reverse for the electrically conductive object, which is described in the seconds figure. Hence, the magnetic field moves away from the object.*

However, Posic uses two secondary coil pairs which are placed in such a way that there are two sinusoidal signals as output but with a phase shift of 90 degrees to each other, as can be seen in Figure 3.8.

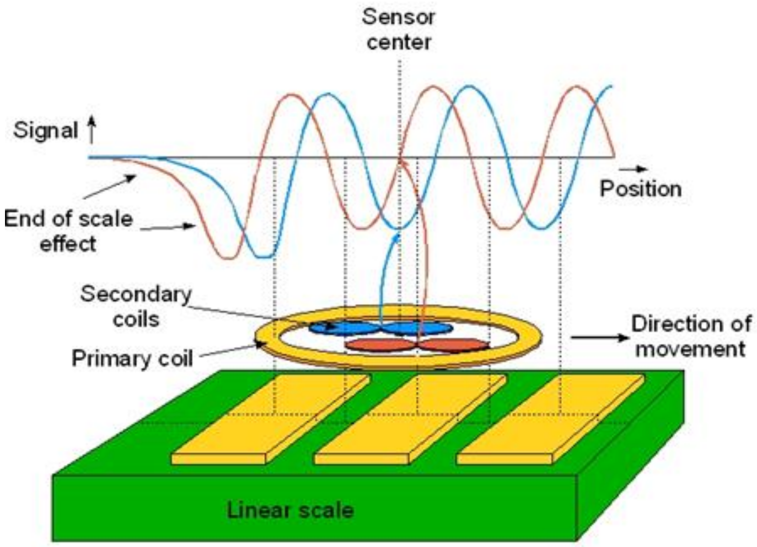


Figure 3.8 *The two secondary coil pairs generates two sinusoids which differ 90 degrees to each other, hence a sin- and a cosine-wave. At the end of the scale the signals goes to zero. The linear scale should then be one period longer than the measurement length.*

The output is therefore quadrature and by interpolation the signals can be expressed as bits, see Figure 3.9. Posic´s linear scale can handle an interpolation scale up to 1024 times per period. This is equal to 4096 states per period where one period is equal to 1.2 mm, hence the length between two markers on the scale. This will result in a resolution of 0.3 µm, since 1.2 mm / 4096 is equal to 0.3 µm for the linear scale sensor.

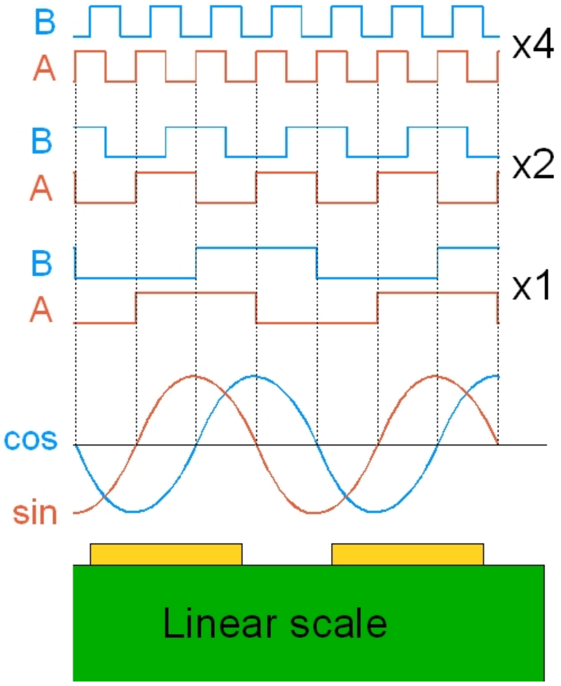


Figure 3.9 *The figure describes interpolation of the two signals at four different resolutions. Higher interpolation factor gives higher resolution, whereas the highest interpolation factor is times four which results in four bits per period.*

Posic states also that the sensor is robust against noise which otherwise can be a problem for systems based on magnetism. There also several ways to compose the sensor for different requirements.

Table 3.7 *ID1101L Dual Channel Linear Encoder specification list*

Resolution	0.3 mm – 0.3 µm
Accuracy	Not given
Sample rate	Maximum 200 kHz
Update rate	Not given
Latency	Not given
Out data	Quadrature output with index pulse
Cost/unit	425 €

3.1.2 Roll movement

As stated before LED and Laser based sensors can be applied to measure rotation and linear movements. The information about these two systems is provided in the previous chapter.

3.1.2.1 Magnetic based sensors

3.1.2.1.1 MAE3 Absolute Magnetic Kit Encoder

MAE3 is a rotary encoder which can measure the position in full 360°, hence (US-digital, 2011). There are two versions of MAE3, either an analog version with 10 bit resolution or a Pulse Width Modulation (PWM) version with 10 or 12-bit resolution. The Kit Encoder is constructed by three parts; a base, a push-on magnetic hub and an encoder body, see Figure 3.10. US – digital doesn't state what kind of magnetic technique they are using.

Figure 3.10 *The three parts of the MAE3 Absolute Magnetic Kit Encoder. The parts are; base, push-on magnetic hub and encoder body.*

3.1.2.1.2 MAE3 – Analog

Table 3.8 *MAE3 -Analog specification list*

Resolution	10-bit equal to 0.35°
Accuracy	< 0,5° at 25 C, but may increase to 0,9° at high temperatures.
Sampling rate	~2,6 kHz
Update rate	2,61 kHz
Latency	Max 384 µs
Out data	Volts, see Figure X.X
Cost	$47.85 (base product)

The analogue version has an output voltage which is linear to the measured rotation degrees, see Figure 3.11.

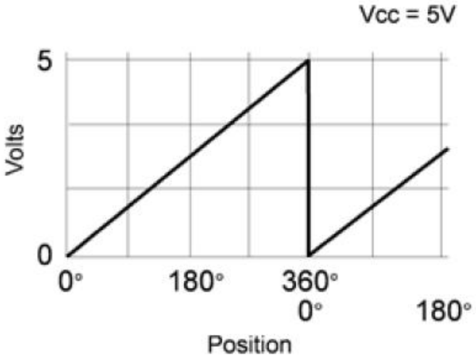


Figure 3.11 *The output voltage of MAE3Analog corresponding to different angles* (US-digital, 2011). *The output voltage is ratiometric to the supply voltage. However, at no load the output voltage will swing within 15 millivolts of the power supply rails.*

3.1.2.1.3 MAE3 – PWM

The accuracy for the PWM version is the same as the analog. There are also several alternatives for the size of the bore (from 2 mm up to 6 mm), two alternatives for the shaft length (5.588 mm or 12.7mm) and three alternatives for the bolt circle (19. 05 mm, 35.512 mm and 46.0248 mm). The output operation of MAE3 PWM is handled by a magnetic RC- oscillator chip and by measuring the duty cycle the angle can be calculated.

Table 3.9 *MAE3 – PWM specification list*

Resolution	10-bit equal to 0.35°, 12-bit equal to 0.08°
Accuracy	0.5° at 25°C, but may increase to 0.9° at high temperatures.
Sample rate	10-bit; 1 kHz 12-bit; 250 Hz
Update rate	10-bit; 0,975 kHz 12-bit; 244 Hz
Latency	10 bit; max 48 µs 12-bit; max 384 µs
Out data	PWM output
Cost	10-bit; $47,85 (base product) 12-bit; 55,98 (base product)

3.1.2.1.4 MRV 50F

MRV 50F from Herbertek works in both incremental an absolute positioning (Herbertek, 2011) and can measure in 360 degrees. MRV 50F uses Hall technique for measuring position, see the chapter about abbreviations.

Table 3.10 *MRV 50F specification list*

Resolution	0.0138˚
Accuracy	±0.17˚
Sample rate	Not given
Update rate	Not given
Latency	Not given
Out data	Volts
Linearity	0.4%
Cost	Not given

3.1.3 Jaw and Pitch movement

MAE3 and MRV 50F which were described in the previous chapter are also applicable for measuring jaw and pitch movements.

3.1.3.1 Magnetic encoder

3.1.3.1.1 ID1101C Dual channel Rotary Encoder Kit

ID1101C from POSIC is based on the same technique as the linear encoder ID1101L from POSIC (Posic, 2010), Figure 3.12.

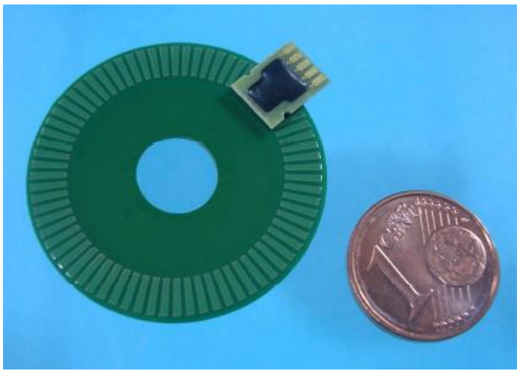


Figure 3.12 *The ID1101C is a rather small sensor and is robust against noise.*

Table 3.11 *ID1101C Dual channel Rotary Encoder Kit specification list*

Resolution	2.8° - 0.08°
Accuracy	Not given
Sample rate	200 kHz
Update rate	Not given
Latency	Not given
Out data	Quadrature output with index pulse
Position error	Typically 0.15°, Max 0.7°
Cost/unit	425 €

3.1.3.2 Potentiometer

3.1.3.2.1 P6500 from Novotechnik

P6500 is an absolute potentiometric encoder with high accuracy (Novotechnik, 2005). The sensor is also able to measure in continuous 360°.

Table 3.12

Resolution	0.007°
Accuracy	0.002%
Sample rate	Not given
Update rate	Not given
Latency	Not given
Out data	Absolute data V
Linearity	±0.06%
Cost/unit	Not given

3.1.3.3 Optical encoders

3.1.3.3.1 A2K Absolute Optical Encoder (kit version)

This is an optical solution from US Digital that has an analogue absolute voltage output (US Digital, 2011). Due to the absolute output there is no need for a calibration, even if the shaft was rotated when the power was off. This is done by an internal EEPROM which stores origin, resolution and direction. As most optical encoders A2K flashes an LED trough a pattern. An encoder reads the pattern and can therefore determine the position.

Table 3.13 *A2K Absolute Optical Encoder specification list*

Resolution	10 - 12 bit, hence 0.35° - 0.087°
Accuracy	Absolute
Sample rate	250 Hz
Update rate	Not given
Latency	Not given
Out data	Volts
Cost/unit	303.50 $

3.1.4 Inertial Measurement Units

Inertial measurement units (IMU) are systems consisting of an accelerometer and gyroscope (Stovall, 1997). With these two types of sensors it is possible to calculate the orientation, velocity and attitude of an object. Gyroscope measures the angular rate and an accelerometer measures the linear acceleration to an inertial frame. Furthermore, the output of a gyroscope is angular rate in a local frame. Therefore the angular rate is integrated twice to distinguish the angle α for the measured object with respect to the inertial frame. This is shown in Figure 3.13. However, this figure is in two dimensions to just show the basic principle of how the system works. In a real system factors like rotation of the earth, that the gravitation differs from different places and the fact that earth is spherical must be taken into account. Another complex area of implementing an inertial system is the many different errors and bias which subdue the performance of the system (Kevin J Walchko, 2002). Bias refers to offsets which the accelerometer can give rise to whereas gyroscope can drift in time. Other factors like temperature and noise must also be taken into account when an inertial system is developed. Normally a Kalman filter is implemented to deal with these factors (Stovall, 1997). The Kalman filter is a recursive method which supports estimations of the past, current and future state of the system and at the same time minimizing the mean of the square error (Greg Welch, 2006).

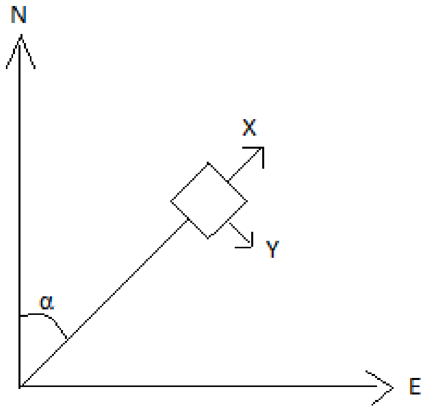


Figure 3.13 *The figure describes an object with a local frame, axis x and y, set in an inertial frame with axis N and E. Angle alpha is the difference between the two coordinate systems. The gyroscope is used to measure this angle.*

There is a lot of ways to construct an accelerometer but one common method is to use the piezoelectric effect (Dimension Engineering LLC, 2011). This method use microscopic crystal structures that are stressed with accelerative forces. These forces generate a voltage that can be measured. The selection of an accelerometer is based on the system in which the accelerometer is implemented. The accelerometer can be selected based on the number of axes it measures, range of detection, bandwidth and power usage. Bandwidth determines how often data can be acquired from the accelerometer while range of detection determines how large changes the accelerometer can detect. Booth these properties determine the precision of the accelerometer and if the range of detection can measure ±250 g, the accelerometer will not be able to detect small movements and the precision will be worse.

