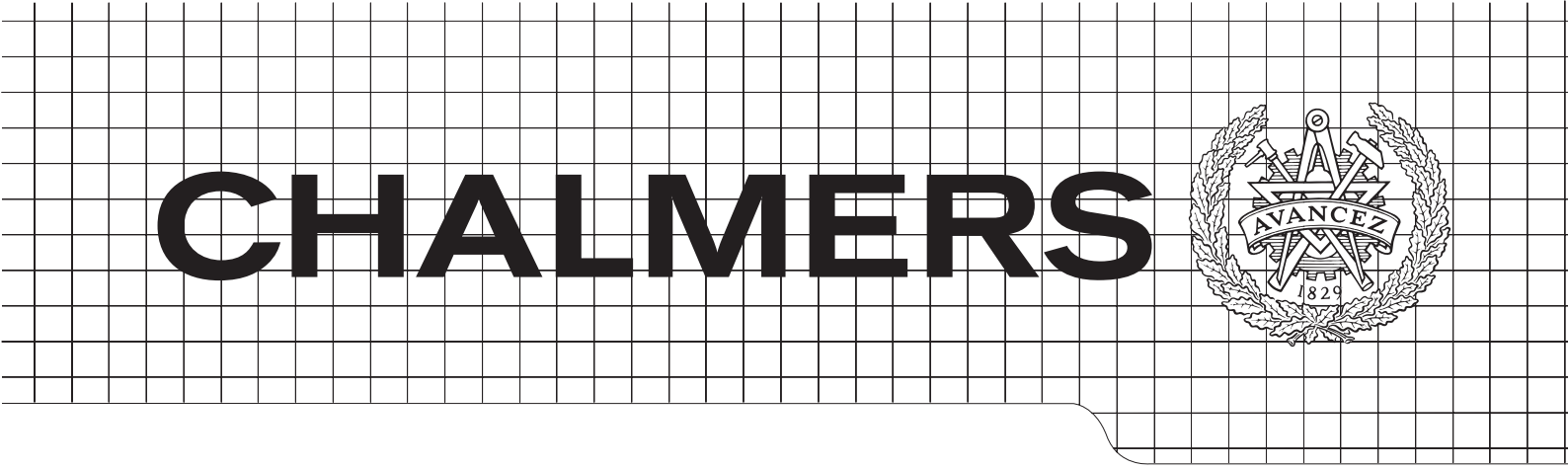

Design and preliminary testing of an MR-compatible eye tracking system

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MASTER THESIS IN BIOMEDICAL ENGINEERING

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Chalmers University of Technology
SE-412 58 Göteborg

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Abstract

Eye tracking makes it possible to track the gaze and analyse the pattern with which a person scans his/her visual field. One interesting possibility with eye tracking is the combination of this method together with other measurement systems. For this project, the other modality of interest is functional magnetic resonance imaging (fMRI), a functional neuroimaging technique. The combination of these two techniques allows for research into the correlation between brain activity and behaviour such as gaze direction, pupil dilation or eye blinks.

The aim of this thesis is to investigate the requirements of using an eye tracking system in an fMRI experiment and to design and propose a system solution that fulfils the requirements. The lead user of the eye tracking system is Smart Eye AB, a manufacturer of eye-tracking systems with commercial interest in developing a system for fMRI use.

A Functional Requirements Specification (FRS) was created that specifies the requirements for the proposed system. The bases for the FRS were from four different methods and sources: a literature study, discussions with Smart Eyes partners, analysis of a survey of potential customers, and investigations of other existing products on the market.

The proposed system consists of a camera, IR illumination, waveguide, enclosure, power source and electronics. It is encased in an RF shielded enclosure that conforms to the requirements of an MRI conditional item. The system design was performed based on the requirements, and the optical components were tested with a simple experimental design to assess compliance with the requirements. Preliminary test results indicate that the proposed long-range one-camera system satisfies most of the requirements of the FRS, but tests with the enclosure and the waveguide needs to be done to comply with all of the requirements.

Keywords. Eye tracking, fMRI, Functional Requirement Specification, MRI Safety.

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The authors, Gothenburg March 17, 2014

Abbreviations

ASTM	American Society for Testing and Materials
CR	Corneal Reflection
ECG	Electrocardiography
EEG	Electroencephalography
EMI	Electromagnetic Interference
fMRI	Functional Magnetic Resonance Imaging
FOV	Field Of View
FRS	Functional Requirements Specification
IR	Infrared
MEG	Magnetoencephalography
MR	Magnetic Resonance
MRI	Magnetic Resonance Imaging
NIR-SPECT	Near-Infrared Spectroscopy
NTP	Network Time Protocol
RF	Radio Frequency
SE	Shielding Effectiveness
TES	Transcranial Electrical Stimulation
TMS	Transcranial Magnetic Stimulation
TR	Repetition time of the MRI
TRS	Technical Requirements Specification
TTL	Transistor-Transistor Logic
VAL	Validation Test Specification
VER	Verification Test Specification

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1 Introduction and motivation

Eye tracking technology makes it possible to follow the movement of the eye using cameras and image analysis software, allowing tracking of features such as the gaze of the eye, and the positions of the eyelids, iris and pupils. This technology can be used together with videos, car simulations or in real cars to track the gaze and analyse the pattern with which the subject scans the visual field. Such data can give information about what kind of shapes and patterns that are noticed first, reaction time after the appearance of new objects, the order in which subjects choose to look at different objects and how long the subject chooses to focus on different parts of the view. All of this information can be of great interest in many different fields of research, such as neuroscience, psychology, traffic research and many more.

One interesting possibility with eye tracking is the combination of this method together with other measurement systems, to be able to match data and get even more information from a certain experiment. For this project, the other modality of interest is functional magnetic resonance imaging (fMRI), which is a method of using a magnetic resonance imaging (MRI) machine for localising neural activity by measuring the changes in oxygenation of the blood flow in the brain [1]. Connecting these two modalities could give access to even more possibilities in many research fields, such as psychology and cognitive neuroscience. This can be used to specify which part of an image on a visual stimuli screen a subject is looking at when a certain part of the brain is activated. An example is a study where mental rotation of two 3D-objects shown to the subjects was performed when the pair of objects were either mirrored or identical [2]. Eye tracking systems can also offer other physiological information for different applications, such as visual acuity determination for ophthalmology applications and reading disorders and as an evaluation of user-interface designs [3].

Smart Eye AB is a developer, manufacturer and retailer of different types of eye tracking systems that are currently in use in fields such as automotive industry, aerospace, psychology and neuroscience. Smart Eye does however not have an eye tracker solution for an MRI environment. The development of such an eye tracking system that can be used together with the MRI poses many different problems. The MRI environment is very peculiar because equipment brought into it can both affect the MRI machine, and be affected themselves by the magnetic fields and radio frequency pulses. Problems include corrupted MR-images, projectile risk, and torque or induced currents in the equipment. The geometry of the MRI room will also influence the design of the system, since the camera needs an optical path to the eyes of the subject. The safety regulations for what can be used in the MRI environment are also very demanding. Regulations and safety documentation re-

garding using external devices in the MRI environment will have to be considered to make it possible to use the device at all. Another consideration is the implementation of the eye tracker in the working routine of current fMRI experiments, where it is important not to interfere with other parts of the examination.

1.1 Aim and purpose

The aim of this project is to investigate the requirements of using an eye tracking system in an fMRI experiment, and to suggest a prototype system design for this purpose.

Potential customers of Smart Eye has shown interested in such an fMRI adapted system, and because of this, the company would like to start getting into this field.

1.2 Problem statement

The main problem of the project is to investigate how a Smart Eye eye tracking system can be adapted to function with fMRI.

The first goal is to investigate the requirements and formulate this information into a requirements specification. The investigation will have to answer the following questions:

- Who are the potential users?
- What research has been conducted with eye tracking in conjunction with fMRI?
- What eye tracking signals are of interest to potential users and at what spatial and temporal resolutions?
- What safety rules must be fulfilled to operate a system in an MRI room?
- What are the physical and geometrical constraints of the MRI room?
- What existing products are there for this application, and what are their general design characteristics?

The second goal is to suggest a design of a prototype that addresses all of the requirements, and then perform preliminary testing to evaluate the feasibility of the design.

1.3 Limitations

The limitations of the thesis are listed here, to emphasise the boundaries of the project.

