Developing MR -compatible robots sensor technology

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Abstract

There is a MR-compatible surgical robot under development at the University of Oulu in the Department of Mechanical Engineering. The idea of development is to be able to use the robot in MRI-device while taking patient pictures. Working with the imaging-device it is easier to identify brain tumours and to save undamaged tissues.

The development of MR-guided surgery has created a need for surgical instruments and other devices with susceptibility tailored to the MR environment. Susceptibility effects can lead to position errors of up to several millimetres in MR-guided stereotactic surgery. Instruments that are used inside the magnetic field are not aloud to be effected by the field. If these kind of instruments are not carefully designed, they can cause enormous harm. Especially problems with the guidance can be fatal. Magnetic field can cause high forces to instruments, that can lead to heating, twisting or loose in manoeuvrability for example in robot arm. Also in very accurate microscopic operations, instrument has to be designed professionally. A use of different instruments has improve the usability of MR-device in locating human cells.

When the robot is designed to be MR-compatible, no magnetic materials are allowed in the imaging region. Electric current also causes magnetism; that is why electrical equipments are also forbidden. Here is introduced non-electric and non-magnetic pulse- and force sensor system into robots joint, which is located in the imaging region.

Keywords: MR-compatibility, robotics, sensor, fibre-optics

1. Introduction

Magnetic Resonance Imaging is based on materials nuclear magnetic resonance (NMR), which was found in 1946. This method is largely used as a research method in physics and chemistry. First MR-picture was taken in 1973. After this it has been widely used imaging method. /1/

There are different MR-devices; open c-type devices like in a figure 1 and closed o-type devices. The difference between these two types is basically a shape of the magnetic coils and power of the magnetic field. Usually the open MR-device is less powerful by its magnetic field than the closed one. The open device is designed especially for operative use. They are used as a help of different surgical operations. There is tried to find common solutions to avoid eddy currents and magnetic forces while using smart surgical instruments within MR-device. No matter what is the level of the magnetic field. There are allowed certain amount of electric currents near by the imaging field, but they always depend on power of the used imaging device. /8/

MRI (Magnetic Resonance Imaging) is accurate imaging technique especially for soft human tissue. But it is not accurate enough for imaging objects under one millimetre size. That is why there has started to development of better imaging methods, which are based on MRI. Some of these are MRM (Magnetic Resonance Microscopy) and Optical Imaging. With help of different instruments it is also possible to get more accurate results from MR-device. /2/

Fig. 1. Open c-type 0, 25T MR-device.

2. Magnetic compatibility of materials

It is very important to know what materials are suitable in magnetic field. Especially when it is used instruments while taking MR-pictures from a patient. If materials are too effective for the magnetic field, it can cause high forces into patient and be very harmful. /3/

Materials are divided into three different categories, when they are divided by their magnetic compatibility. In a first class there are materials, which are totally incompatible within MR-device. In a second class there are materials, which does not cause enormous magnetic forces and moments when they are brought into the magnetic field. In a third class there are materials, which are most compatible for the MR-environment. For the third class material, the magnetic field affects only a little. By using the third class materials, it is able to obtain accurate localisation when there is only small magnetic forces and torques. /3/