A gyroscope can be described of an axis together with a disk (Pearson, 2011). The disk can rotate around the axis almost frictionless. When the disk is not spinning it behaves like any other object, but when the disk starts to spin it will start to resist to some certain axis movements depending on the structure of the gyroscope. This effect is called gyroscopic precession and follows Newton's first law of motion. Gyroscopes have many application areas. For example it can be used to show direction in a navigation system and/or regulate the turning speed in different directions. Together with an accelerometer the two sensors could be used to measure more precise the orientation in a 3 dimensional space because gyroscopes are not affected by gravity like accelerometers so they make a good complement to each other. When selecting a gyroscope the properties should be selected on the needs of the system and the sensing range should be as close as possible to the expected maximum of the range. The number of measured axes is also a property, which should be selected based on the system.

As mentioned before a drawback with an IMU is the drifting over time. This makes the accuracy decrease and an external measurement system is therefore necessary. For outdoors measurement, such in airplanes, a GPS system is often used. In indoor environment a camera system or other sensors can be used to measure the position (VectorNav Technologies, 2010).

Suppliers of IMUs are e.g. Analog devices (Analog Devices, 2011), Imego (Imego, 2005), Xsens (Xsens, 2011) and Vectornav (VectorNav, 2011).

3.1.4.1.1 VN - 100

VN - 100 is an IMU from Vectornav (VectorNav Technologies, 2009). The size of the sensor is less than 2.54 mm which makes it suitable to be placed on an laparoscopic tool. To compensate for errors and bias VN – 100 utilizes an extended Kalman filter which combines an accelerometer, a gyroscope and a magnetometer. The inertial system can be sensitive to other magnetic object. Vectornav handles this by tuning the Kalman filter after how much the magnetic measurement should influence the result. VN – 100 also provides an algorithm which accounts magnetic distortion from nearby objects.

Table 3.14 *VN-100 specification list*

Resolution	<0.05°
Accuracy	<2.0°
Sample rate	200 Hz
Update rate	Not given
Latency	Not given
Out data	Not given
Cost/unit	Not given

3.2 Complete Systems

This chapter describes systems which are fully developed for measuring positions of an object.

3.2.1 Optical systems

Optical systems are systems which are applying the physics of light to distinguish movements and the position of an object. Since light is an electromagnetic wave, systems based on infrared (IR) light and laser will be covered in this chapter.

There are several different types of optical systems. One common method utilizes a combination of cameras and markers. The markers are placed on the measured object which the cameras are tracking. These markers can either be passive or active. Passive markers refer to markers which reflect light from a source close to the cameras. The cameras can then be adjusted to only sample light above or below a set threshold. Active markers generate a light by their own, which then can be measured by the cameras.

Optical systems with no markers will also be covered.

3.2.1.1.1 Oqus

Oqus is a rather small, weight 1.9 kg, motion camera system from Qualisys which can also be used as a high-speed camera recorder (Qualisys, 2011). The communication from a camera to a computer is normally done by an Ethernet cable, with a speed of

100 Mbps, but could also be done by WLAN, with a speed of 54 Mps. There are three different series of Oqus; the Oqus 1, 3 and 5 series. The differences between the series are the optical sensors. This results in that the user can specify their camera after performance and price. Qualisys claim that due to the high resolution the camera is able to use small markers without influencing the accuracy. They also state that their solution is made to minimize the latency from sensors to the computer. It is able to send the marker´s position as soon as the data is read out from the sensor. The camera has also an integrated time-stamping which makes the latency calculation fast and precise. Oqus can also measure active as well as passive markers. The price for a camera is 60 000 SEK, but varies depending on what lens is applied, and the needed software cost around 90 000 SEK.

Figure 3.14 *Oqus from Qualisys is a small high resolution camera.*

In a research report from 2009 was Oqus used for measuring tooth movement in a 3D-enviroment (Dr Helen Liu, 2009). The accuracy was ranging from ±1,7% up to ±2,37% in the range 20-200 µm. The accuracy was different due to what markers they used on the tooth. The resolution was measured to be 10 µm. The researcher also states that the motion analysis system can be used to measure movements in the micro meter level.

Table 3.15 *Oqus specification list*

Resolution	Not given
Accuracy	Not given
Sample rate	1 series; 250-1000. 2 series; 500-10000. 3 series; 180-10000.
Update rate	Same as sample rate
Latency	4.2 ms
Out data	Marker coordinates
Cost/unit	60 000 SEK

3.2.1.1.2 ProReflex MCU

ProReflex is another motion capture camera from Qualisys (Qualisys, 2006). There are four different models of MCU120 which operates in 120 Hz, MCU240 operates in 240 Hz, MCU500 in 500 Hz and MCU1000 in 1000 Hz. Qualisys states that since ProReflex uses a resolution of 20000x15000 subpixels makes the camera able to detect movements around 50 µm. However, ProReflex is an expired product, but is available lower price than other solutions from Qualisys.

Table 3.16 *ProReflex specification list*

Resolution	Not given
Accuracy	Not given
Sample rate	1 -1000 Hz
Update rate	Not given
Latency	Not given
Out data	Not given
Cost/unit	25 000 SEK

3.2.1.1.3 Polaris Family of Optical Tracking Systems

Ndigital (NDI) uses an optical position-tracking device that works as a sensor and detects infrared-emitting or retro-reflective markers that are fixed to an object (Ndigital, 2011). Hence, the tracking device can use both active and passive markers.

The system itself is divided into two different products, which can be combined in many ways depending on the field of use. The first configuration is called Polaris Vicra® which is the basic system. This system works only with passive markers and the size of it is smaller than the other system. The second configuration is called Polaris Spectra® as is shown in Figure 3.15, which has two under laying products, passive Polaris Spectra® and hybrid Polaris Spectra®. The later configuration works with active as well as passive markers. All configurations are able to use wireless active markers.

Figure 3.15 *Passive Polaris Spectra System®, which consists of a position sensor, a USB converter and a power adapter.*

Furthermore, the markers in a passive system need to be replaced after single use, which is less cost effective and the configuration itself becomes troublesome. However, NDI states that the system itself is easy to setup and has a manageable API.

Table 3.17

	Passive Spectra	*Vicra*
Resolution	Not given	Not given
Accuracy	0.25 or 0.30 mm depending on what markers are used	0.25 or 0.35 mm depending on what markers are used
Sample rate	Not given	Not given
Update rate	60 Hz	20 Hz
Latency	Not given	Not given
Out data	Not given	Not given
Cost/unit	Not given	Not given

3.2.1.1.4 PrimeSensor™ Reference Design

PrimeSense is the maker of the control unit in the Xbox kinect controller (PrimeSense, 2010). They have developed a system on chip called PS1080. This chip is a multi-sense system, which provides a synchronized depth image, a color image and an audio stream and it is markerless. To create the images the chip projects the scene with an IR light-coding image. The image is then read by a complementary metal oxide semiconductor image sensor and processed by the PS1080 chip. The processed image can then be compared to the previous image to determine orientation and movements.

Figure 3.16 *PrimeSensor is a camera system which is used e.g. in game control unit Xbox kinect controller.*

PrimeSense is offering a reference system that offers simple API and easy installation. The solution is also immune to ambient light and has a USB connection to the monitor.

Table 3.18 *PrimeSensor specification list*

Resolution	x/y: 3mm z: 1 cm at 2m
Accuracy	Not given
Sample rate	60 fps
Update rate	Not given
Latency	Not given
Out data	Not given
Cost/unit	Not given

3.2.2 Magnet tracking systems

Magnet tracking systems consists of a transmitter and a receiver (Tatar, 2006). The transmitter uses pulsed coils to create magnetic fields. The receivers are magnetic sensors which can determine the strength and angles of the fields. The pulsed magnetic field can either be AC or DC. Systems using AC may have a better resolution than the DC alternative but is more sensitive to eddy currents and other magnetic objects (Ascension Technology Corporation, 2009).

3.2.2.1 TrakSTAR from Ascension

Ascension use DC magnetic fields. According to Ascension is the use of pulsed DC less affected by distortion to other magnetic surfaces by more than 80% compared with AC (Ascension Technology, 2010). They also mention if two sensors with AC technique are close to each other, less than 33mm, they can cause interference. The system has six degrees of freedom and can be utilizing different sensor configurations. The difference between the sensors is the size, ranging from 0.9 mm up to 8.0 mm.

The size of a sensor determines how far away it can be placed from the transmitter and in the same time live up the resolution and accuracy specifications.

Table 3.19 *TrakSTAR specification list*

Resolution*	Position 1.4 mm; Orientation 0,1˚
Accuracy*	Position 1,4 mm; Orientation 0,5˚
Sample rate	Not given
Update rate	240 Hz
Latency	Not given
Out data	X, Y, Z positional coordinates, orientation angles, orientation matrix or quaternion
Cost	> 3000 €

*Depending on sensors and transmitter that are used. The mean value of different selections is however around the specified values for both accuracy and resolution.

3.2.2.2 FASTRAK from Polhemus

In contrast to Ascension's solution uses FASTRAK AC magnetic sensors (Polhemus, 2010). Polhemus argue that using AC magnetic fields results in a better SNR, improved accuracy and have faster update rate. However, as written before Ascension claims the opposite (Ascension Technology Corporation, 2009). As with TrakSTAR from Ascension can Fastrak measure in six degrees.

Table 3.20 *FASTRAK specification list*

Resolution*	*See Figure 3.17*
Accuracy*	Position: 0,762 mm RMS; Orientation: 0,15°
Sample rate	Not given
Update rate	120 Hz (divided by number of sensors)
Latency	4 ms
Out data	X, Y, Z positional coordinates
Cost	4s755 €

* *The system will provide the specified performance when the receivers are within 76,2 cm (30 inches) of the transmitter.*

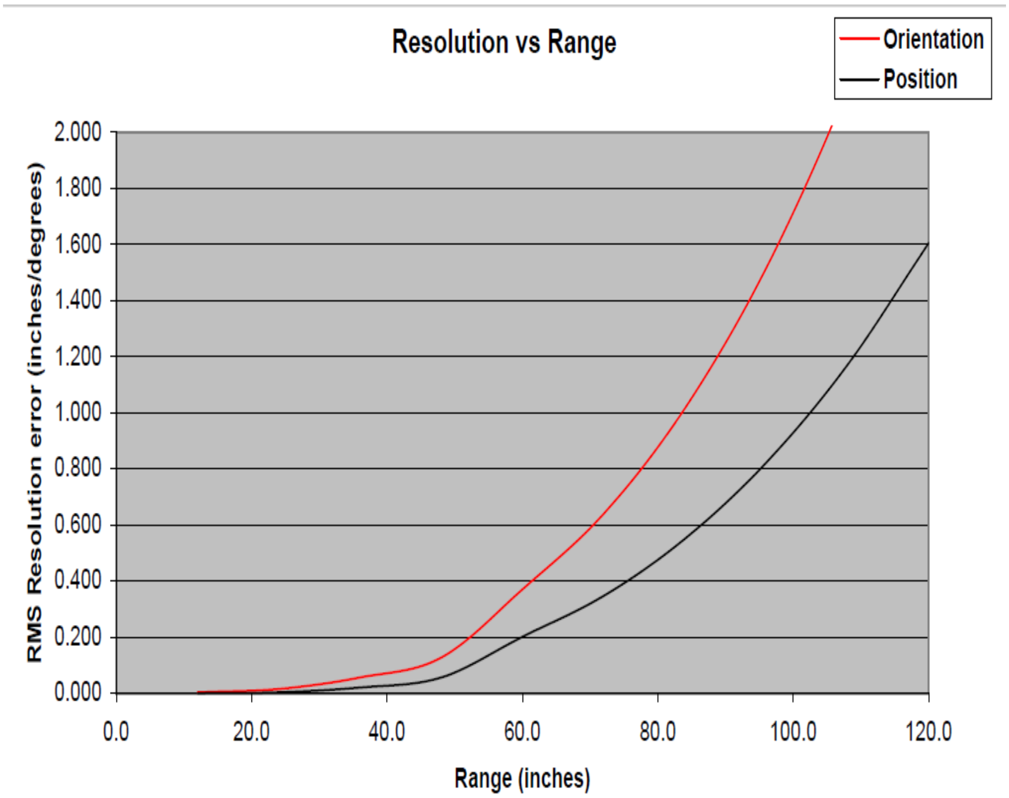


Figure 3.17 *The figure describes how the resolution of the system changes due to the range between sensor and transmitter unit.*

4 Results

4.1 Weighting of solutions

The solution will be divided into three areas. First is linear movement and second the roll of the tool, third is the movement in x and y, which is yaw and pitch. The selection of the solution will be based on the requirements below[1], theses requirements are prioritized and set by Surgical Science. The requirement D.4, Grasper resolution 8 bits, will not be considered high when weighting solutions for precision, since the focus of the project lies with the movement of the tool.