- The project must fit inside the time limitations of a master's thesis.
- The prototype will only use off-the-shelf components.
- The system shall only output data, and not perform any analysis on it.

1.4 Outline of report

This section summarises the contents of each of the chapters in the report.

- Chapter 2 - The Method chapter describes how the information has been gathered, how the requirements specification has been created and how the prototype should be tested.
- Chapter 3 - In the Theory and background chapter the reader can learn about the background information gathered through literature studies. The information is also used as one of the bases for the requirements specification.
- Chapter 4 - This section contains the collected information from the three sources other than papers and literature; a survey to researchers, discussions with partners and existing products. The information from these sources are also the basis for the requirements specification.
- Chapter 5 - In the Results chapter, the requirements specification for the system are presented, and how the system has been designed accordingly after these. Test results of the prototype are also presented in this chapter.
- Chapter 6 - Discussion, in this chapter the suggested system is evaluated, what changes could be done, a comparison with other systems and a look into the future.
- Chapter 7 - The conclusion chapter ends the thesis with how well the aims of this thesis have been fulfilled.

2 Method

The methods that were used during the information collection were literature review, interviews with partners of the company and a review of existing products on the market. A questionnaire was also created for potential customers to get their input at an early stage of the development of the prototype. The components of the prototype were tested with a simple experimental design.

2.1 Requirements information collection

The investigation for the requirements specification will be carried out using four different information sources. Each of the sources have their own advantages and address part of the questions posed by the problem statement, and will when combined together give a good foundation for the requirements specification.

Research papers, literature and web resources The first source of information consists of research papers and literature on the subjects connected to the project. These sources will give information to the questions and requirements that are associated with the basics of fMRI and eye tracking, what research has been conducted in the intersection of those modalities and what concerns have to be addressed regarding the safety aspects of MRI. The information from these sources has been put in Section 3.

Discussions with partners The second source of information is a series of telephone meetings with partners of Smart Eye that have experience in the area of equipment used in conjunction with MRI. The focus of the topics discussed in these meetings are on potential users, what eye tracking signals that are interesting and general design characteristics of equipment for MRI rooms. Summaries of these telephone meetings can be seen in Section 4.1.

Potential customers To get input from researchers and other potential customers, a questionnaire was created and sent to contacts that had expressed interest in an MRI adapted eye tracker from Smart Eye. The questionnaire was designed to consider questions that could give information that could not be obtained through any of the three other sources. It was made using a survey tool from Google that utilizes Google documents and collects the answers automatically in a spreadsheet format. The questionnaire can be seen in its entirety in Appendix A, and a summary of the results can be seen in Section 4.2.

Other existing products The last source of information was other already existing products in this market. This was surveyed to learn what already exists on the market and what those products generally look like. The results of this survey can help with general design parameters and geometric constraints to which the solution must conform. A summary of the products surveyed can be read in Section 4.3.

2.2 Requirements specification

The collected information regarding requirements was made into a specification using a Functional Requirements Specification template provided by Smart Eye. This format was chosen since it had been used earlier in the company, and could fit in well with this type of product.

The template makes a distinction between the requirements of the customer and the developer. The requirements of the customers are expressed in condensed paragraphs, that does not include any specification of technical information, but rather what that functionality should be able to do. In the results section, the specifications are referred to as Functional Requirements Specifications. The requirements of the developer is then based upon those of the customer and specified in a more technical way how the functionality will come about. In the results section, the technical specifications are referred to as Technical Requirement Specifications. In this project, the participants are both the customer and the developer of the product.

To make sure that the sets of functional and technical requirements are met, both of them will have testing specifications that show whether the requirements have been reached or not. The test on the customer side is referred to as Validation Test Specification, and on the developer side as Verification Test Specification.

2.3 Preliminary testing

The prototype and its individual components were tested during the course of the project, to see their performance during varying circumstances and in conjunction with each other. A simple experimental design was created to preliminary test the proposed system. The setup of the test can be seen in Section 5.4, and the idea behind these experiments was to find a solution for the optical components of the proposed system.

3 Theory and background

The theory and background chapter presents the background knowledge that is used through the rest of the thesis. Theory of eye tracking, applications and physics of fMRI, MRI safety and electromagnetic shielding and interference are included.

3.1 Eye tracking

The process of measuring either the position of the gaze or the motion of an eye relative to head is called eye tracking. The most popular eye tracking method today is videooculography remote gaze tracking which usually consists of infrared (IR) light sources and a camera. The advantages of video camera-based systems are the easy and fast setup and the non-invasive comfort to use, which makes them appropriate for long-term use, i.e. experiments longer than 30 minutes [4].

The advantages of using IR light instead of natural light are several. IR light is comfortable for the user because it is not visible and hence does not distract the user. One other advantage is that there are few IR sources of illumination in typical environments, which allows one to filter out other optical wavelengths and include only relevant IR contrast in the image [5].

The eye position is extracted from the video image where two main reference points are detected, the pupil and the corneal reflection, which defines a vector that can be mapped to screen coordinates on a computer screen. The pupils are hard to detect due to the lower contrast between the pupil and the iris boundary, but by using IR light the contrast is enhanced and easier to detect [4]. The position of the IR source determines if the pupil is dark or bright. If the IR light source is on the optical axis of the camera, the pupil is bright because the light that hits the retina is reflected back along the same optical path. The pupil appears as black when the IR source is off the optical axis of the camera, since the light that hits the retina is reflected away from the camera [5]. The different positions of the IR sources can be seen in Figure 1. In general the bright pupil technique gives the best result due to the clear contrast between the iris and the pupil. However for this to be optimal the environment should be dark and the subject should have blue or light eyes [6]. Bright and dark pupil can be seen in Figure 2.

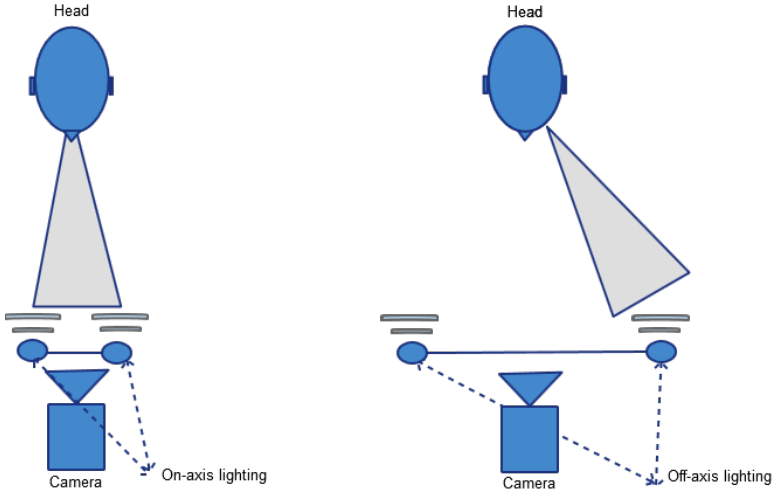


Figure 1: Left: On-axis lighting leading to bright pupils, Right: Off-axis lighting which gives dark pupils.

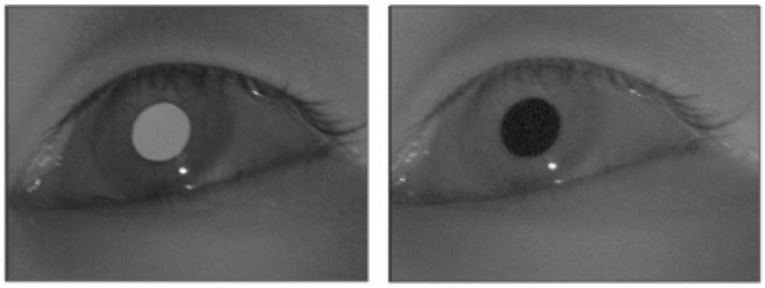


Figure 2: Left: Bright pupil, Right: Dark pupil. Corneal reflection can also be seen as a small but bright spot near the pupil. Image courtesy of *InTech Open* [7].

The IR source also creates a corneal reflection (CR) which can be seen in Figure 2 and in Figure 3 near the pupils. Assuming that the camera and the IR source are fixed and that the eye is a sphere that only rotates around its center, the position of the CR does not move with the eye rotation, and can therefore be used as a simple and accurate reference point [4].