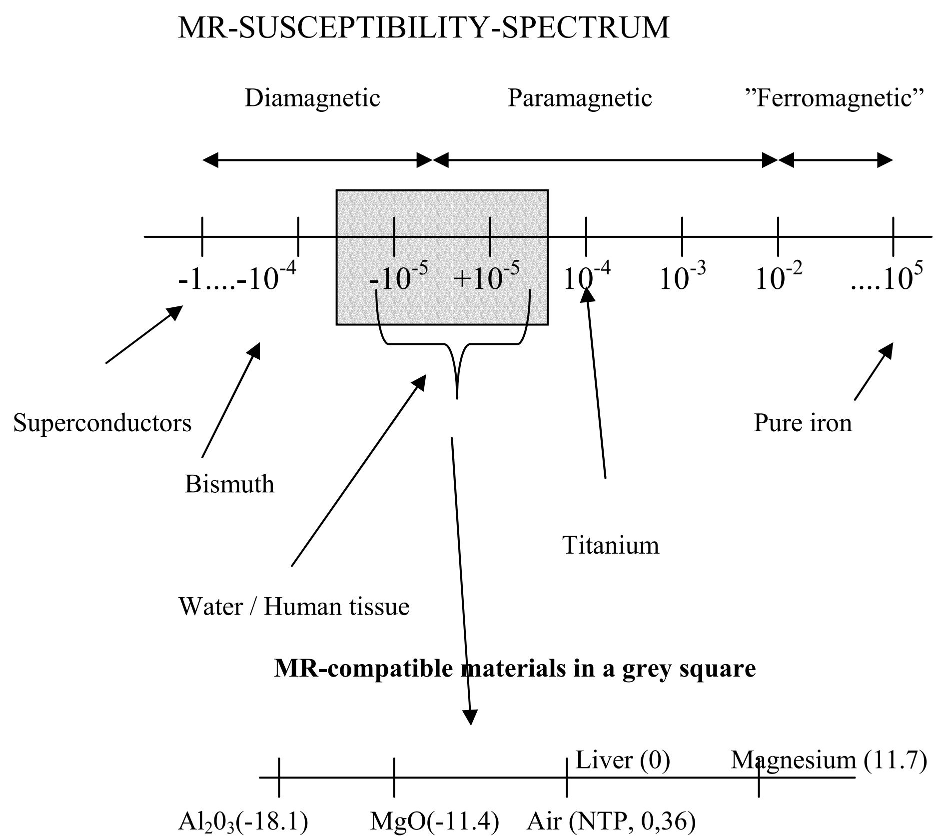


Fig. 2. Materials MR-susceptibility-spectrum expressed by magnetic susceptibility value. /3/

For a good help to find suitable materials for MR-compatible instrument is a list, which is collected from a source 3. In figure 3 there is usual materials selected in a list. These materials belong to MR-suitability class 3. Most of these materials are also easy to machine.

Material	Density (g/cc)	Atom- or Molecule weight	Susceptibility value ($x10^6$)
Graphite	2.26	12.011	-595
Carbon	2.26	12.011	-204
Bismuth	9.75	208.98	-164
Gold	19.32	196.97	-34
Mercury	13.546	200.59	-28
Silver	10.5	107.87	-24
Corundum	3.97	101.96	-18.1
Zinc	7.13	65.39	-15.7
Silicone	3.44	140.28	-9
Copper	8.92	63.546	-9.63
Water	0.933	18.015	-9.05
Aluminium	2.7	26.98	20.7
Titanium	4.54	47.88	237
Austenitic Steel	8		3250-6700

Fig. 3. A list of common MR-compatible materials. /3/

3. Using fibre optics to avoid eddy currents and magnetic forces in MR-environment

It is very important to notice, that in MR-environment there are lot of different aspects designer must remember when he is designing instruments to used inside the MR-Imager. The materials are of course one of the most important thing. But you can not forget the patients safety either. Magnetic fields in MR-device can harm picture quality and also cause high forces into instruments that might be used i.e. surgically use. One of the biggest cause of external magnetic fields in MR-environment are electric currents. They are usually located in small electric motors or encoders. Especially in robotic arms has electronic devices inside. If the electric currents are low enough, these systems can be used inside a certain MR-devices, but it has to be tested separately in every MR-environment. Electric wires are dangerous in MR-environment, because there might shown eddy currents and magnetic fields in them /3/. Wires should be shielded, but it is always possible that a shield breaks or it is magnetic material.

To avoid all the electric currents inside the imaging device, when sensors and motors are used, is to take electrical instruments away from imaging region. It is possible with help of lasers and fibre optics. With help of them it can be send and received the light meters away from imaging region. The light brings needed information.

There are two different main types of fibre optics, multimode fibres and single mode fibres. These are usually made of glass. Normal glass includes mainly silicon dioxide (SiO_2). It is also optical cable for sale, which are made of plastic. They have very large diameter and they also have very poor heat durability. /5/

Multimode fibres inner diameter is normally about 50-60µm an single mode fibres it is about 10-20µm. Multimode fibre can transmit many different wavelengths of light and single mode fibre is able to transmit only very accurate wavelengths. Multimode fibres are normally used with LED-light source, where the wavelengths of light are 850-1300nm. Multimode fibres are used i.e. in local LAN-nets. Single mode fibres are used with laser light sources, which wavelengths are about 1300-1550nm. They are used with high performance phone and data connections. The structures of different types of fibres are shown in figure 4. With multimode fibres it is also possible to have different shapes of light intensity. There is an example of one, graded index multimode fibre in figure 5. /5,6/