A. General requirements
   - A.1 Low cost
   - A.2 Robust
   - A.3 USB interface
   - A.4 Easy calibration
   - A.5 Size
   - A.6 Quick response

B. Inputs
   - B.1 Minimum of two buttons
   - B.2 More buttons

C. Working volume/range
   - C.1 Insertion range 200-250 mm
   - C.2 Unlimited rotation around z-axis

D. Precision
   - D.1 Resolution 0.1 mm
   - D.2 Movement error A->B->A RMS 0.1 mm
   - D.3 Rotation angle 0.25°
   - D.4 Grasper resolution 8 bits

These requirements have also been weighted and compared with each other to determine their individual weight and how much it determines the final system. Precision requirements together with the requirement for robustness, quick response and insertion range are all requirements that have greater value then the others in the final system Figure[2] 4.1 the requirement value matrix by (Joachim Karlsson, 1997) below shows each requirements weight in percent.

---

[1] More details about the requirements can be found in Appendix A

[2] More details regarding the diagram and the method that has been used is detailed in The Analytic Hierarchy Process by Karlsson and Ryan (Joachim Karlsson, 1997).

The method in short can be divided into 4 steps:

Step 1. Setup all the requirements in and n×n matrix.

Step 2. Perform a pairwise comparison of all requirements, the values ranges from 1 - 9, where 1 is of equal value, and 9 is of extreme value. The values are all based from Surgical Science demands[3].

Step 3. Normalize each column to get eigenvalues of the matrix.

Step 4. Calculate the relative value based on the eigenvalues to get each requirements' weight in percent which can be found in figure 4.1 below.

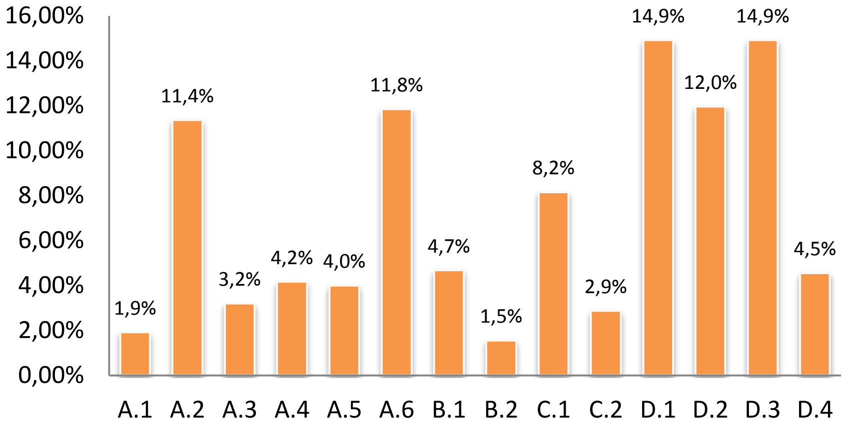


Figure 4.1 *As The diagram shows the importance of each requirement. The requirements resolution and accuracy are of higher importance compared to the other requirements and the requirements for more buttons and low cost have the lowest importance.*

Each requirement now has its own weight and this weight will later be used to determine a winning solution. Some solutions are already a complete solution but there are also components and technologies that can be put to together into one complete solution. The components have been brought together into the fields which they belongs to which can be seen below. Each component within each field have been analyzed and compared with each other. For the final complete systems, only the best matched systems have been considered.

---

[3] The matrix can be found in Appendix C

Linear movement

- Optical sensors
  - Mouse technology
  - Linear sensors

Roll movement

- Optical sensors
  - Mouse technology
- Rotary encoders
  - Potentiometric sensors
- IMU technology

Yaw and pitch movement

- Optical sensors
  - Mouse technology
- Rotary encoders
  - Potentiometric sensors
- IMU technology

There were 3 different complete systems setups as can be seen in figure 4.2 below where each technology is matched up depending on the criteria they belong to.

Number Criteria	**1**	**2**	**3**
Linear movement	Mouse sensor technology	-	Linear sensor
Roll movement	Mouse sensor technolgy	IMU technology	Potentiometric sensors
Yaw and pitch movement	Mouse sensor technology	IMU technology	Potentiometric sensors

Figure 4.2 *All solutions have been put together into a morphological matrix, where each row refers to each area of solution.*

There can be a number of selected combinations form the matrix. But there are some combinations that do not add up to the rest and in the end only two combinations of solutions were selected. If mouse sensors are used for linear movements, there is no need to pick any other sensor for roll movement. Magnetic sensors, which include rotary and linear solutions, have been removed because of their sensitivity to other magnetic object.

There is merely no difference in price between LED and Laser based sensors. The Laser sensors are more accurate and are able to function more properly on different kinds of surfaces compared to a LED sensors, hence, the LED sensors were excluded from the selection.

IMU technology is not an option either because it is has a drifting issue when the IMU has been powered up for a long time. For a robust system were accuracy is of greater importance in the system this kind of technology is not enough. The accuracy can however be improved but it gets very expensive when selecting these IMU. IMU could however be used in combination with other solutions to calibrate the instrument during start up, but this will not be covered in this project.

In the end two combinations of solutions have been selected from the matrix and are moved to the final Pugh matrix for comparison. These two solutions are:

Solution 1 - Avago system:

- Linear movement
    - Mouse technology using ADNS-7550
- Roll movement
    - Mouse technology using ADNS-7550
- Yaw and pitch movement
    - Mouse technology using ADNS-7550

Solution 2 - Posic system:

- Linear movement
    - Posic linear encoder
- Roll movement
    - Posic rotary encoder
- Yaw and pitch movement
    - Posic rotary encoder

A number of different full solutions are put together and are compared with the system that Surgical Science is using today. These systems have detailed descriptions in the previous chapter. These systems are trakSTAR, FASTRAK, Oqus, ProReflex, Polaris Family and PrimeSensor™, and by being a complete system they do not need to be assembled to be functional like the other solutions. The system, which Surgical Science uses, is the G-CODER system simball™ 4D[4] and it is chosen to be the reference system for comparison with the other solutions.

All these systems have been placed in the Pugh matrix[5] and compared and weighted according to the diagram above. The winning solution from the Pugh matrix was the Avago system and the second solution was the Posic system, but the small compact configuration, flexibility and the price of the Avago system was better than the Posic system. The Avago system also offers different kinds of system setups. This is because the sensor does not need to be in contact with the surface it should measure, and the system also offers image analysis of the surface it covers, which can be used for calibration.

---

[4] Specification list regarding simball™ 4D can be found in Appendix B

[5] The Pugh matrix can be found in Appendix C

4.2 Prototype development

Two prototypes were developed. The first version that didn't work but the second one did work. The problem with the first prototype was the selection of the electronic components and the setup of the sensor with the first version of the PCB board. The problems itself concerned length between the electronic components[6] and the sensor.

When the selection phase was completed, the selected sensor was ordered from Avago Technologies. The ordering process took some time and there was some delay until receiving the sensor. A simple microcontroller was also ordered to communicate with the sensor, and the selection of microcontroller was majorly based on the simplicity of the microcontroller when it comes to programming the sensor. The microcontroller should also be able to handle the specifications required of the sensor, and therefore the Arduino Uno USB board, (Arduino, 2011) was selected due to its simplicity, it is well documented and several application examples, including programming code, are available. The programming language of Arduino is a simplified form of C and C++, hence libraries from C and C++ can be used.

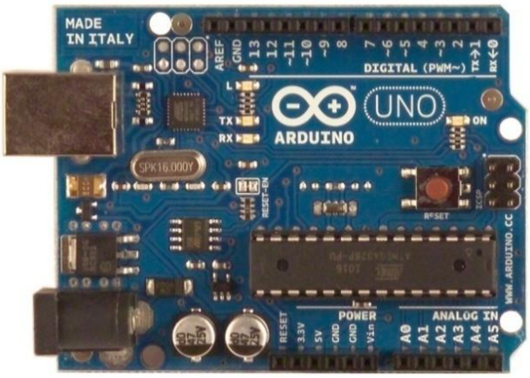


Figure *4.3 Arduino Uno board. ATmega328 is the microcontroller which is standard for Arduino Uno. Arduino develops complete platforms which makes programming and communication with a microcontroller more adaptive and straightforward.*

The work can be divided into three steps; create a PCB for the sensor, order the components for the sensor and finally write programs for the microcontroller to communicate with the sensor.

The first step was to construct the PCB. The PCB schematic was constructed in EAGLE with the dimensions mentioned in the data sheet. The sensor was not in the standard library in EAGLE and therefore this component had to be created in EAGLE. The figure below is the first PCB schematic made in EAGLE for the first prototype. The schematic is only made for the ADNS-7550 sensor and every pin had to be connected to a breadboard as no other components can be implemented in this PCB.

---

[6] The components is based on selected components matched the component list for the Avago mouse sensor. First through hole technology components were used than SMC was used instead to exactly match the component list in the Avago data sheet for the sensor. Hereafter the components will be referred only as components.

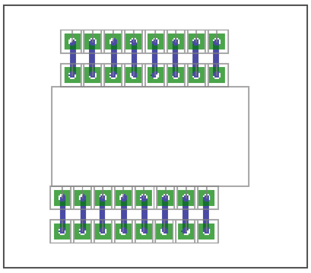


Figure 4.4 *The first PCB schematic which was made in the software program EAGLE. Pin holes are placed very close to the sensor pins.*

This prototype did however not work, due to the length of the connection between other components and the sensor. The second PCB was made with integrated circuits for the components connected to the sensor as well as connection inputs for the sensor to the microcontroller as well as power supply.

The next step was to order the components that were required for the sensor to work. The components were all within the specification of the datasheet and was all ordered from ELFA (ELFA, 2011). The component list can be found in Appendix F for both prototypes. For the first prototype THT was used and for the second prototype SMC. The components for the first prototype were placed on a breadboard and then connected to the PCB based on the first prototype board, which did not work. The components for the second were placed as seen in the figure above.

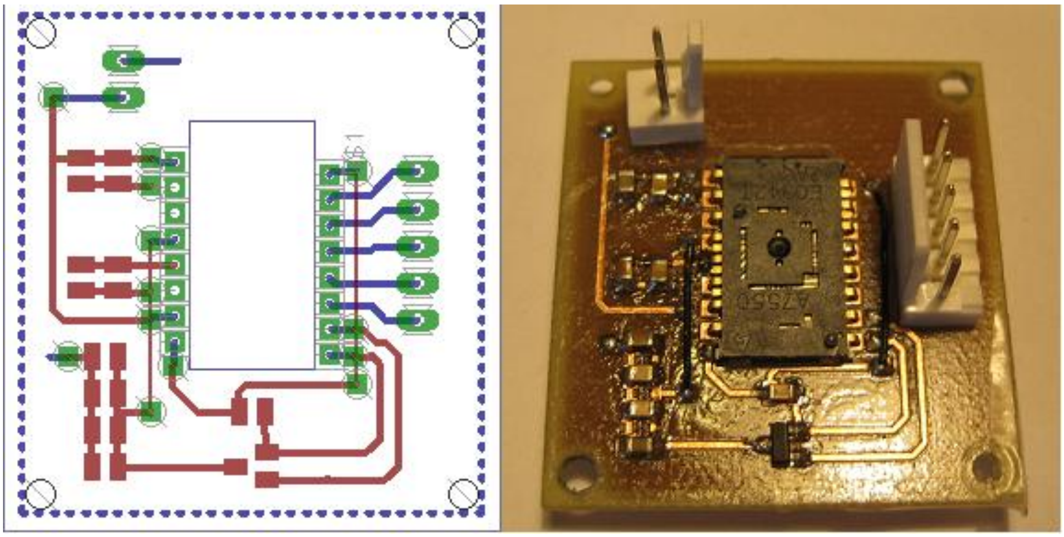


Figure 4.5 *The second schematic, to the left, and the resulting PCB, to the right. SMC and pins for easier attaching SPI cables and power supply are led into the PCB. There are holes in every corner for mounting the PCB to another device easier.*

The third step was to program the microcontroller to control and receive data from the sensor. Recommendations from the datasheet were followed to get the best performance out of the sensor. The sensor is communicating with the Arduino Uno with the SPI interface. The SPI interface allows the microcontroller to synchronously transfer and receive data from the sensor (EE Times, 2002). The data sent and received by the sensor is in a 8 bit shift register and is shifted out with the SPI clock of the microcontroller. The SPI clock in Arduino Uno can be adjusted, and for ADNS-7550 the SPI clock should be 1 MHz.

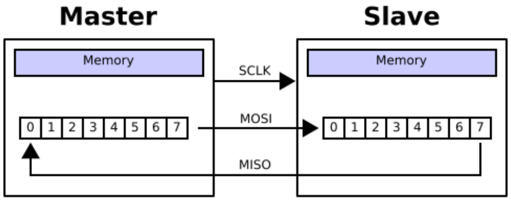


Figure 4.6 *The picture shows how data from master, in this case the Arduino microcontroller, is shifted out to the slave, ADNS-7550, and each bit from the slave is at the same time shifted out during each pulse of the clock* (Wikimedia Commons, 2010).