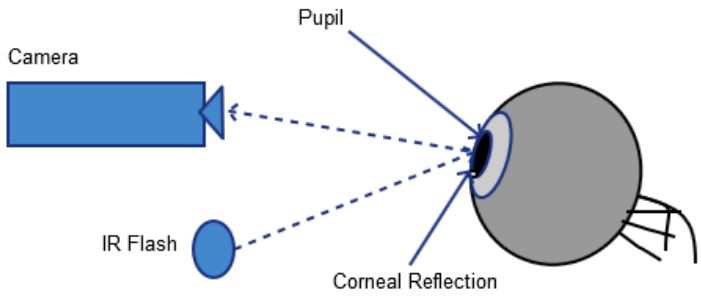


Figure 3: The IR source creates a corneal reflection near the pupil that can be used for eye tracking.

3.1.1 Smart Eye AntiSleep

The Smart Eye AntiSleep software is used as a software base for this project due to being the most similar application in terms of output data, and the experience and expertise that Smart Eye can provide to further develop the software for eye tracking in fMRI. Smart Eye AntiSleep is a fully automatic one-camera system designed for automotive in-cabin applications, such as measuring visual cues of driver fatigue and inattention. Three of the major cues are eyelid closure, gaze direction and head motion. AntiSleep measures 3D head position, head orientation, gaze direction and eyelid closures [8].

The hardware of AntiSleep consists of one camera and two IR-illuminators, which gives the above mentioned advantages. The image analysis process of the system is described in Figure 4. The initial step of the tracker builds a generic 3D head model based on statistical measurements of a large set of facial training images. In the head model, relative 3D distances between generic facial points such as eye features, nostrils and mouth corners are included and projected onto the image to give spatial constraints on the image positions. From these points, an initial head pose can be estimated. The tracker's algorithms adapts the head model for the current driver, and tries to refine the estimated points as the session continues [8].

A 3D model of the eyeball and eyelids is built and projected into the image with help of the estimated eye features and head model. The eyelids model makes it possible to estimate the eyelid opening. The iris is found by performing a fast ellipse finding algorithm, and by using the centre positions of the eyeball and the iris, the gaze directions are calculated. In summary, the output of the system is for each frame, the driver's 3D head position and orientation, the gaze direction in 3D and the eyelid opening of each eye [8].

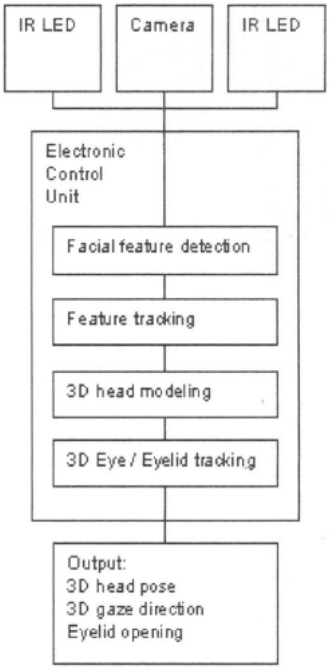


Figure 4: System overview of Smart Eye AntiSleep showing the image analysis process. Image courtesy of *Bretzner, L., Krantz, M.* [8].

3.2 Functional magnetic resonance imaging

Functional magnetic resonance imaging (fMRI) is a method used to measure the activation of different parts of the brain. This can for example be done by acquiring images with an MRI camera while the subject is switching between performing a task, such as pushing a button when a stimulus is present, and not performing a task. The goal with such a experiment is to detect correlations between brain activation and a task. The signal change is however weak, and several series of switching has to be done. Other goals of an fMRI experiment can be to identify regions within the brain linked to critical functions such as language and moving [1]. fMRI uses magnetic resonance imaging, which is a powerful imaging method that utilizes a phenomena that is called nuclear magnetic resonance to create detailed 2D and 3D images of the human body.

This background and theory section on fMRI and MRI will go through applications of the technology, geometry of the equipment, physics behind the mechanisms and lastly MRI safety.

3.2.1 Applications of fMRI

Eye tracking during fMRI scanning can be used for research on the visual and attentional systems of the brain, and is also an important technique for information of the neural systems controlling eye movements [9]. One example of research was conducted by Miall et al. (1999) where they investigated cerebellum dysfunction by using a combination of eye tracking and fMRI. The cerebellum is a region of the brain that is important for motor control, and a dysfunction leads to a substantial worsening of movements performed under visual guidance. Miall et al. showed the first direct evidence from a functional imaging study for cerebellar activation in eye and hand coordination [10]. An examples of an fMRI image can be seen in Figure 5, where the response comes from memory tasks being performed by the subject.

One of the big advantages of MRI technology is that it uses non-ionizing radiation, as opposed to other imaging methods such as x-ray radiography, computer tomography or positron emission tomography [11].

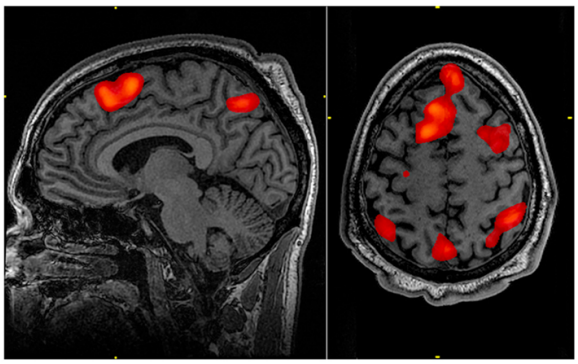


Figure 5: fMRI scan image of a human performing memory tasks. The greyscale represents the anatomy of the human skull and brain, while the coloured regions indicate an area of activity. Image courtesy of *Wikimedia Commons* [12].

3.2.2 Geometry of the MRI machine

The MRI machine itself is large and require its own specially designed room. The machine has a bore, in which the patient is inserted to perform the measurements. A typical bore diameter for a 3T MRI machine is 70 cm [13][14], but can vary between different models. An example of the machine and the bore can be seen in Figure 6.

When performing fMRI scans of the head, the head is placed inside a head coil. This head coil limits the movements of the subject, but also contains mirrors that allows looking out of the bore. One way to track the eyes of the subject is by using these head coil mirrors as an optical path for the eye tracking camera. A picture of a head coil with mirrors can be seen in Figure 7. The dimensions of the mirror in the figure are 14 cm in width and 3.5 cm in height (based on own measurements).

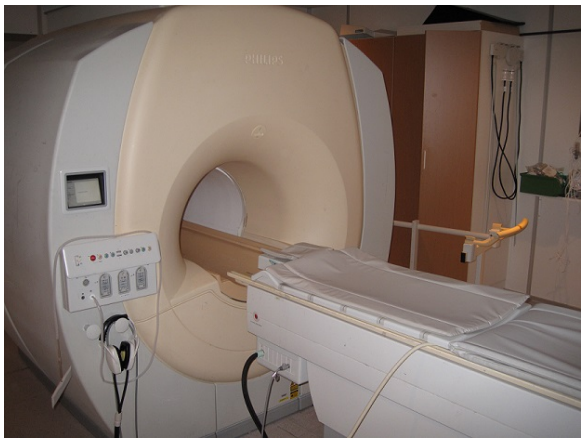


Figure 6: A typical MRI machine, showing the bulk of the machine, the bore and the bed that is used to insert the subject into the bore.

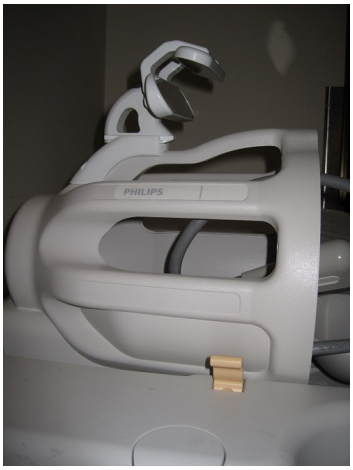


Figure 7: MRI head coil with mirrors.

3.2.3 Physics of fMRI

Activation of neurons requires energy, which increases the blood flow to deliver more oxygen and glucose in the areas were the activation has taken place. The ratio between oxygenated and deoxygenated blood in the brain is used to form the fMRI images. This ratio changes depending on the activation of neurons, which makes it possible to indirectly examine which parts of the brain that are active [1].

The magnetic characteristics are different between oxygenated and deoxygenated blood, which causes them to distort magnetic fields in different ways. By measuring the distortion they cause with an MRI machine, the ratio between them in the blood stream can be found out [1].