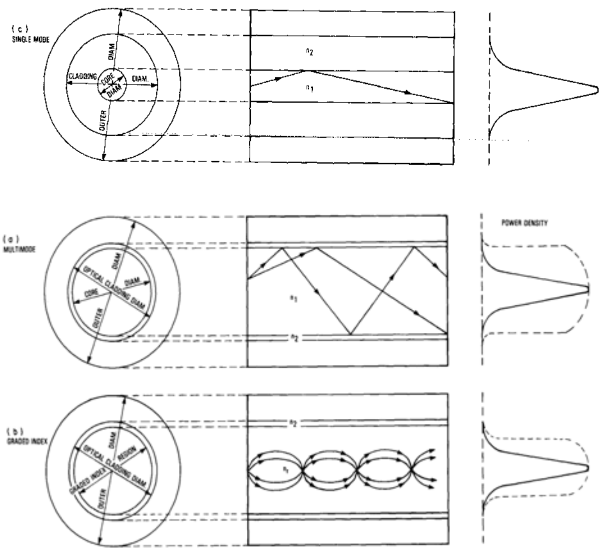


Fig. 4. The most common fibre glass types: Multimode fibre, Graded index-type fibre and Single mode fibre. Graded index-type is actually multimode fibre, because it can transmit many wavelengths. In figure you can also see the intensity dispersion of outcoming light. /5/

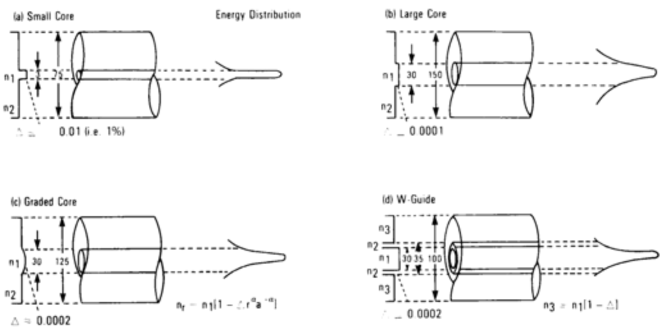


Fig. 5. Single mode fibre and its intensity spectrum of outcoming light with different diameters. /5/

Optical fibres breaks easily. While inserting them into instrument you have to be very careful with them. A shield around fibres should improve the fibre cables mechanical properties, especially torsion- and bending forces. There are always such forces while inserting fibre systems. Usually the fibres are shielded with Kevlar or glass fibre.

3.1 Fibre optic sensors

Optical fibres can be used passive or active elements, when using as a sensor. A system is called passive when a light or radiation is only transmitted thru a fibre. It is actually an intensity sensor. The radiation transmitter is used in heating process i.e. process industry. /7/

The system is called active (extrinsic/ intrinsic) when sensor include reflective displacement sensors (extrinsic) where light exits and re-enters optical fibres. In the intrinsic sensor light intensity modulates without leaving the fibre. Extrinsic and intrinsic fibres needs dedicated light sources and detectors coupled to the sensing fibres. /7/

With a help of fibre optics it is possible to do i.e. temperature, pressure, fluid level, flow, position, vibration, chemical analysis and current-voltage measurements. Into position sensors belongs also the strain sensors. With strain sensors it is possible to find out the forces inside a different mechanical systems.

A main advantage in using fibre optical systems in MR-environment is, that we can avoid taking magnetic and electrical fields inside an Imaging area.

3.2 Fibre optic position sensor

To measure position it is possible to use different fibre optical solution. The solution mainly depends on how long distances it is designed to measure. If there are very short distances, about millimeters, it could be used strain sensors in measuring i.e. linear movement with piezo systems. Also if it is wanted to measure long distances, it could be used light intensity measurement; these are largely used method in industry as fibre optical and non-fibre optical systems.

A little bit complicated system is needed when it is wanted to measure angles or distances accurately, digitally. There is designed optical sensors into aerospace systems which are based on the idea of normal pulse sensor systems. The light is only transmitted and received far away from code wheel or code plate. The idea of normal pulse coded motion-/ displacement sensor is shown in figure 6 and the structure of fibre optical position sensor is shown in figure 7. In Figure 6 there are light sources and photo detectors near the code wheel. /7/