The SPI also includes a slave select functions which the master controls and with this function the master can control and communicate with more than one sensor. The microcontroller is the master. The SPI output pins on the Arduino Uno are located from pin positions 10-13 and each pin represent the following:

- 10 Slave select
- 11 Master output slave input, MOSI
- 12 Master input slave output, MISO
- 13 SPI clock

A digital pin on the Arduino Uno be used to select a slave device.

ADNS-7550 SPI protocol works in two ways. The microcontroller can write data to the sensor or read data from the sensor, depending on which operation the microcontroller should do. The microcontroller always has to address the correct register address before it could either read or write to that register. With read operation the most significant byte (MSB) should always be 0 and write operations the MSB should be 1.

The code was first programmed to control one sensor, but later it was configured to control two sensors and this code can be found in Appendix D. When the Arduino Uno receives data from the sensor through the SPI it transfers the data to the serial port, which for Arduino Uno is an USB connection. This data can then be interpreted by a program on the host computer, e.g. LapSim.

Instead of using LapSim, which needs drivers to interpret the data to visual the sensor movements, the LabVIEW program was used to track the movement. The graphical code schematic for the program can be found in Appendix G. The program will read the data from the serial port and print it in an x-y graph where the scale corresponding to the sensor movements in pixels, see Figure 4.7. The sensor itself report the change in position in pixels from last report and the data is based on a binary number representation system that is called two's complement. This makes the sensor able to report both negative and positive values.

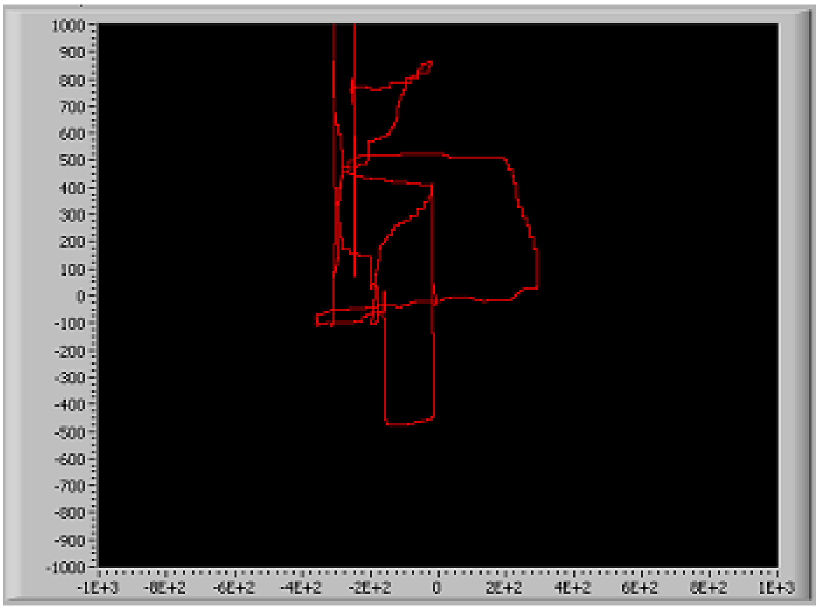


Figure 4.7 *The figure shows the position change of the ADNS -7550.*

4.3 Test results of ADNS 7550

4.3.1 Measurement of accuracy and resolution

The test was performed by attaching the sensor to a stable suspension construction, see Figure 4.8. This construction was placed over a moveable wooden board where the moveable distance was set to 46 mm. By pushing the wooden board back and forth within this distance the accuracy could be determined, see Figure 4.8.

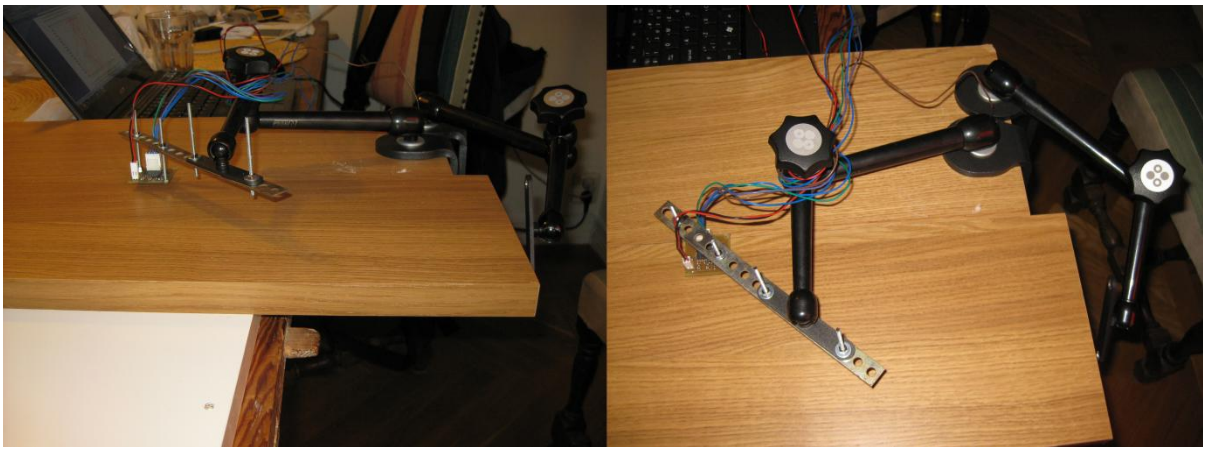


Figure 4.8 *The test rig which includes the sensor, a suspension construction, and a board. The right image shows the distance by which the board was moved.*

The sensor was configured to run with a resolution of 2000 CPI, hence with a distance of 0.0127 mm between every dot. The Figure 4.9 shows the result of the measurement.

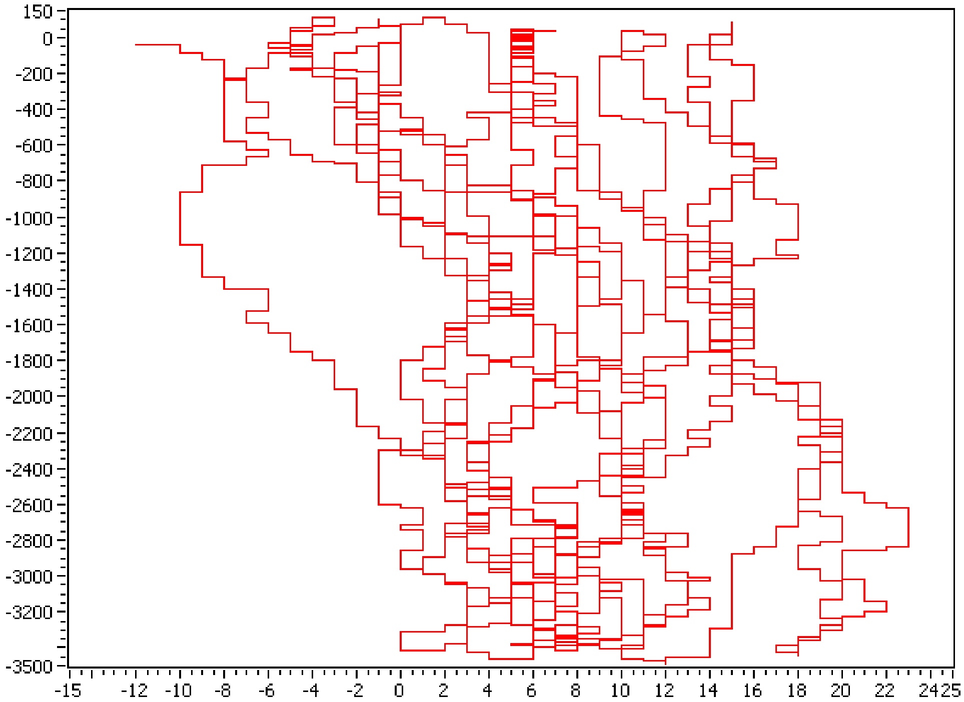


Figure 4.9 *The graph shows how the wooden board was moved a distance of 46 mm eight times. It's the Y- axis which is of real interest since the drifting in the X-trail is due to the tree board is not mounted completely straight. The range of the Y-axis is set to 3600 CPI, which is almost equal to 46 mm.*

By measuring the end values on the Y-axis in Figure 4.9, the mean and variance values could be calculated. The maximum values were measured to 52.9 ± 36.8 CPI. The minimum values of the mean and variance were measured to -3431.9 ± 11.7 CPI. The average values of the variances were then calculated to 23.7 CPI, which is equal to 1.1 mm.

Table 4.1 *End values from measuring a board moving 46 mm.*

Max values [CPI]	Min values [CPI]
-39	-3415
110	-3465
100	-3410
108	-3400
50	-3490
84	-3390
40	-3445
-30	-3440

The resolution was calculated to 0.01mm by measuring the amount of counts in 46 mm.

4.3.2 Parallel working sensors

Two sensors were attached to a laparoscopic simulator machine body to measure the ANDS-7550 ability to work simultaneously, see Figure 4.10.

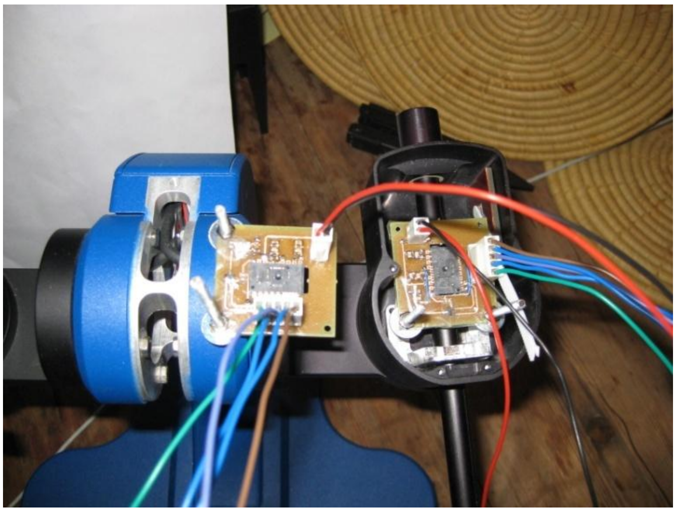


Figure 4.10 *Two sensors attached to a laparoscopic machine body. The length, rotation and pitch movement was measured, hence three degrees of freedom.*

One sensor measured the roll and length movements while the other measured the pitch movement. Hence, three degrees of freedom were measured. Two diagrams in LabVIEW where created to follow each sensor´s movement, see Appendix G. The test showed no perception delay between movements of the instrument and the corresponding result in LabVIEW.

4.3.3 Surface quality tests

Surface quality (SQUAL) is the measure of valid features visible in the current frame. The maximum value is 242 and is nearly zero if there is no surface below the sensor. To get the optimized SQUAL value the sensor should be placed at the nominal z-height from the measured surface. Table 4.2 shows different SQUAL values corresponding to different materials.

Table 4.2 *SQUAL values of different surfaces*

Material	*Mean value*
Foil	214
Laminated tree	162
White paper	130
Soft mouse pad material	147
Immersion tool material/ black metal	165

4.3.4 Calibration sequence

ADNS-7550 was also tested for how it could be implemented to be used for calibration of the instrument. By reading a specified register which in result gives the average pixel values could the starting position of the sensor be determined. However, it is important to take into account that ADND-7550 read gray levels in a way which is not very similar the human eye. Almost black surfaces for the human eye can be interpreted by the sensor as almost white. Therefore it is necessary to choose correct materials of the instrument if a calibration sequence with ANDS-7550 is to be applied.

5 Discussion

5.1 Solutions

In this report we have compared different measurement systems, weighted and ranked them after how they meet the requirements given by Surgical Science. Even though this is a quite efficient method to compare different solutions it may not always be very accurate. A solution which gets just a couple of more points than another may not be more applicable. This was one of the reasons why we programmed and did tests on ADNS -7550 which is typically used in computer mice. Other major reasons were due to the low cost, small size and high resolution which made the sensor interesting for further investigations by Surgical Science.

5.1.1 LED and Laser based sensors

LED based sensors are cheap, robust, small and work on all reflective surfaces with small deviations. The sensors also uses a low current to operate and can go into sleep state which can be regulated by a pin on the sensor which reports if movements have occurred. This makes this sensors perfect for wireless operations.

The problem with LED based sensors is that they do not work well on smooth, gloomy or glass surfaces. The readings will get less accurate or give misreads or jumpy readings. The specification for LED sensors is however within the requirements but with the exception of misreadings on surfaces other than those specified for LED sensors.

The Laser based technology works in a similar way as the LED based technology except that Laser sensors sense movements on almost all surfaces. Sensors based on Laser also use low current and does not differ much in size compared to LED sensors. However, overall outperform Laser sensors LED sensors on all levels when it comes to accuracy, movement registrations speed etc. More discussion about Laser sensors can be found in chapter 5.2.