MRI utilises the magnetic moment exhibited by hydrogen nuclei. If a strong homogeneous magnetic field is applied on the hydrogen nuclei, a certain ratio of them will orient along the field lines because of the magnetic moment. The ratio of hydrogen nuclei that align according to the field depends on the magnetic field strength of the magnet, the characteristics of the nuclei that are being measured and the temperature. The magnetic moment orientation will precess [11] with a frequency that is described by the Larmor relationship, which can be seen in Equation 1,

$$f = \frac{\gamma}{2\pi} B, \tag{1}$$

where f is the precessional frequency, γ is the gyromagnetic ratio of the hydrogen nuclei and B is the magnetic field strength.

The orientation of the magnetic moment of the hydrogen nuclei can be shifted from the alignment through excitation by a radio frequency pulse. The excitation can only be performed when the frequency of the pulse is equal to the Larmor frequency of the hydrogen nuclei. The shift of the hydrogen nuclei orientation will correspond to the amount of energy transferred, and can for example be chosen to shift it 90° or 180° about the static magnetic field orientation axis. When the radio frequency pulse ends, the orientation of the hydrogen nuclei will start going back to its original state. During the realignment, the precession will cause the magnetic moment to move in a spiral fashion until it is once again oriented with the homogeneous external field [15].

The precession of the magnetic moment generates a time-varying magnetic field that can induce electric currents in the coils placed around the subject in the bore. The induced electric currents form the signals that are used to make MRI images

[15].

The most common static field strengths of MRI machines range from 0.5 T to 3 T [15]. A magnetic object at a distance of 1 meter outside the isocenter of the magnet (just outside the bore), has an acceleration of around 45 g [16]. Switching gradient strength in modern MRI machines is around 80 mT/m, and the radio frequency pulse used in a 3 T machine is 128 MHz. The characteristics of these field strengths and frequencies are of importance to the safety in MRI rooms, for example in the design of shielding for third party products [17].

3.2.4 MRI safety

Every MR magnet has perimeter fields, and the extent of the perimeter depends on the magnets field strength, the design and shielding of the magnet and the room in which it is located. The surrounding structures, i.e. large metal objects such as supporting beams, make every MR room different. A manufacturer of MRI systems calculates the perimeter fields for the specified MR room and then outlines them on a drawing prior to installation. The 0.5 and 3 mT lines should be displayed in the MR room and the space within the 0.5 mT line is considered as the MR environment [17].

MR safety and compatibility are important subjects for all medical implants, surgical tools and electrical equipment to be used within an MR environment [19]. Equipment that is safe to use in other areas can be potentially fatal near MR systems due to the large invisible magnetic fields. The magnet is powerful and similar in strength to junkyard magnets that lift cars [18]. ASTM International, formerly known as as the American Society for Testing and Materials (ASTM) has identified five types of MR hazards that need to be taken into concern: projectile effect, twisting, burns, image artifacts and device malfunction [18]. ASTM has also developed and established basic testing methods, but the purpose of these methods are to test implants for MR safety and image artifacts. There does not exist any standard methods for testing other equipments than implants. Further research and development of standard methods needs to be done for other medical devices, e.g. eye trackers, as well [19].

Magnetically Induced Displacement Force - Projectile effect A strong magnetic field applies a force on ferromagnetic materials directed towards the center of the bore; hence the safety risk to the patient. Objects that have been reported to become projectiles are wheelchairs, patient lifts, stethoscopes, scissors, pens etc. and fatal accidents has occurred with ferromagnetic objects [17].

Magnetically Induced Torque - Twisting Twisting occurs when magnetic objectives tries to align with the MR's magnetic field. This is especially dangerous for people with implants fixed in their bodies, e.g. a pacemaker can get displaced in the chest wall [17].

Radio Frequency Induced Heating - Burns The RF pulses of the MR system is transmitted from the RF coil to the patient. When conductive materials, such as metals in clothing, are placed within the RF field, excessive heating and tissue damage can occur due to the concentration of induced currents caused by the RF pulses. Burns can also occur when the arms or the legs of the patient have been positioned in such a way that a conductive loop pathway has been created [17].

MR Image Artifacts Image artifacts generally does not affect patient safety directly. In some cases however exact positions are needed, e.g. for needle insertion or implementation of x-ray markers. If the quality of the images is bad enough to void information, it could lead to pathology being masked or pathology misinterpretations. If that is the case, safety issues become critical due to misinformation from the image [19].

Device malfunction The static magnetic field can affect the electronics or the mechanics of the device such that it malfunctions, e.g. pacemakers can pace at the wrong point in the cycle [18].

Due to the potential hazards that exist in the MR environment, MR testing of medical devices is required for device approval by regulatory agencies such as the Food and Drug Administration and European Union Notified Bodies [19]. ASTM has also developed standard markings of devices brought into the MR environment. ASTM published the marking standard in 2005 [17] with the following definitions: MR Safe, MR Conditional and MR Unsafe. These markings can be seen in Figure 8. Items with no known hazards in all MR environments are labeled with MR Safe. Items that pose no known hazard in a specified MR environment are labeled with MR Conditional. In this case, the conditions where the item has been tested need to be specified. Items that are known to be hazardous in MR environments are labeled with MR Unsafe [17].

From our discussion with Company 1, see Section 4.1.1, we know that MRI manufacturers do not put approval on third party products such as eye trackers at all, and it is the manufacturer of the third part product that classifies if it is compatible or not. However local sites can have their own security protocols as well for

Figure 8: MR standard markings: MR Safe (green), MR Conditional (yellow), MR Unsafe (red). Adapted from [17].

external equipment, and one example is from the Kronoberg County Council. The security protocol states that all external equipment or material that is brought into the MR room, temporarily or permanently, has to be controlled and approved by authorized staff, i.e. medical physicist [20].

The external equipment is classified as active or passive. All equipment with any kind of electronics, including battery-operated devices, are classified as active equipment. Examples of passive equipment are chairs and litter bins. For both active and passive equipment, the projectile effect has to be evaluated. This is done outside the MR room first with a permanent magnet to find any ferromagnetic materials within the equipment. If the control is negative, the equipment is brought into the MR room, and slowly moved closer to the bore to deduce if the magnetic fields applies any pulling force on the equipment. If the equipment is still not affected when it is placed next to the bore it can be classified as MR Safe [20].

Additional tests have to be done for the active equipment due to the risk of affecting the MR images and/or malfunction of the equipment. The test is done with the equipment in operation mode on a reproducible position in the MR room, by scanning a phantom and evaluate the MR images for image artifacts. At the same time the equipment is evaluated for malfunctions, such as heating or induced currents. If none of them are affected, the equipment can be classified as MR Safe. However, if the equipment can be used in the MR room, but not over a specific magnetic field, the equipment is labeled as MR Conditional with the specified maximum magnetic field strength indicated on the label [20].

3.3 Visual stimuli system

When conducting an fMRI experiment, a projection screen or monitor can be used to show visual stimuli to the subject, with the purpose of investigating how this stimuli influences the brain. This is usually conducted using a visual stimuli system that can also be used to design entire experiments. One example of a visual stimuli system that Smart Eye has worked with is E-Prime from Psychology Software Tools. E-Prime has the possibility to receive transistor-transistor logic (TTL) pulses, which are electrical signals from the MRI machine that are sent at image acquisition start and can also be synchronised with Smart Eye systems [21].

3.4 Electromagnetic shielding and interference

During operation every electrical equipment radiates electromagnetic waves, which have both electric and magnetic components. The electric and magnetic field radiation diminish as the distance from the source increases, but sometimes that is not enough. The radiation can still affect other equipments, and it is important to shield the radiation instead. The importance of shielding relates to the high demand of reliability of electronics and the rapid growth of radiation sources [22].

Electromagnetic interference (EMI) shielding refers to the reflection and/or absorption of electromagnetic radiation which is usually in higher frequencies, e.g. radio waves. A metallic partition is usually placed between two regions of space, which thereby acts as a shield against the penetration of the radiation. The metallic divider is electrically conducting and the electrons and holes in the material interact with the radiation and reflects or absorbs it. Metals with high conductivity are silver, copper, gold and aluminium and they are great reflectors [22]. The shield can surround the noise source, and thereby control the propagation of electromagnetic fields, or it can be used to keep radiation from a certain region, e.g. a specific equipment within the region. Overall it is more efficient to shield the source rather than shielding the receivers [23].