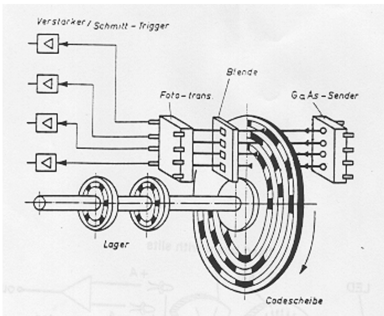


Fig. 6. Operational principle of non-fibre optical code sensor. /4/

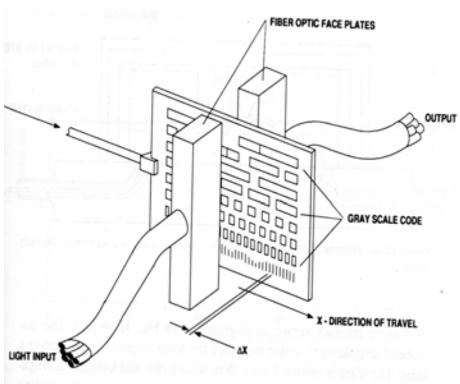


Fig. 7. Gray code position sensor with fibre optic arrays for transmitting and receiving light. /9/

4. Designing fibre optic pulse sensor into robotic arm operating in MR-environment

One of the most important thing in designing a fibre optic sensor into robotic arm, is the magnetic compatibility of a code-/ pulse wheel. It has to have good magnetic susceptibility. The second is, how big the code wheel can be, if it is inserted into a robot joint. The smaller the wheel is, the less pulses can be inserted into it. It is very hard to manufacture with traditional methods, like laser cutting, a normal small code wheel. These days they are mainly done with methods that are used to make i.e. a circuit board. One of these methods is etching: wet and dry. The other method is photolithography. If we use one of these methods we face a big problem; how to focus a fibre optical cable into right place. It is very hard if there is not accurate focusing instruments.

In this project it is used laser cut nonmagnetic steel plate as a pulse wheel. The wheel was not made to code type as seen in figures 8 and 9. The reason is troubled manufacturing with available machine tools. There is only normal pulse wheel with three channels. The wheel is dimensioned as big as it can be inside the robotic joint. In this case its diameter is about 28mm and physical pulse width is about 50µm and the distance between pulses is about the same. The thickness of the wheel is about 0,1mm. The designed robot joint is shown in figure 10. In the same figure you can also see how the pulse wheel and the fibre optic cables are mounted into it. With pulse sensor inside a robot joint we are able to control a link connected to the joint.

In this project the laser light sources were hot clued straight to the multimode fibres. The laser were about 4mW by their power and 630nm by their wavelengths. Lasers were good choice because of their coherent light. Laser light is more focused than LED-light. It is easier to coupled into the fibre. After cluing the laser lights were measured with light power meter. The power of light was over 4mw after passed 1,5meters multimode fibre. There was also tried single mode fibres, but it was very small by its diameter and intensity of light thru it wasn't enough. The lasers wavelength was neither the best for the single mode fibres. It was also tried normal plastic fibre with diameter of 1mm. That type of fibre were very complicated to use without any focusing lenses, because the light refracted very much while penetrating the pulse wheel. It was not possible to find out clear pulses while using the plastic fibres. That system would need a good lenses. While using the multimode fibre, there is not lenses needed because fibers diameter is near about physical pulse widths. The diffraction becomes significant if the light sources diameter is much bigger than the gratings . /10/

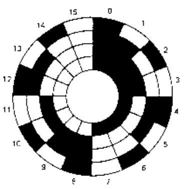


Fig.8. Gray coded wheel. /4/

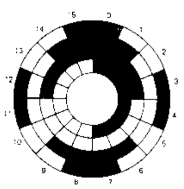


Fig.9. Binary coded wheel. /4/

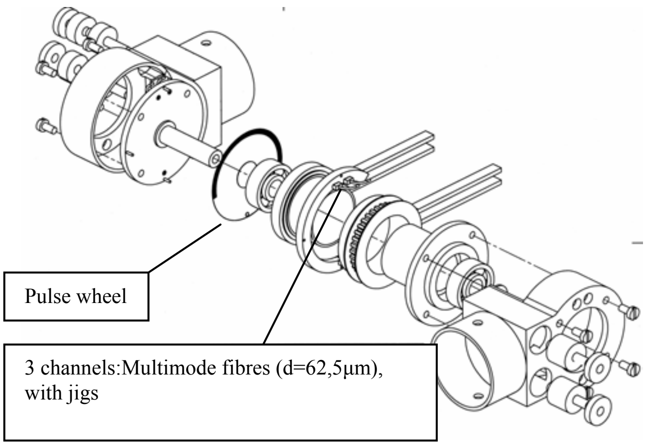


Fig. 10. Designed and manufactured robot joint with mounted pulse wheel and three fibre optical channels.