5.1.2 Magnetic tracking devices

Magnetic tracking devices are very easy to implement and use. Several complete measurement systems already exists. Hence, no need for making any major adjustments, which will probably make the implementation phase quite short.

The main advantage is the flexibility. The sensor can be fixed to the instrument wherever you want. Furthermore, the output from the device to the PC will be in Cartesian coordinates.

A disadvantage with the Ascension solution is that it doesn't meet the specification-document. However, a more expensive model could meet the requirement. The costs for the two solutions are very high. Another disadvantage, which Ascension mention, is that two sensors placed close to each other or magnetic and conducting objects that are placed closed to the sensors can cause interference.

There is also a disagreement of what magnetic method is superior between Polhemus and Ascension. Polhemus argues that AC magnetic is the best choice while Ascension argues that DC magnetic is the best alternative. However, Ascension system seems to be more reliable due to published data concerning this area. Magnetic tracking devices are still very expensive, but if the cost of the systems is reduced in the future it is recommended to look more into these kinds of systems.

5.1.3 Optical systems

Video tracking systems, as well as the magnetic tracking systems, are expensive. However, with the cost come great resolution, speed and reliability where all these parameters meet the requirements. We never got our hands on any systems, but people who have tried the ProReflex system says it is easy to setup and apply. Another negative side, except the cost, is that the sensors can be blocked. If something is between the markers and the cameras there is no information. This situation can of course also occur with the markerless systems. The calibration of a camera system may be another negative aspect. Calibration of the measured object has to be done for every new placement. This makes the system not very flexible. Due to these negative aspects an optical system is not recommended to implement.

5.1.4 Inertial systems

Inertial systems are very complex systems where many parameters have to be taken into account to get a good result. Calibration for disturbances from magnetic materials and that the fact that the earth´s gravity varies for different places must be taken into account. Drifting in position is also very common and therefore is a second measurement system a necessity. In airplanes, where inertial systems are used, is this solved by using GPS but for measurements indoors a camera system can be applied. This makes the system less suitable for measurement of a laparoscopic tool. However, if the drifting problem is solved inertial systems may become very suitable, since the sensors can measure in six degrees and have a satisfying resolution. Then only one sensor would be needed for positioning measurements. Due to drifting problem we recommend that if an inertial system is to be implemented it should only be used for calibration.

5.1.5 Rotary and linear encoders

Sensors which only measure one degree of freedom are a reliable and robust way to measure. However, the most accurate and robust solutions, like the rotary encoder A2G from US digital or the sensors from Posic, are quite expensive. If the requirements are involves a robust and accurate solution where the final price of the product is not the most important aspect it is recommended to apply rotary and linear encoders.

5.2 Prototype testing and development

The development of a prototype using ADNS-7550 has been the most time consuming part of the project. Malfunction of the sensor was a great problem. However, by using SMC components instead of THT components the problem was solved. We don’t know why this fixed the fault, but it could be that the length between the components is shorter with SMC which makes the signals less noisy. By implementing SMC components in an earlier phase of the project the project time could be reduced extensively. But, the support from Avago was not very forthcoming and we didn’t think that the problem was the size of the electrical components.

The tests showed sufficient results. However, the testing equipment was not of a very high standard. By using a wooden board, which is not very straight, the accuracy measurements may not be very accurate. The resolution was measured to a sufficient level and two sensors worked very smoothly together with no noticeable delay. Due to the very high resolution it is very important that the sensor is mounted to the machine body in an exact position. Drifting in non wanted directions could otherwise very likely appear, see Figure 4.9. The current material which the Immersion tool is made of showed good surface quality. But, the material seems dark for the human eye but the sensor will still interpret the gray level quite bright. A darker tone is therefore recommended to the tool if a calibration sequence is to be applied.

We had planned to mount a third sensor to measure all the degrees of freedom. But, the drill machine faulted and we could therefore not finish this task. The sensor with the PCB is quite a small package and is very easy to mount to a machine body. Compared to the Surgical Science´s currently solution, Simball 4D, is the resolution higher with ADNS- 7550 but the accuracy may be less true. However, as stated is the price very low for what you get. An easy calibration method together with high resolution and straightforward assembly makes ADNS-7550 a good alternative to Simball 4D and more established sensors such as rotary and linear encoders.

6 Conclusion and recommendations

The ADNS-7550 is a precise and accurate sensor, but sensitive, which we discovered during our tests. We had some problems with fixing the sensor in place, which somewhat affected our test results. This could be improved but not with the equipment, and time we had left for the project. There is no doubt that the sensor would prove much better with a setup and a construction better suited for the sensor.

The major advantage with the sensor, compared to other solutions, is its low cost and the possibility of the freedom from the surface it measures. This means it will be no wear on the tool, more than the rotation. The production cost of an instrument could also be much less than that of a Simball 4D, where the market price is above 30 000 SEK. The sensor does not need any expensive electronic components to control it other than capacitors and microcontrollers.

The sensor could be used with LapSim with the right drivers developed to connect the sensor to LapSim. With a complete system a number of nine sensors should be used, six for the surgery tools, three in each tool, and three for the camera tool. Each tool should be connected to the PC using an USB connection. With this sensor configuration and with a proper construction of the tool it should work as good as any solution on the market today.

6.1 Future improvements

As we said above the test needs to be improved to justify the sensor accuracy and for that the sensor needs better testing equipment. The sensors needs to be fixed properly at the measurement position. For this we used tools that were meant for rotary encoders.

With a proper tool there should also be improvements to the PCB to make it smaller which makes the tool smaller as well. The PCB should be able to be constructed almost as small as the sensor with the output pins.

Avago technologies is constantly improving their supply of sensors and recently they released an even smaller sensor but with better specifications and a better accuracy. This sensor is called ADNS-9500, and with this sensor the PCB could be even smaller. It is recommended to use this sensor instead of the sensor ADNS-7550 in this project, as it has and resolution of 6000 instead of 2000 CPI.

The connection between LapSim and the sensor needs to be tuned to work smoothly when the instrument is moved. With this we mean that the movements of the tool have to match the movements on the screen. This is one of the problem when it comes to light sensors where you manually have to control the sensitivity. If the movement from the sensor is transferred directly to LapSim we can expect a difference in movement when we are using different screens and resolutions. If we only transfer the data as pixel movements. Accordingly we need to take the sensitivity into consideration when making the drivers for connecting LapSim and the sensors.

The calibration is also an area which needs more consideration. The question is how LapSim should locate were the tool is at the moment. The sensor as we know will not translate the absolute location for the tool, and when we say the location of the tool we mean how much the tool is pitched, yawed, rolled and inserted. The ADNS-7550 has the ability to report the average greyscale values but this function has not been covered more than some minor tests in this project. The function however could be used to determine the location and position of the tool with the use of different colours on the measured surfaces of the tool.

Another way to calibrate is to start up with a starting position, and this starting position has to be used every time the tool is powered up. This method however makes it a little bit unstable if the start position moves or is displaced in some way.

7 References

Analog Devices. (2011). *Semiconductors and Signal Processing ICs*. Retrieved June 14, 2011, from Analog Devices: http://www.analog.com

Arduino. (2011, July 11). *Arduino Uno*. Retrieved September 06, 2011, from Arduino: http://arduino.cc/en/Main/ArduinoBoardUno

Ascension Technology. (2010). *3DGuidance trakSTAR.* Retrieved June 15, 2011, from Ascension Technology: http://www.ascension-tech.com/medical/pdf/TrakStarSpecSheet.pdf

Ascension Technology Corporation. (2009). *Magnetic Fact Sheet and Video: DC vs. AC Tracking.* Retrieved June 15, 2011, from Ascension Technology Corporation: http://www.ascension-tech.com/docs/ASCWhitePaperDCvAC.pdf

Avago Technologies. (2009, November 9). *ADNS-3060 High-performance Optical Mouse Sensor.* Retrieved March 30, 2011, from Avago Technologies: http://www.avagotech.com/docs/AV02-0117EN

Avago Technologies. (2010, June 7). *ADNS-6090 Enhanced Professional Gaming LaserStream™ Sensor.* Retrieved March 31, 2011, from Avago Technologies: http://www.avagotech.com/docs/AV02-1362EN

Avago Technologies. (2010, June 10). *ADNS-7550 ADNS-7550.* Retrieved March 31, 2011, from Avago Technologies: http://www.avagotech.com/docs/AV02-0685EN

Dimension Engineering LLC. (2011). *A beginner's guide to accelerometers*. Retrieved June 13, 2011, from Dimension Engineering: http://www.dimensionengineering.com/accelerometers.htm

Dr Helen Liu, D. Y. (2009, June 11-13). Applications of Motion Analysis System Measuring Micro-Movements in Three-Dimensional Space. *Bioinformatics and Biomedical Engineering* , pp. 1-4.

EE Times. (2002, Februariy). *EE Times*. Retrieved September 06, 2011, from Introduction to Serial Peripheral Interface: http://www.eetimes.com/discussion/beginner-s-corner/4023908/Introduction-to-Serial-Peripheral-Interface

ELFA. (2011). Retrieved September 06, 2011, from ELFA: www.elfa.se

G-Coder Systems AB. (2009). *simball 4D*. Retrieved March 25, 2011, from G-Coder Systems AB: http://www.g-coder.com

Greg Welch, G. B. (2006, July 24). *An Introduction to the Kalman Filter.* Retrieved June 13, 2011, from The Kalman Filter: http://www.cs.unc.edu/~welch/kalman/kalmanIntro.html

Herbertek. (2011). *MRV 50F 360 graders analog givare*. Retrieved April 1, 2011, from Herbertek Lägesgivare och Sensorer: http://www.herbertek.se/index.php?sida=3&meny=2&produkt=7

Imego. (2005). *The Institute of Micro and Nanotechnology*. Retrieved June 14, 2011, from Imego: www.imego.com

Immersion Coporation. (2011). *Immersion Coporation*. Retrieved March 25, 2011, from http://www.immersion.com/

Joachim Karlsson, K. R. (1997, September/October). Retrieved September 07, 2011, from A Cost–Value Approach for Prioritizing Requirements: http://www.cse.chalmers.se/~feldt/courses/reqeng/papers/karlsson_1997_cost_value_prioritization_of_requirements.pdf

John A. Sokolowski, C. M. (2009). *Principles of Modeling and Simulation: A Multidisciplinary Approach.* New Jersey: John Wiley & Sons.

Kevin J Walchko, D. P. (2002). *Inertial Navigation.* Retrieved June 13, 2011, from University of Florida: http://www.mil.ufl.edu/publications/fcrar02/walchko_inertial_navigation_fcrar_02.pdf

Lindström, G. B. (2010, Januari 04). *1177*. Retrieved March 23, 2011, from Laparoskopi: http://www.1177.se/Fakta-och-rad/Undersokningar/Laparoskopi/

McLeroy, C. (2008, September 1). History of Military Gaming. *Soldiers Magazine* .

Moore, A. (2009, January 26). *Understanding Quadrature Encoding*. Retrieved March 03, 2011, from prototalk.net: http://prototalk.net/forums/showthread.php?t=78

Nationalencyklopedin. (2011). *Nationalencyklopedin*. Retrieved March 22, 2011, from Nationalencyklopedin: http://www.ne.se.proxy.lib.chalmers.se/sok/simulator?type=ENC

Ndigital. (2011). *Polaris Family of Optical Tracking Systems*. Retrieved June 08, 2011, from NDI Measurement Solutions in Medical: http://www.ndigital.com/medical/polarisfamily.php

Novotechnik. (2005, August). *Standard Potentiometers P6500 Series.* Retrieved April 1, 2011, from Novotechnik Position Sensor Leader: http://www.novotechnik.com/catalogs/pdfs/P6500.pdf

Pearson, C. (2011). *How a gyroscope works*. Retrieved June 14, 2011, from Gyroscopes.org: http://www.gyroscopes.org/how.asp

Polhemus. (2010, December). *Fastrak.* Retrieved June 15, 2011, from Polhemus: http://www.polhemus.com/polhemus_editor/assets/FASTRAK%20Brochure.pdf

POSIC. (2010). *ID1101C Dual Channel Rotary Encoder Kit.* Retrieved March 31, 2011, from POSIC: http://www.posic.com/d2wfiles/document/186/163/0/ID1101C-Rotary-Encoder-Kit.pdf

Posic. (2010). *Posic.* Retrieved March 30, 2011, from ID1101L Dual Channel Linear Encoder Kit: http://www.posic.com/d2wfiles/document/221/163/0/ID1101L-Linear-Encoder-Kit.pdf

Posic. (2008). *Technology*. Retrieved March 30, 2011, from Posic: http://www.posic.com/default_en.asp/2-0-87-12-6-1/

PrimeSense. (2010). *Product Technology*. Retrieved June 09, 2011, from PrimeSense Ltd.: http://www.primesense.com/?p=487

Qualisys. (2011, Arpil 11). *Oqus.* Retrieved June 06, 2011, from Qualisys Motion Capture Systems: http://qualisys46.kaigan.se/archive/product_information_pdf/PI_Oqus.pdf

Qualisys. (2006, September 25). *ProRefl ex MCU.* Retrieved June 06, 2011, from Qualisys Motion Capture Systems: http://qualisys46.kaigan.se/archive/product_information_pdf/AN_ProReflex.pdf

Ryan, D. (2010). *Patent No. U.S 2010/0167253 A1.* United States.