Magnetic shielding refers to the shielding of magnetic fields at low frequencies, e.g. 50 Hz. Magnetic shielding and EMI shielding differs in both materials and mechanism of the shielding. Magnetic fields can't be removed, only redirected. There are no known materials that blocks magnetic fields without itself induce a force of attraction, so the primary mechanism of magnetic shielding is absorption. Materials who have high magnetic permeability, i.e. metals with electric and/or magnetic dipoles, interacts with the electromagnetic fields in the radiation. Examples of such metals are mumetal and superpermalloy [22], [23].

One way to measure the performance of the shielding is the shielding effectiveness (SE) which is expressed in decibel. The SE depends on the frequencies, and therefore it is calculated by measuring the electrical field and the magnetic field separately, and with and without shield. The following formula is used to calculate the SE for electrical fields,

$$SE = 20 \log 10(E_{unshielded}/E_{shielded}), \tag{2}$$

where $E_{unshielded}$ is the electric field strength without shield and $E_{shielded}$ is the electric field strength with shield. The same formula is used for the magnetic field, but with the magnetic fields strength with and without shield. Good shielding is achieved for SE values of 100 dB and greater [23].

4 Discussions with partners, survey results and existing products

This section contains summaries of the information from sources other than papers and literature, that was collected as a basis for the requirements specification. The first source consists of summaries of the discussions that were held with several Smart Eye partners regarding eye tracking in fMRI. The opinions of potential users was also surveyed through the usage of a questionnaire. Finally to get an overview of the market and what kind of products exist for this purpose, two existing products were investigated from two companies; Applied Science Laboratories (ASL) and SensoMotoric Instruments (SMI).

4.1 Discussions with partners

These meetings consisted of discussions with three different partners regarding many topics related to eye tracking in fMRI. The identity of the companies have been removed, the discussions have been summarised in short informative sentences, and the topics discussed with that particular company is represented by one paragraph each. This format has been chosen to display just the most important points, and make them easy to overview and reference in later design decisions made for the design of the prototype. The topics brought up are mostly similar between the three meetings, with some small variations.

4.1.1 Company 1

Fields of research There is a focus on research rather than clinical usage. The fields are mainly cognitive neuroscience: Visual perception, memory and learning.

System positioning and visual stimuli The most common visual stimuli software are E-Prime, Presentation and Python. The most common visual stimuli equipment is projector, projection screen and mirrors. They think that long range tracking is desirable. In the projection screen case, it is mostly positioned 0.5-1 m from the bore at the back side or at least one bed length (2m) at the front side.

Data signals Subject attention and gaze direction are probably the most interesting data signals. Pupil diameter might be interesting, but that is more specialised. More specialised signals could be interesting, but much further on and would require very good quality. A video feed of the subject can be interesting in some applications, but it is more of a nice feature bonus rather than a main

feature. There is a lack of systems that do head movement monitoring to warn the operator or mark the frames for usage in post processing.

Temporal and spatial resolution, accuracy, synchronisation requirements They agree that very high resolution and accuracy is probably not necessary, but there can be instances where it matters. Transcranial magnetic stimulation (TMS) requires less than 1 ms resolution. EEG/NIR-SPECT: 3kHz, would probably require 100 μs - 1 ms sampling interval and the pulses are of similar length.

Synchronisation The MRI room usually has a box with USB and a BNC output for TTL. Standard BNC TTL, isolation depends on if the subject is connected directly or not. An eye tracking system would probably need to have a TTL input.

Data analysis Separate analysis are often carried out for the different modalities. Analysing different modalities together really only requires good synchronisation. MATLAB analysis tools, often used when using several modalities, are developed specifically for a research centre or group.

Other modatlities and systems They work a lot with transcranial electrical stimulation (TES) and TMS, which are big research fields right now.

Materials and safety concerns They recommend using fibre optics for data transfer. There are no set standards for research. The manufacturer of the third party equipment classifies it as compatible or not. MRI manufacturers do not put approval on third party products at all.

4.1.2 Company 2

Fields of research There is a focus on research rather than clinical usage.

Common MRI systems and headcoils 1.5 T and 3 T are the most common scanners. Siemens is common for research (60%), after them is Philips (25%), and GE (15%). Some specialised labs use ”home made” head coils. Using a eye tracking system on the head coil would require different types of hardware for each headcoil, and would be very challenging.

System positioning and visual stimuli They think goggles seem to complicated, and advice to keep cameras away from the magnet. They do not understand why some companies have gone for a goggle solution. They have mainly seen two companies that work with projection hardware: Nordic Neuro Lab and Invivo (bought by Philips), which are both clinically approved. Usually the clinical MRI machines have video monitors instead of projection screens, and they are not as common in research. The projector is usually outside and project through the waveguide onto a screen that is inside the room.

Data signals They think the most interesting signal is observing if the subject is paying attention, and maybe giving some kind of warning to the operator. They also think that all the signals that are interesting in normal eye tracking is probably also interesting when it is brought into MRI.

Temporal and spatial resolution, accuracy, synchronisation requirements Most eye tracking systems for MRI they have seen have a camera frame rate of 250 and 500 Hz, but they can't really tell what that would be useful for. It is probably because large numbers look nice when selling it. A camera frame rate of 120 Hz is definitely enough.

Synchronisation TTL pulses are used to synchronise with the MRI machine. It is less common with the third party equipment controlling the MRI than the other way around. The TTL pulses can be counted to keep track of the TR (repetition time of the MRI).

Data analysis Nordic Neuro Lab and Invivo both provide analysis software. There are opensource MATLAB plugins that are used for correlating MRI and EEG data. Two of them are SBM and FSL.

Other modalities and systems Sometimes they have seen interfacing with ECG (electrocardiography) or respiratory monitoring. The most interesting modality to synchronise is probably EEG (electroencephalography). They also think that the MEG (magnetoencephalography) market might be interesting, even though it is small. If a system was developed that was compatible with MRI, it could also already be compatible with MEG. MRI compatible glasses are used in some cases, and the system would have to work with them.

Safety concerns They suggest using fibre optics for the data transfer. They use batteries, and strongly recommend it, since drawing power cables is often forbidden. In the EU, a CE verification is enough for clinical use of a medical device. The ASTM standard for MRI safety should be followed, and collaboration with fMRI experts is recommended.

4.1.3 Company 3

Fields of research The systems they have worked with were almost exclusively used in research and not clinical applications. The importance of the eye tracker is the addition of another level of data points. In their experience, researchers were most interested in blink events (for filtering), saccades and coarse fixation.

Common MRI systems and headcoils The most common manufacturers encountered are Siemens, GE and Philips. Siemens is the largest in research, but GE might be increasing in that regard. There are not only geometrical restrictions from the rooms, but also from the scanners themselves. For example, GE has an extension from the back of the gantry instead of a flat ending like Siemens has on their machines.

System positioning They strongly worded that the RF and magnetic environment close to (and in) the bore is very hostile, and that equipement very close will always get the blame if some error occurs in any part of the experiment. Noise from the third party equipment is completely gone at long range. Cameras are usually placed on the back of the bore. Goggle solutions are very often plagued with problems. They strongly recommend long range.

Temporal and spatial resolution, accuracy, synchronisation requirements A high temporal resolution in normal fMRI is not necessary, 20-30 ms at most. Correct time stamping is very critical.

Synchronisation They use TTL-pulses from each slice acquisition that is sent from the MRI machine.

Data analysis Researchers often use BrainVoyager or software developed by the MRI scanner companies.

Other TMS is sometimes used in conjunction with fMRI. They recommend using fibre optic cables for data transfer.

4.2 Survey results

The questionnaire was sent out to eleven contacts, and was answered by four. The explicit answers will not be included in this report because of privacy, and will instead be summarised. The main field of research that the people who answered were interested in was cognitive neuroscience and fMRI research, one was interested in using eye-tracking for MEG instrumentation development. Most had used an eye-tracker before, and noted that the main feature they wanted improved from other systems was faster and easier calibration and setup of the system. In their setups, the majority used projectors and projector screens for visual stimuli. The software used in the experiments was very varied, including E-Prime, MATLAB, Presentation and custom-developed applications. The temporal resolution was not very important to any of the people who answered, and the data that was of interest included gaze position, pupillometry, blink events and fixation/saccade classification.

4.3 Existing products

Two different eye tracking systems for fMRI were investigated for the market research on existing products, and summaries about their design and features can be seen in the following sections.