One of the problems in this system is also grinding of the fibres, because inside the robot joint there is not enough room for ferrules/ connectors that are normally used with the fibres. Connectors might also be magnetic. The fibres are mounted into ferrules and clued. After that they are polished with a jig. In this project there is tried to polished multimode fiber and plastic fibres without ferrules, but they need a jig while polishing. Polishing needs to be done with diamond paste at last, to obtain a good surface enough. The polishing is necessary, because the fibres surface after cutting looks very grainy. The results have been good enough; the system works after polishing.

Theoretical accuracy to manufactured pulse sensor is 500 pulses/ round. As we used Hewlett-Packards counter-circuit HCTL-2016 we can get the results in quadrature. Results were read thru a computers serial port with self made program. So the accuracy is now 2000pulses/ round. The real accuracy were tested with refence pulse sensor, type Heidenhein ROD 424M.0000. It has 3600 pulses/ round. There is mount both sensors into same mechanics. While the mechanics rounds we get two different sensor counts. In figure 11 there is pulse counts from a reference pulse sensor and in figure 12 there is pulse counts from a self manufactured pulse sensor. While comparing these test results and repeating tests, we find out that the self manufactured robot joints pulse sensor is very accurate. We are able to do the comparing, because we know both sensors theoretical accuracy. Its error of accuracy is about 4-5 pulses/ round. The error of that amount could easily become from environmental effects.

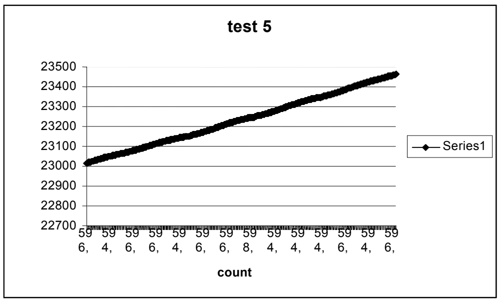


Fig. 11. Pulse counts from a reference pulse sensor.

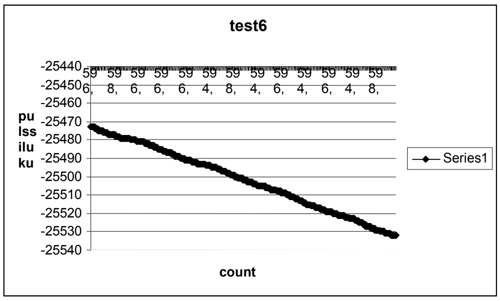


Fig. 12.Pulse counts from a self manufactured pulse sensor.

In figure 13 there is one of the test mechanisms. In here is a motor to control an axis, which goes thru both of the sensors.

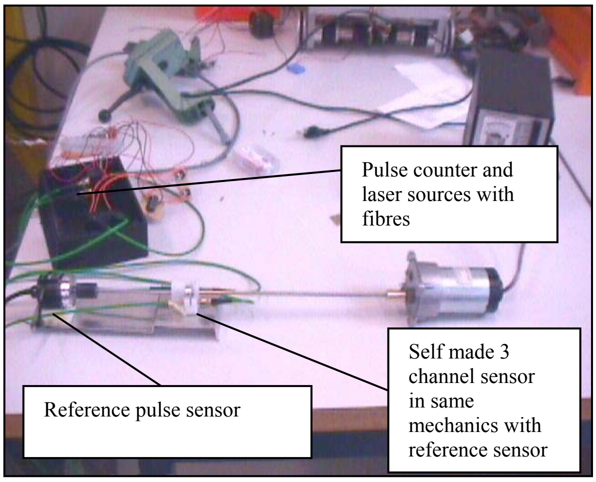


Fig. 13. Test mechanism. With help of this it was able to measure both sensors in same time in same mechanism thru a serial port of PC.

5. Designing fibre optic MR-compatible force sensor

There are many possible solutions for a force sensor to put inside the robot joint. It depends on the need what kind of sensor is suitable. For example in surgical applications it is important to measure the contact between robot arm and a patient. Patient must be secured when operating. The sensor could be on-/ off-type if the maximum force is well known. Usually the robot can be used in different surgeries, that is why possibility to measure i.e. strain is important. First of all criteria is a size. Inside a robot arm it is not possible to use big laboratory systems, especially if one of the design criteria for the joint is its small size and magnetic compatibility. That is the reason to use fibre optic strain sensors to sense the forces. With fibre optical force sensors it is also possible to measure even a surgical instruments i.e. needles inner strains. These force sensors are so small. Some of these systems are commercially available.