Sensor Control Nordic AB. (2011, March 17). Retrieved March 31, 2011, from Sensor Control Nordic AB: http://www.scn.se

Sensor Control Nordic AB. (2011). *Magnetostrictive linear sensors*. Retrieved March 31, 2011, from Sensor Control Nordic AB: http://www.scn.se/scn/default.asp?lid=1

Shun, A. (2005). *Patent No. U.S 6,887,082 B2.* United States.

Stovall, S. H. (1997, September). Retrieved June 09, 2011, from Federation of American Scientists: http://www.fas.org/spp/military/program/nav/basicnav.pdf

Surgical Science. (2011). *Surgical Science*. Retrieved February 16, 2011, from www.surgical-science.com

Tatar, F. (2006, June 6). *Ultrasound 3D Positioning System for Surgical Instruments.* Retrieved June 15, 2011, from TU Delft Repository: http://repository.tudelft.nl/view/ir/uuid%3A25d80828-efc2-4255-8719-1fd297380109/

US Digital. (2011). *A2K Absolute Optical Encoder: Kit version.* Retrieved June 4, 2011, from US Digital: http://usdigital.com/assets/general/84_a2k_datasheet_1.pdf

US-digital. (2011). *EM1 Transmissive Optical Encoder Module*. Retrieved February 22, 2011, from US-digital: http://usdigital.com/products/encoders/incremental/modules/em1

US-digital. (2011). *HEDS Transmissive Optical Encoder Module*. Retrieved February 22, 2011, from US-digital: http://usdigital.com/products/encoders/incremental/modules/heds

US-digital. (2011). *LIN Transmissive Linear Strip*. Retrieved February 22, 2011, from US-digital: http://usdigital.com/products/encoders/incremental/linear/lin#description

US-digital. (2011). *MAE3 Absolute Magnetic Kit Encoder*. Retrieved April 1, 2011, from US-digital: http://usdigital.com/products/encoders/absolute/rotary/kit/mae3

US-digital. (2011). *MAE3 Absolute Magnetic Kit Encoder Data Sheet.* Retrieved April 1, 2011, from US-digital: http://usdigital.com/assets/general/102_mae3_datasheet_0.pdf

VectorNav. (2011). *Orientation Sensors*. Retrieved June 14, 2011, from VectorNav: http://www.vectornav.com/

VectorNav Technologies. (2010). *Inertial navigation.* Retrieved June 14, 2011, from VectorNav Technologies: http://www.vectornav.com/index.php?option=com_content&view=article&id=21&Itemid=11#unaided-position-estimate

VectorNav Technologies. (2009). *VN -100(T).* Retrieved June 14, 2011, from VectorNav Technologies: http://www.vectornav.com/Downloads/Support/UM001.pdf

Wikimedia Commons. (2010). *Wikimedia Commons*. Retrieved September 07, 2011, from SPI: http://upload.wikimedia.org/wikipedia/commons/thumb/b/bb/SPI_8-bit_circular_transfer.svg/500px-SPI_8-bit_circular_transfer.svg.png

Wikipedia. (2005, Januari 31). *Wikipedia The Free Encyclopedia*. Retrieved March 23, 2011, from Laparoscopic surgery: http://en.wikipedia.org/wiki/File:Laparoscopic_stomach_surgery.jpg

Xsens. (2011). *3D Motion Tracking*. Retrieved June 14, 2011, from Xsens: http://www.xsens.com/

Xu, R. C. (2010). *Patent No. U.S 7,706,000 B2.* United States.

Zumbahlen, H. (2008). *Analog Dialouge*. Retrieved March 30, 2011, from Linear Variable Differential Transformers: http://www.analog.com/library/analogdialogue/archives/42-08/lvdt.html

Appendix A – Requirements list

The following list was handed by Surgical Science which shows what parameters are required to be met by the solutions which are presented in the report.

The unit should have support for at least three tools and at least one foot pedal with two digital buttons. Flexibility would of course be improved if one “unit” would have one tool and one foot pedal and several units could be hooked up to the same computer to provide one, two, three or more tools.

Overall

- Low cost
- USB / FireWire interface
- Simple to calibrate
- Robust, High quality
- Easy to maintain

Input to microcontroller

- Two digital inputs for foot pedals or buttons
- Additional analogue inputs is preferred for tools that has more than the basic "grasper" functionality. This is most probably a limitation of the microcontroller that is chosen for the project.

  Total of inputs both digital and analogue inputs= foot pedal buttons (2) + grasper tools locations (3) + grasper tools buttons (3) + additional tool (1) = 9 inputs

Working volume/range

- Insertion range along instrument axis: 200 - 250 mm
- Rotation around instrument axis should preferably be unlimited. Some devices put a restriction on the rotation which limits the usability. The main reason behind the limitation is cable management where one cable goes from the handle into the unit. The restriction is there to stop the cable from getting tangled up in the tool if it rotates along its axis. Having a separate cable from the grasper sensor and into the unit itself is not a big problem if it can be found to be a cheap, robust and effective solution.

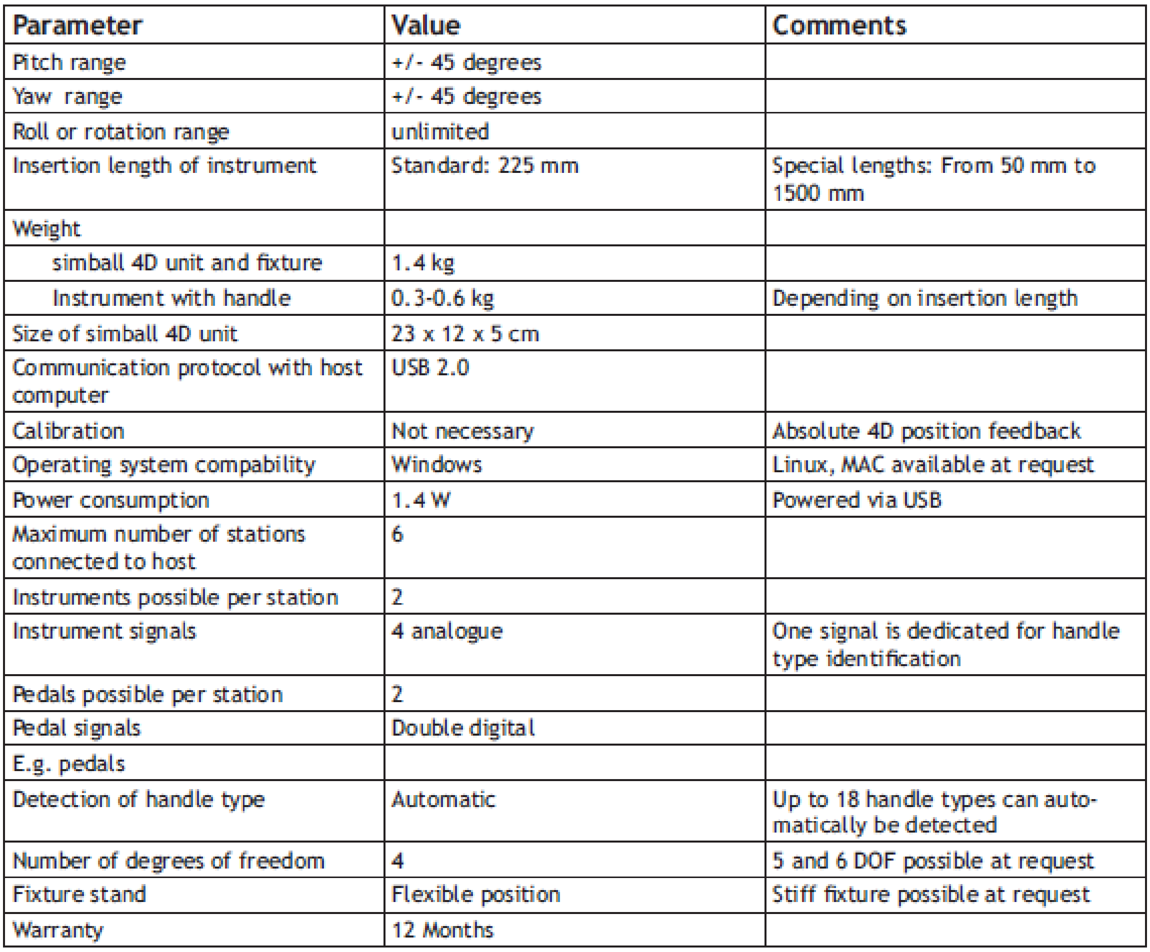
Precision

- Position within working volume <= 0.1mm^3. Note this is not absolute positioning but rather relative. Small movements of the tip <= 0.1 mm must be captured but moving from point A to point B and then back is not required to return point A's position with a maximum absolute error of 0.1mm.
- Rotation angle around instrument axis should be detectable in steps of <= 0.25 degrees.
- Grasper resolution 8bits over the whole range typically mapped from 0 to 1.

Programming Interface

- Simple to use, since LapSim already manages all kinematics we only need the position or the orientation of the tool plus insertion and any additional values such as binary buttons or analogue values from tools or extra inputs.

Appendix B – Specifications of Simball 4D



Parameter	Value	Comments
Pitch range	+/- 45 degrees	
Yaw range	+/- 45 degrees	
Roll or rotation range	unlimited	
Insertion length of instrument	Standard: 225 mm	Special lengths: From 50 mm to 1500 mm
Weight		
simball 4D unit and fixture	1.4 kg	
Instrument with handle	0.3-0.6 kg	Depending on insertion length
Size of simball 4D unit	23 x 12 x 5 cm	
Communication protocol with host computer	USB 2.0	
Calibration	Not necessary	Absolute 4D position feedback
Operating system compability	Windows	Linux, MAC available at request
Power consumption	1.4 W	Powered via USB
Maximum number of stations connected to host	6	
Instruments possible per station	2	
Instrument signals	4 analogue	One signal is dedicated for handle type identification
Pedals possible per station	2	
Pedal signals	Double digital	
E.g. pedals		
Detection of handle type	Automatic	Up to 18 handle types can automatically be detected
Number of degrees of freedom	4	5 and 6 DOF possible at request
Fixture stand	Flexible position	Stiff fixture possible at request
Warranty	12 Months	

Appendix C – Weighting diagrams

The matrix below is used to construct figure 4.1 and based on Karlsson and Ryan method for comparing requirements (Joachim Karlsson, 1997).

	A.1	A.2	A.3	A.4	A.5	A.6	B.1	B.2	C.1	C.2	D.1	D.2	D.3	D.4
A.1	1	1/7	1/5	1/3	1/5	1/6	1/2	2	1/6	1	1/8	1/7	1/8	1
A.2	7	1	3	3	2	2	3	5	1	3	1	1	1	2
A.3	5	1/3	1	1/2	1/3	1/5	1	3	1/4	1	1/5	1/5	1/5	1/2
A.4	3	1/3	2	1	1	1/3	2	4	1/3	1	1/4	1/4	1/4	1/2
A.5	5	1/2	3	1	1	1/3	1/2	2	1/4	2	1/5	1/5	1/5	1/3
A.6	6	1/2	5	3	3	1	3	5	2	4	1	1	1	4
B.1	2	1/3	1	1/2	2	1/3	1	5	1	2	1/3	1/3	1/3	1
B.2	1/2	1/5	1/3	1/4	1/2	1/5	1/5	1	1/5	1/2	1/7	1/7	1/7	1/3
C.1	6	1	4	3	4	1/2	1	5	1	3	1/3	1/2	1/3	2
C.2	1	1/3	1	1	1/2	1/4	1/2	2	1/3	1	1/5	1/4	1/5	1
D.1	8	1	5	4	5	1	3	7	3	5	1	2	1	4
D.2	7	1	5	4	5	1	3	7	2	4	1/2	1	1/2	3
D.3	8	1	5	4	5	1	3	7	3	5	1	2	1	4
D.4	1	1/2	2	2	3	1/4	1	3	1/2	1	1/4	1/3	1/4	1

This figure shows a Pugh matrix. The weight of each requirement is based from opinions and demands from Surgical Science and the process found in the beginning of chapter 4 were the requirements also can be found. The weight vales ranges from 0 - 5 were 0 is of no weight at all while 5 is of high influence on the system. Then each requirement is compared with the functionality in Simball 4D if its better or worse the values can range from -5 to 5, where -5 is much worse than Simball 4D, 0 is equal to Simball 4D and 5 is much better than Simball 4D . The sum will determine which of the solutions is the winner.