4.3.1 Applied Science Laboratories

Applied Science Laboratories (ASL) is an American company whose eye tracking system has been installed and used in fMRI's in over 70 locations worldwide [24].

The ASL model R-LRO-XG is a long range optical module with camera and illumination placed within the module. It is placed well away from the magnet and uses the bright eye technique. The optical module has an aiming mirror which is used to direct the eye tracker's optical path and illumination beam at the head mount's mirror inside the bore of the magnet. The module also have inputs for custom DC power cables and for a fiber optic cable to transfer the video signal. The video signal is taken cared by the EYE-TRAC®PC, which handles X,Y coordinates and pupil size in real time and it can also export and import event flags. The system data is available in digital and analogue form and it has also an input for transistor-transistor logic (TTL) pulses. The standard configuration of the system records in 60 Hz, but the camera frame rate can be changed to 120, 240 or 360 Hz. The R-LRO-XG has been installed in MRI's ranging from 1.5 T to 4 T and it is compatible with MATLAB, Presentation and E-prime [25].

4.3.2 SensoMotoric Instruments

SensoMotoric Instruments (SMI) is a German company who was first with offering a commercial, vision-based 3D eye tracking solution [26].

SMI's eye tracking solution for fMRI applications is named iViewX^{TM}MRI-LR and consists of one customized mirror box and a separate eye camera with Faraday shielding. The mirror box is customized and mounted to the head coil and has integrated IR illumination, the supported head coils are not specified. The eye camera can be mounted in two different ways. It can be mounted at the top end of the scanner on a mobile, non-magnetic tripod or fixed to a table mount customised to fit the foot of the patient bed. The interface of the system consists of fiber optics for the IR illumination, fiber optic for video transmission and a power supply (110-230 VAC) or an optional rechargeable battery. The MRI-LR uses dark pupil technique and has a camera frame rate of 60 Hz. The data is handled by a dedicated workstation and it records measurements of horizontal and vertical gaze position and pupil size. It can also provide online fixation control for synchronization with magnet and stimulus data. The system is compatible with MATLAB, Presentation and E-prime [27].

5 Results

The first part of the results consists of the requirements specification that has been formulated using the investigation of the requirements. This result has been created in the form of a spreadsheet template that presents the functions in a matrix form. To present these results in the report, this matrix has been broken up into two parts and placed in one table each. The first table consists of the customer specifications and the second consists of the developer specifications. The short reference names of the functions that can be seen in the tables will be used in later results subsections to specify which functions the design choice refers to.

The second part of the results consists of the system design and descriptions of each chosen component. This part also includes the principles of the system software, synchronisation and interface.

The third part of the results consists of the preliminary testing that has been performed on the components.

5.1 Functional Requirements Specification and Validation Test Specification

In this first section, the table shows the first part of the specification matrix: requirements and test specifications on the customer side.

Table 1: A table outlining the customer specifications of the system. The first column represent the function reference name, the second explains what the function entails, the third represents the reference name of the validation test associated with the function, and the fourth column explains the procedure of that validation test. Each row represents one function each.

	Functional Requirements Specification		Validation Test Specification
F1	The system shall be able to output timestamped eye tracking data, i.e. gaze direction, gaze intersection, pupil diameter, blink events.	F1-VAL1	Setup the system in the MRI environment according to the manual instructions. Run the eye tracker and validate that all the signals specified in F1 are present.

F2	The system shall provide a live video feed of the subject.	F2-VAL1	Setup the system in the MRI environment according to the manual instructions. Run the system and see if the live video of the subject's eyes are present.
F3	The system shall be able to output a warning if the subject is not attentive.	F3-VAL1	Setup the system in the MRI environment according to the manual instructions. Run the system and provoke a warning by letting the subject looking outside the visual stimuli screen.
		F3-VAL2	Setup the system in the MRI environment according to the manual instructions. Run the system and provoke a warning by letting the subject closing the his/her eyes.
F4	The system shall be able to operate for 10 hours.	F4-VAL1	Setup the system according to the manual instructions. Run the system for 10 h.
F5	The system shall be able to mount on a tripod.	F5-VAL1	Mount the system on the provided tripod.
F6	The battery shall be easy to change.	F6-VAL1	Perform a battery change according to the manual instructions.
F7	The system shall be able to operate in different kind of MR rooms and setups.	F7-VAL1	The system shall be able to operate in the customer's specified MR room geometry.
F8	The system shall have a quick setup.	F8-VAL1	
F9	The system shall be quick to setup between different subjects.	F9-VAL1	
F10	The system shall be MR Conditional for a 3 Tesla system.	F10-VAL1	The projectile risk is tested by an experienced MRI operator by following standard protocols for that site.
		F10-VAL2	An experienced MRI operator tests if the system is affected by any torque by following standard protocols for that site.

		F10-VAL3	An experienced MRI operator tests if the system is heated up or experience other problems from induced currents by following standard protocols for that site.
		F10-VAL4	An experienced MRI operator tests if the system distorts the MRI images by following standard protocols for that site.
F11	The eye tracking data shall be synchronised with the MRI data and the visual stimuli data.	F11-VAL1	Synchronisation test; More detailed later.

5.2 Technical Requirements Specification and Verification Test Specification

This subsection contains the second part of the specification matrix, and shows the requirements and test specifications of the developer.

Table 2: A table outlining the developer specifications of the system. The first column represent the technical specification reference name, the second explains what the technical specification entails, the third represents the reference name of the verification test associated with the technical specification, and the fourth column explains the procedure of that verification test.

	Technical Requirements Specification		Verification Test Specification
F1T1	The eye tracking software shall be modified to fulfill the MR geometry constraints, i.e. working with most of the face covered, using only the eyes. In addition to the software modifications, the light conditions for the hardware must be sufficient for the algorithms.	F1T1-VER1	Setup a test environment that imitates the geometrical constraints of an MR room. More details in chapter 3.4.1.Verify that F1T1 is fulfilled.

F2T1	The live feed must have a maximum delay of <15 ms.	F2T1-VER1	Setup a test environment that imitates the geometrical constraints of an MR room. More details in chapter 3.4.1. Monitor the latency, and verify that F2T1 is fulfilled.
F3T1	The eye tracking software shall be modified so the system submits a warning if the subject's gaze is outside of the defined area of the visual stimuli screen for > 1 s.	F3T1-VER1	Setup a test environment that imitates the geometrical constraints of an MR room. More details in chapter 3.4.1. Let the subject provoke a warning by looking outside the computer screen, and verify that F3T1 is fulfilled by monitoring the output data.
F3T2	The system must submit a warning if the subject has closed his/her eyes for > 1 sec.	F3T2-VER2	Setup a test environment that imitates the geometrical constraints of an MR room. More details in chapter 3.4.1. Let the subject provoke a warning by letting the subject close his/her eyes, and verify that F3T2 is fulfilled by monitoring the output data.
F4T1	The system shall have a battery solution with enough Ah to power the system for the required time.	F4T1-VER1	Setup the system and run it continuously while monitoring the power consumption, and verify that F4T1 is fulfilled.
F5T1	The system shall use a non-magnetic tripod on which it can be mounted.	F5T1-VER1	Mount the system on the chosen tripod, and verify that F5T1 is fulfilled.

F6T1	The battery shall be easy to detach from the system and not require any interference with the other components inside the enclosure. Write clear manual instructions for a battery change.	F6T1-VER1	Perform a battery change and verify that F6T1 is fulfilled, and verify that manual exists.
F7T1	The minimum working distance shall be 0.5 m and the maximum working distance shall be 4 m. The system shall be able to be placed in front and behind of the bore, and use the head coils mirrors as an optical path for the eye tracking.	F7T1-VER1	Setup a test environment that imitates the geometrical constraints of an MR room. More details in chapter 3.4.1. , Verify that F7T1 is fulfilled.
F8T1	A manual shall be written for a quick setup.	F8T1-VER1	Verify that manual exists.
F9T1	A manual shall be written for a quick setup between different subjects.	F9T1-VER1	Verify that manual exists.
F10T1	The system shall be used outside the 3 mT line. The system shall be built with materials that have a high ratio of non-magnetic and magnetic materials.	F10T1-VER1	F10T1 is tested and verified by an experienced MRI operator by following standard protocols for that site.
F10T2	The system shall be used outside the 3 mT line. The system shall be built with materials that have a high ratio of non-magnetic and magnetic materials.	F10T2-VER1	F10T2 is tested and verified by an experienced MRI operator by following standard protocols of that site. The eye tracking shall be verified that it is not affected by vibrations. The components shall be verified that they have not been affected by vibrations.