Here is introduced one prototype of switch type force sensor. It can be mounted straight into robots arm head, where the surgical instrument is locked. It should switch the robot off, when too big force is attached to the instrument. This prototype has been made and tested. It worked very well, but the biggest problem for this system is, that it does not work in all surgical operations unless you are not able to control the switch force. With this solution it could be made with changeable instrument holder-heads. In figure 14 there is shown the idea of switch type fibre optical force sensor.

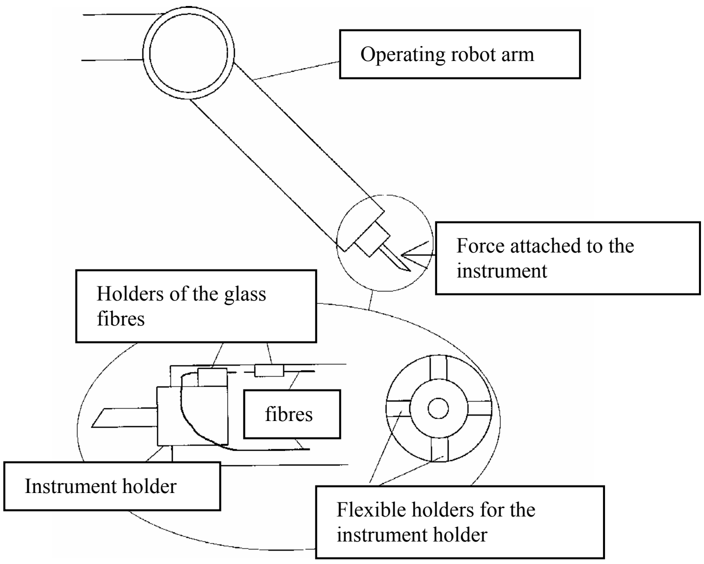
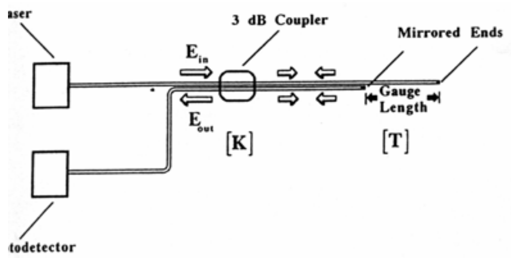


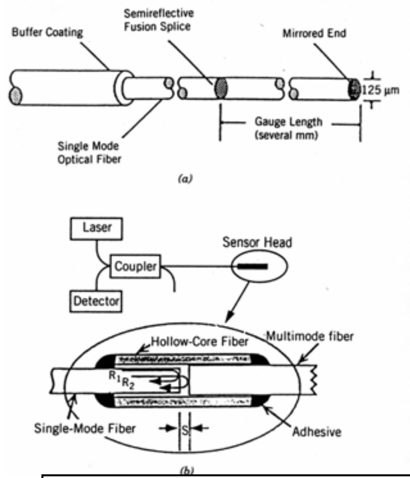
Fig.14. The idea of switch type fibre optical force sensor

The other instrument systems that could be used as measuring strain non-magnetically from instrument or instrument holder are Fabry-Perots, Michelson interferometric sensor or Intracore Bragg Gratings system./9/ They can be inserted inside a small mechanical structures. For a structure shown in figure 14 it could be very effective to use one of these systems inside the instrument or in the instrument holder. It helps us to get continuous strain (force) information from very critical point; between patient and operating robot. In figure 15 there is operational principles of Michelson, Fabry-Perot and Bragg Grating sensors.

Michelson interferometric strain sensor



Fabry-Perot strain sensor



Bragg grating strain sensor

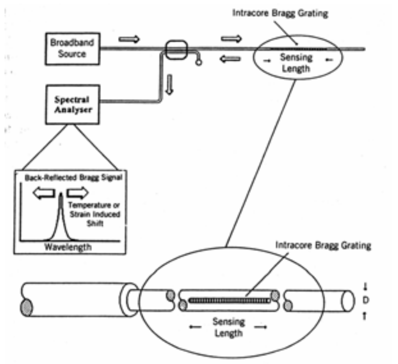


Fig.15. Operational principles of Michelson, Fabry-Perot and Bragg grating fibre strain sensors. /7/

6. Results and conclusions

Here is succesively made MR-compatible fibre optical pulse sensor, which can be used inside MR-environment i.e robotic joint. Test results were very promising by sensors accuracy. There is also done and tested MR-compatible switch type force sensor and introduced some good improving methods for force sensing. Tests in MR-environment are ment to be done in the next step. With help of fibre optics it is possible to design smart instruments inside the MR-environment.

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