		Weight	simball™ 4D	trakSTAR	FASTRAK	Oqus	ProReflex	Polaris Family	PrimeSensor™	Solution 1	Solution 2
Genral requirements	A.1	1	0	0	-1	-5	-3	-2	3	5	2
	A.2	4	0	-1	-2	-1	-1	-2	3	3	3
	A.3	2	0	0	0	0	0	0	0	0	0
	A.4	2	0	-2	-2	-3	-3	-3	-1	1	1
	A.5	2	0	2	2	-3	-3	-2	2	1	1
	A.6	4	0	-1	-3	-2	-1	-3	-2	1	1
	Subtotal			-2	-6	-14	-11	-12	5	11	8
Inputs	B.1	2	0	-2	-2	-2	-2	-2	-2	0	0
	B.2	1	0	-1	-1	-1	-1	-1	-1	0	0
	Subtotal		0	-3	-3	-3	-3	-3	-3	0	0
Working volume/range	C.1	3	0	2	2	2	2	2	2	2	2
	C.2	2	0	2	2	1	1	0	0	2	1
	Subtotal		0	4	4	3	3	2	2	4	3
Precision	D.1	5	0	-1	-1	3	2	-1	-3	2	2
	D.2	4	0	-2	-2	3	2	-1	-3	2	2
	D.3	5	0	1	1	3	2	-1	-3	2	2
	D.4	2	0	1	1	2	1	-1	-2	0	0
	Subtotal		0	-1	-1	11	7	-4	-11	6	6
Total	**Sum**		0	-2	-6	-3	-4	-17	-7	21	17
	# of pos. values		0	5	5	6	6	1	4	10	10
	# of neg. values		0	7	8	7	7	11	8	0	0

Appendix D – Microcontroller code

Following part includes the code which controls the sensor with the microcontroller. Each function has been commented and to get further knowledge concerning the register values refer to the data sheet which can be found on the Avago website (Avago Technologies, 2010).

```
#include <SPI.h>

#define NCS 10      // SlaveSelect
#define SCLK 13     // SerialClockInput
#define MOSI 11     // MasterOutputSlaveInput
#define MISO 12     // MasterInputSlaveOutput
#define SS2 9       // Slaveselect 2

byte SPCR_SET = B01011101; // Enable SPI, set SPI master, cpol=1, cpha = 0,
set SPI speed to 1MHz
byte clr; // Clear byte

void setup (void) {

  pinMode(SS2,OUTPUT);
  Serial.begin(9600);

  digitalWrite(NCS,HIGH);
  digitalWrite(SS2,HIGH);


  // Beginning of Power-Up //
  SPI.begin();

  SPCR=SPCR_SET;
  clr=SPSR;
  clr=SPDR;


  // Reset sensor 1
  //Set slave high and low
  digitalWrite(NCS,HIGH);
  delayMicroseconds(500);
  digitalWrite(NCS,LOW);
  reset_sensor();
  digitalWrite(NCS,HIGH);
  // Set laser power
  digitalWrite(NCS,LOW);
  config_laser();
  digitalWrite(NCS,HIGH);
  // set resolution
  digitalWrite(NCS,LOW);
  set_resolution();
  digitalWrite(NCS,HIGH);

  // Reset sensor 2
  //Set slave high and low
  digitalWrite(SS2,HIGH);
  delayMicroseconds(500);
  digitalWrite(SS2,LOW);
  reset_sensor();
  digitalWrite(SS2,HIGH);
  // Set laser power
  digitalWrite(SS2,LOW);
  config_laser();
  digitalWrite(SS2,HIGH);
  // set resolution
  digitalWrite(SS2,LOW);
  set_resolution();
```

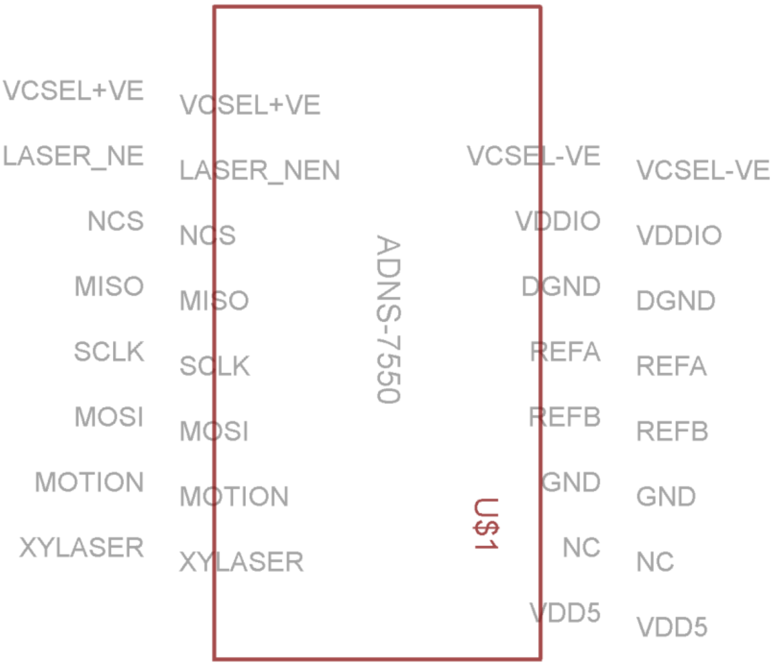
```
  digitalWrite(SS2,HIGH);


 }

void loop()
{
  digitalWrite(NCS,LOW);
  read_laser();
  digitalWrite(NCS,HIGH);

  delayMicroseconds(10);
  digitalWrite(SS2,LOW);
  read_laser2();
  digitalWrite(SS2,HIGH);
}

//Sensor 1
void read_laser(){
  byte data = 0,dump;
  int  x_mov = 0, y_mov = 0, xy_delta = 0;

  //Read motion register
  data = spi_read(0x02);
  if ( (data & _BV(7)) && !(data & _BV(4)) && (data & _BV(3)) && !(data &
_BV(2)) ) {
    x_mov = spi_read(0x03);
    y_mov = spi_read(0x04);
    xy_delta = spi_read(0x05);


    Serial.print("DATAX:");
    Serial.print(x_mov, DEC);
    Serial.print("Y:");
    Serial.print(y_mov, DEC);
    Serial.print("xy:");
    Serial.println(xy_delta, DEC);
  }
  else if ((data & _BV(7)) != 1) {
    Serial.println("No motion 1");
  }
  else if (data & _BV(4)) {
    dump = spi_read(0x03);
    dump = spi_read(0x04);
    dump = spi_read(0x05);
    Serial.println("Overflow has occured");
  }
  else if (!(data & _BV(3))) {
    Serial.println("Laser power is not valid");
  }
  else {
    Serial.println("Fault detected, VCSEL may be shorted");
  }
}

// Sensor 2
void read_laser2(){
  byte data = 0,dump;
  int  x_mov = 0, y_mov = 0, xy_delta = 0;

  //Read motion register
  data = spi_read(0x02);
  if ( (data & _BV(7)) && !(data & _BV(4)) && (data & _BV(3)) && !(data &
_BV(2)) ) {
    x_mov = spi_read(0x03);
    y_mov = spi_read(0x04);
    xy_delta = spi_read(0x05);
```

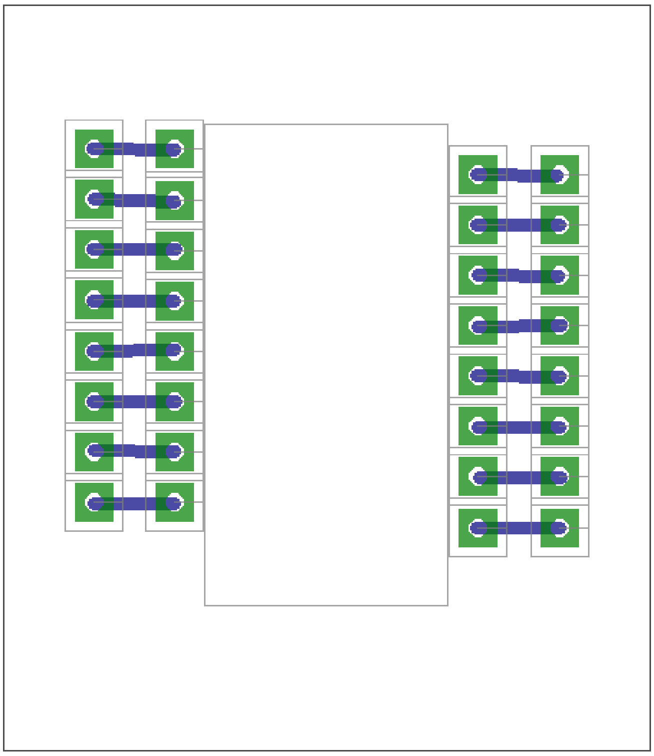
```
    Serial.print("HHPPX:");
    Serial.print(x_mov, DEC);
    Serial.print("Y:");
    Serial.print(y_mov, DEC);
    Serial.print("xy:");
    Serial.println(xy_delta, DEC);
  }
  else if ((data & _BV(7)) != 1) {
    Serial.println("No motion 2");
  }
  else if (data & _BV(4)) {
    dump = spi_read(0x03);
    dump = spi_read(0x04);
    dump = spi_read(0x05);
    Serial.println("Overflow has occured");
  }
  else if (!(data & _BV(3))) {
    Serial.println("Laser power is not valid");
  }
  else {
    Serial.println("Fault detected, VCSEL may be shorted");
  }
}

//Config laser, set to highest power
void config_laser() {
  spi_write(0x1A,0xCA); //B1100 1010
  spi_write(0x1F,0x00);

  spi_write(0x1C,0xFF); //B1111 1111
  spi_write(0x1D,0x00);
  delay(50);
  // Cancel calibration
  spi_read(0x02);
}

void set_resolution() {
  // Set sensor to 2000 cpi
  spi_write(0x36, 0x1A); //2000 DPI
}

// Reset the sensor (Power-up sequence) according to data sheet
void reset_sensor() {
  byte data = 0;
  clr=SPSR;
  delay(10);
  clr=SPDR;

  // Reset the sensor
  spi_write(0x3A,0x5A);
  delayMicroseconds(500);
  delay(1);

  //Clear the observation register
  delayMicroseconds(100);
  spi_write(0x2E,0x00);
  delay(1000);
  byte datao = spi_read(0x2E);

  //Read data from motion registers to clear stored data
  data = spi_read(0x02);
  data = spi_read(0x03);
  data = spi_read(0x04);
  data = spi_read(0x05);

  // Write to reserved register for further resetting of the sensor
  spi_write(0x3C,0x27);
```

```
  spi_write(0x22,0x0A);
  spi_write(0x21,0x01);
  spi_write(0x3C,0x32);
  spi_write(0x23,0x20);
  spi_write(0x3C,0x05);
  spi_write(0x37,0xB9);
  delay(50);
}

// Write to register and set the register value to value
// MSB have to be 1
void spi_write(byte reg, byte value) {
  reg = reg | B10000000;
  SPI.transfer(reg);
  delayMicroseconds(30);
  SPI.transfer(value);
  delayMicroseconds(30);
}

// Read the register
// MSB is 0 and data from the register is returned
byte spi_read(byte reg) {
  byte data = 0;
  reg = reg | B00000000;
  SPI.transfer(reg);
  delayMicroseconds(10);
  data = SPI.transfer(0xFF); //Shift out data from Sensor
  delayMicroseconds(10);
  return data;
}
```