F10T3	The system shall be used outside the 3 mT line. The system shall be built with materials that have a high ratio of non-magnetic and magnetic materials. All of the components shall be shielded from RF radiation.	F10T3-VER1	F10T3 is tested and verified by an experienced MRI operator by following standard protocols for that site. The system shall be verified that it has not been affected by any induced currents.
F10T4	The system shall be used outside the 3 mT line. The system shall be built with materials that have a high ratio of non-magnetic and magnetic materials. All of the components shall be shielded from RF radiation.	F10T4-VER1	F10T4 is tested and verified by an experienced MRI operator by following standard protocols for that site.
F11T1		F11T1-VER1	

5.3 Proposed system design

This section includes the proposed system design, including an overview, component descriptions, software and synchronisation concerns, as well as a basic interface outline.

5.3.1 Overall system description

The system can be separated into two parts, the first being situated inside the MRI room and the second being placed in the control room. The camera system inside the MRI room contains the camera, IR illumination, power source and electronics. It is encased in an RF shielded enclosure to abide by the requirements of an MRI conditional item (F10 of the FRS). The camera system is connected to the control room through a fiber optic cable, to reduce the risk of interference (F10 of the FRS). The control room system outside of the MRI room consists of a Smart Eye computer that has the software to control the camera system through the fiber optic communication link. Because this system is in the control room rather than the MRI room, it does not have to comply with the safety concerns of the camera system. Additional systems are also connected to the two-part eye tracking system. The eye tracking can be controlled by the users own computer through LAN. Accurate time stamping is performed by synchronising the Smart Eye computer with the visual stimuli computer through NTP (F1 and F11 of the

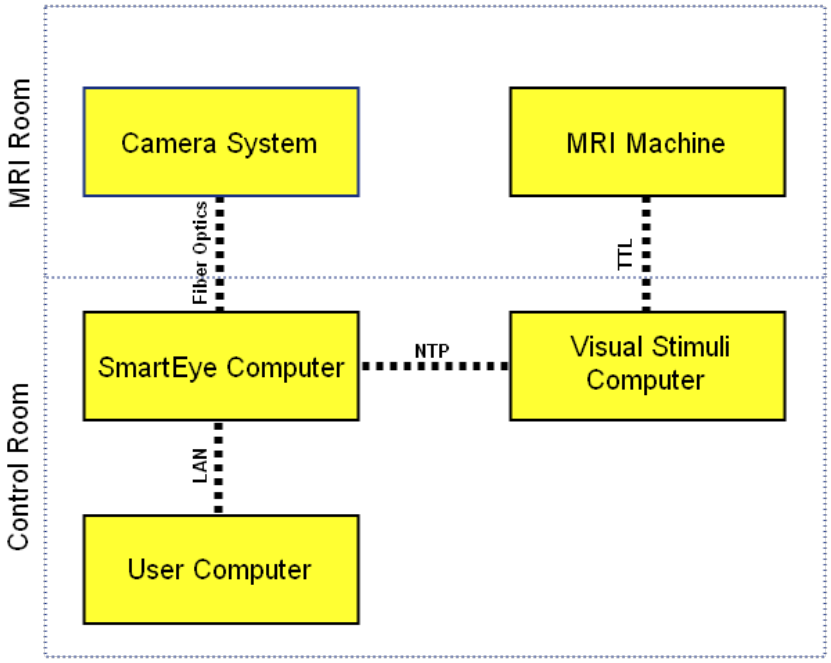


Figure 9: A block diagram displaying the relation between the different parts of the system. The separation between the two rooms can be seen, as well as what consitutes the connections between the subsystems.

FRS). The visual stimuli computer, in its turn, receive image acquisition signals from the MRI system through TTL. The relationship between these systems can be seen expressed in a block diagram fashion in Figure 9.

The system was designed to be used in a long range setting to ensure compliance with the MRI conditional standard marking (F10 of the FRS). To provide an optical path to the eyes, this requires the use of the head coil mirrors, which also allows us to adapt to different MR room configuration (F7 of the FRS). The system will use bright pupils instead of dark, because it is more practical to have the IR illumination close by to the camera. Additionally, dark pupil would require the illumination to be very far to the side of the camera since the distance to the mirror is so long, making it infeasible. An early and simplified concept sketch of the placement of the system can be seen in Figure 10.

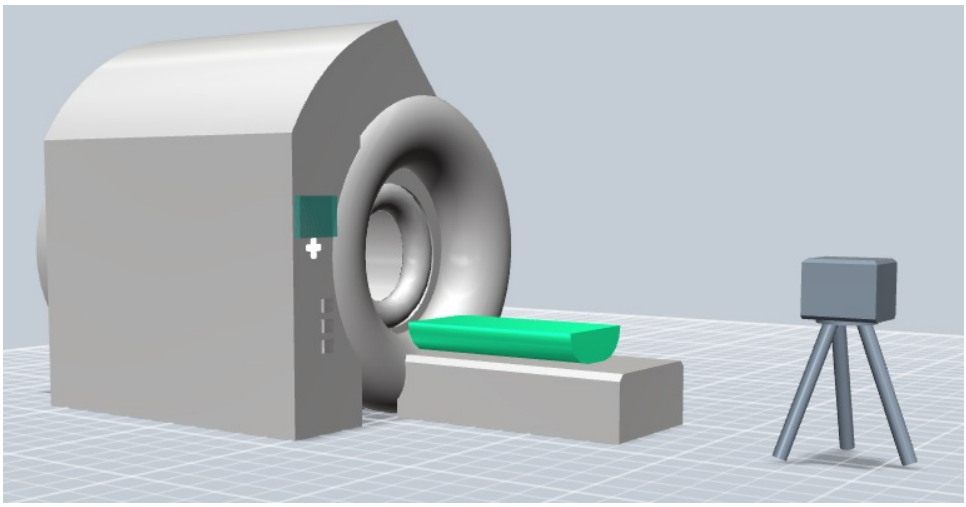


Figure 10: A 3D sketch of a camera system mounted on a tripod, placed in front of the MRI machine bore.

5.3.2 Component descriptions

A mock-up enclosure was created with dimensions to fit all of the components inside it and to illustrate the size of an actual RF enclosure. The mock-up enclosure was also used as a tool for how the mechanical solution of the prototype could be done. The camera and the IR-illuminators need an optical path through the enclosure for image acquisition, and two solutions were proposed: a shielded window or a waveguide. An illustration of all of the components (detailed descriptions below) fitted inside the enclosure can be seen in Figure 11. In Figure 11, a mock-up representation for the IR-illuminator is also used. The IR-illuminator mock-up was used as a reference point for the design of the printed circuit board, where the IR-illuminators are placed on.

Camera The camera used in the prototype is a Basler Ace acA640-120gm/gc C-Mount. This is a camera that has been used extensively by Smart Eye, and it was natural to use it in the project as the experience of utilising it already exists in the company. The camera will run with a frame rate of 120 Hz, as high sampling rates are becoming more interesting in the research performed with eye tracking in MRI, see Section 4.1.1.

Lens The lens that was used for the camera is a Tamron (M118FM50, C 1/1.8 50mm F/2.8). To be able to work inside of the intended range (F7 of the FRS), the retailer of lenses that was usually used by the company was then contacted

and consulted, through which it was decided that a focal length of 50 mm would be sufficient.

IR illuminator The IR illuminator uses four OSLON Black Series (850 nm: SFH 4715S, 940 nm: SFH 4725S), with LISA2 lenses (FP11852_LISA2-O-90-PIN) to focus the light. These flashes have been used previously, and were chosen since the experience of using them existed in the company.

Exponator The exponator is used to trigger the IR illumination at the same time as the camera is taking an image. It is also used to control the illumination pulse duration, the exposure time of the camera and the frequency of the pulse. The exponator used in the prototype was the same as those used by SmartEye in other applications, and were constructed in house.

Media converters D-Link media converters (DMC 700-SC) were used to convert from TP to fiber SC, and the other way around.

Battery The battery that was used is a lead accumulator. This battery technology was chosen for its stability and ease of use (F6 of the FRS). Lithium ion technology was not chosen because the risk of battery explosion could be very dangerous in an MRI environment, even though the risk is low (F10 of the FRS). Nickel metal hydride was not chosen because of the difficulties in charging parallel connected packs.