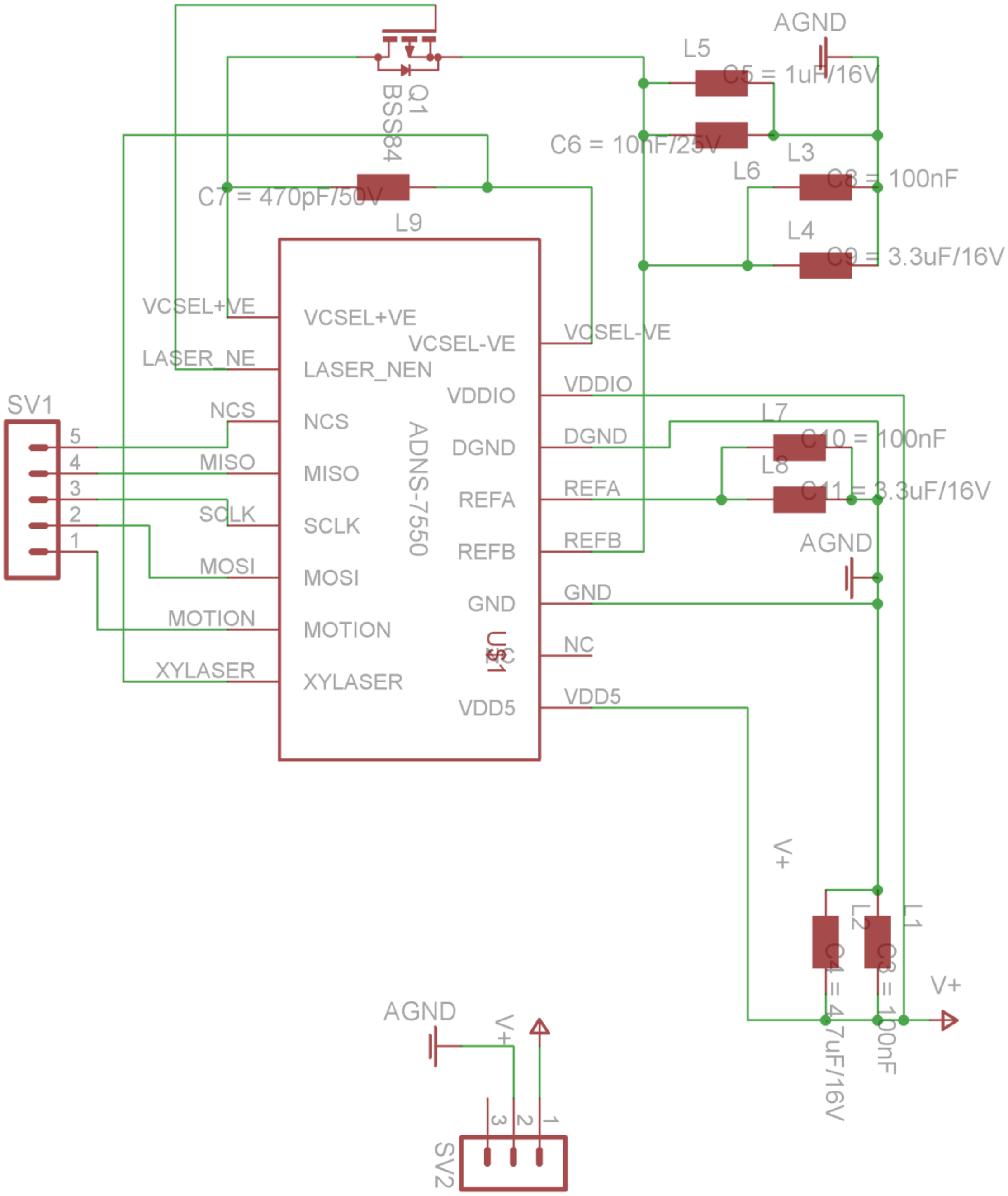
Appendix E - PCB layouts

First model schematic and board layout.

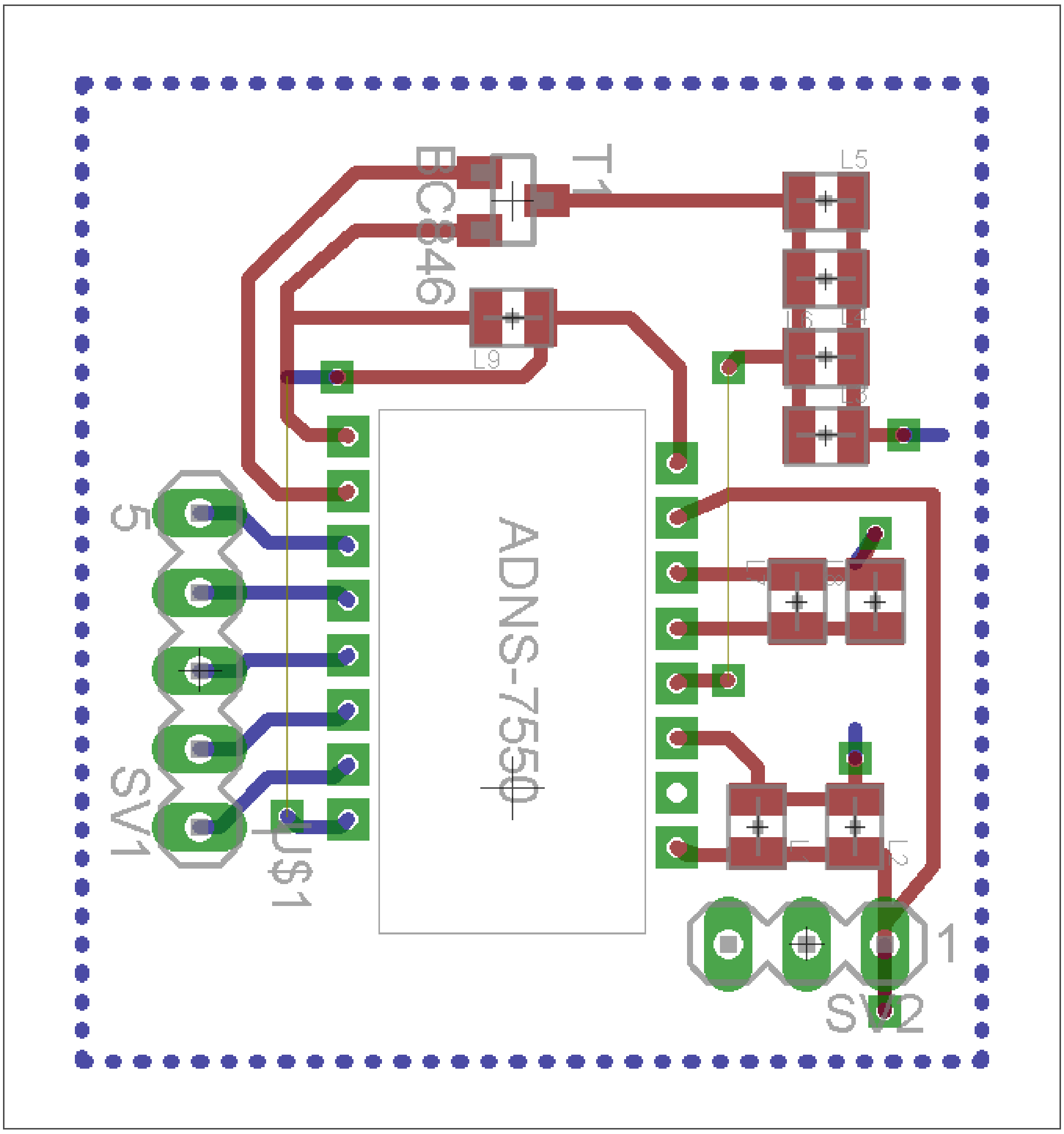




Second model schematic and board layout. The components can be found in the component list Appendix F.



Board layout where red marks the top layer and blue marks the bottom layer.



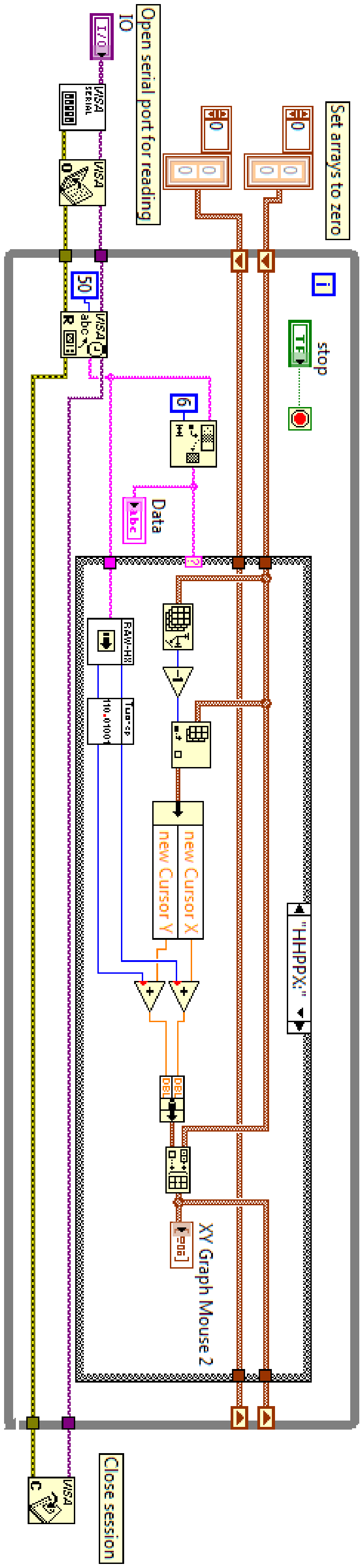
Appendix F – Electrical component list

Component list, based on the schematic from the data sheet of the sensor. The components are all of SMC type.

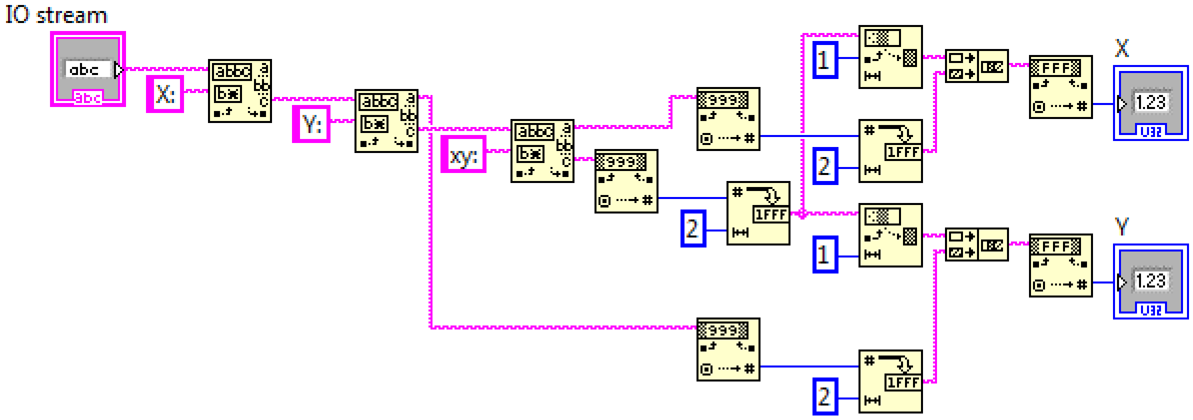
- C3 - 100nF,25V
- C4 - 4.7uF,16V
- C5 - 1uF,16V
- C6 - 10nF,25V
- C7 - 470pF,50V
- C8 - 100nF,25V
- C9 - 3.3uF,16V
- C10 - 100nF,25V
- C11 - 3.3uF,16V
- ADNS-7550 Integrated High Precision Small Form Factor LaserStream™ Navigation Sensor.
- SV1 5 pin connection for SPI interface and Motion pin.
- SV2 3 pin connection for power supply, ground and one no connection pin.
- Q1 - Mosfet which is not the same model as in the schematic in Appendix E. This is IRLML6401TRPBF by INTERNATIONAL RECTIFIER.

Appendix G – LabVIEW schematics

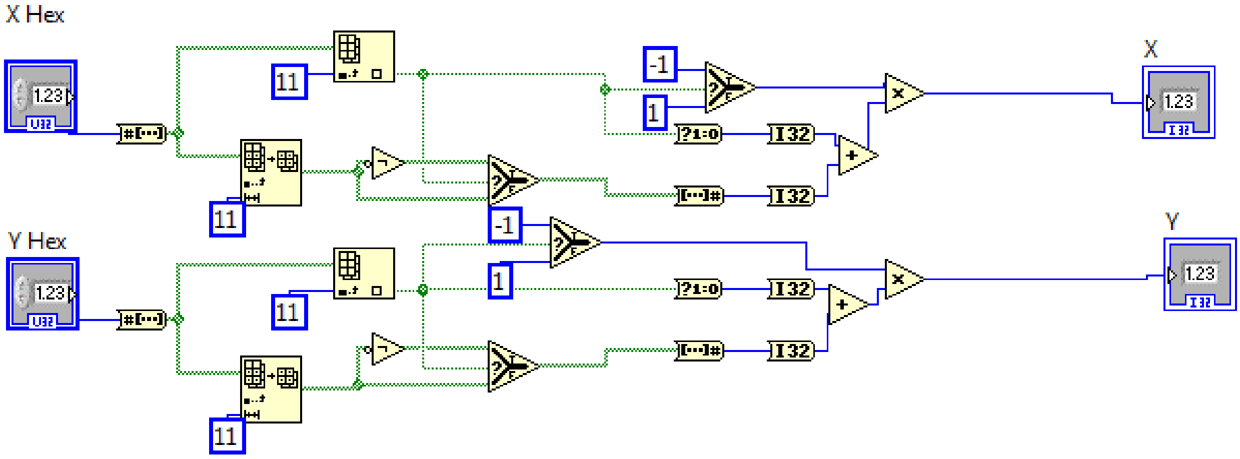
LabVIEW schematic



SubVI for Raw-HX, which reconfigure the stream to hex values.



SubVI for Two-cp which takes X and Y value and transform the hex decimal value to the correct decimal value.



The window where the movements of each sensor can be followed. The sensor updates each position based on the previous one.