Shielded windows The first solution for the optical path through the enclosure was a shielded window. Two foil samples, 9000 Mesh Foil and 9900 Transparent Foil, were ordered from a company in Holland. The foils could be applied on the camera lens and they had different characteristics in terms of transparency and shielding.

Waveguide The second solution was a waveguide through the enclosure. Both of the proposed solutions shields electromagnetic waves (F10 of the FRS). A waveguide mock-up was built with dimensions to not give any FOV constraints, and was also used to determine where it should be placed.

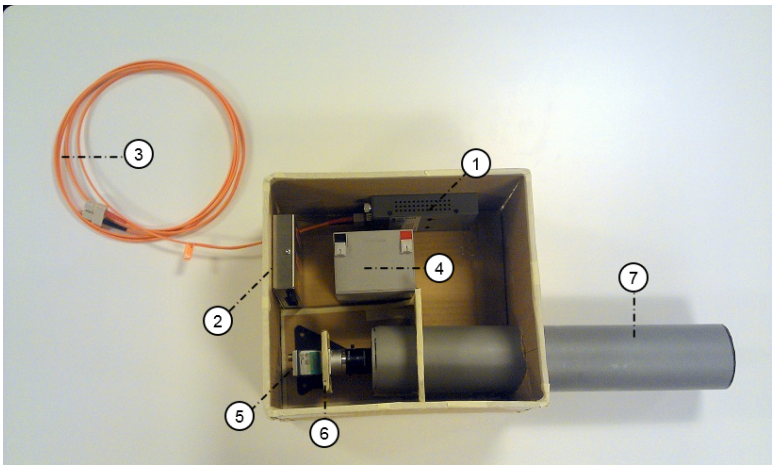


Figure 11: Picture of the mock-up enclosure with the components fitted inside. All of the components are numbered. 1. Media converter, 2. Exponator, 3. Fiber optic cable, 4. Battery, 5. Camera with lens, 6. Mock-up IR illuminator and 7. Mock-up waveguide

5.3.3 Software

The system uses Smart Eye AntiSleep, which is described in Section 3.1.1, as the software platform but with some modifications. For this application, the subject will be laying down and looking through a mirror. This introduces constraints that makes it hard to use the original software as it is. There are mainly two concerns that have to be taken into account and modified in the software.

The first is the size of the mirror, which makes it impossible to see the whole face, and thereby identify all of the features that are usually used. To solve this problem, additional constraints can be introduced to the algorithms for the 3D head model to make up for the information from the missing facial features. In addition, the head coil will also constraints the possible movements of the head. Because of this, the tracking would only be required in fewer degrees of freedom than that of a freely moving head.

The second concern is that the eyes of the subject will exhibit bright pupils, as opposed to dark, because of the positioning of the IR illumination. Having the IR illumination mounted close to the camera, as it will be in this application, will lead to this effect at long distances, as described in Chapter 5. AntiSleep was originally designed with the dark pupil technique, and the software needs to be developed to handle bright pupil.

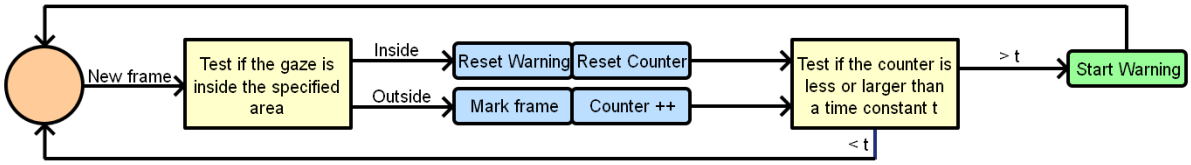


Figure 12: A simple block diagram sketch of how the warning system can be designed. Yellow boxes represent if-statements, blue represent setting of variables and green the calling of another function. The warning is started if the subject keeps the gaze outside the specified area for a time t.

Both of these concerns are directly connected to the tracking of the head and eyes. In addition to the tracking, there are also another function that was identified as beneficial for this system. To make sure the subject is following instructions for the experiment and stays attentive, a warning system could be implemented to alert the people running the experiment if that is not the case (F3 of the FRS). This function would mark frames and alert the users if certain conditions are not met in the output data. The two conditions identified that would be interesting to monitor is whether the subject is closing the eyes for too long, which can be identified by a loss of eye tracking, and if the subject is looking outside the screen for too long, which can be assessed by checking if the gaze position falls inside the area that represents the visual stimuli screen in the coordinate system. A suggestion for how this algorithm might be designed can be seen in Figure 12.

5.3.4 Synchronisation

The synchronisation part of the system can be divided into two parts; the synchronisation between the different system parts and the synchronisation of timing errors. The different parts that needs to be synchronised are the MRI system, the stimulus presentation and the eye tracker. We divide the MRI room in two sections as well, the scanner room where the magnet and the subject is located, and the control room, outside of the magnet room. A block diagram that illustrates these relationships can be seen in Figure 9.

A MRI usually has TTL outputs that can be used to synchronise the timestamps, for example a signal sent at the beginning of image acquisition, see Section 4.1. Our system however does not have a TTL input, which is why we cannot have a direct synchronisation to the MRI scanner. The alternative is to have a indirect synchronisation through a system that does support TTL input. The visual stimuli programme E-prime has support for TTL-input, and has integration with Smart

Eye's software. The assumption behind using this integration with E-prime is that for experiments that involve an eye tracker, visual stimuli is used in the majority of cases. Because of this it is a sufficient solution to indirectly synchronise with the MRI scanner with the help of E-prime. We also assume that timing errors between the visual stimuli and the MRI scanner is handled by E-prime. The synchronisation between E-prime and Smart Eye's systems is performed through a network time protocol (NTP) and this solution has been used in the synchronisation of these two systems in other applications.

5.3.5 Interface

The software interface of the eye tracking system will also have to consider the importance of easy use, just as it has been an important point through all aspects of the product. The most important parts of a software interface for this system is closely related to the main features: the live stream of the subjects face, the gaze and other data such as eye blinks or pupil dilation, and thirdly the inattention warning system. All of these must be the focus of the interface, and be easily accessible. The main purpose of the inattention warning system is so that the users can react directly, and instruct the subject so that the experiment data is not rendered useless. Figure 13 shows a rough sketch of how such a interface might look, and what information we think is the most important for the user. In the development of an user interface like this, the users of it must of course be consulted to arrive at something that is tailored to their needs.

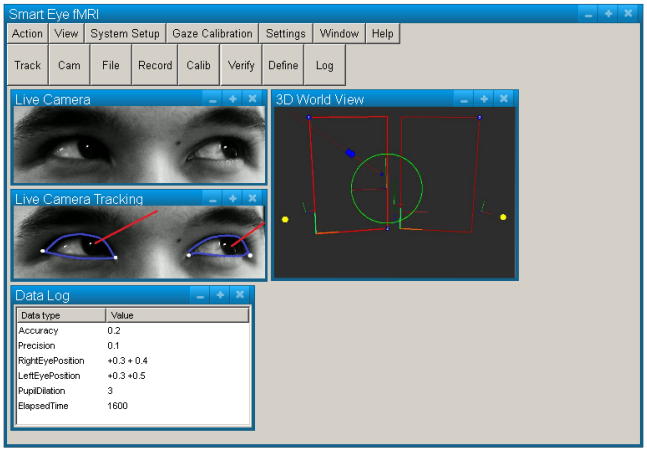


Figure 13: A simple sketch of the main components of interest for this system's graphical user interface, including a live feed of the subject's eyes, the features and gaze, world model with gaze direction and data log with updating information.

5.4 Preliminary system testing

Before testing the entire system inside the MRI room, parts of the system were tested as part of the development. These tests were performed at the office of Smart Eye. The setup of the tests will be described in the next section, and the results of the tests will be shown in the section following that.

All the results in this section come from the same set of data, that can be found in Appendix B. The data has been reorganised into separate tables, one for each of the issues that they investigate, for display purposes. This means that a measurement value in one of the tables can come from the same experiment as a measurement in another table. To allow for comparison with the source data, the experiment ID has been included for all measurements that are shown in the tables.

5.4.1 Setup

Preliminary testing was performed on all the components required to capture images outside of an MR room, i.e. without an RF-shielded enclosure. The components tested in this preliminary round was the camera, IR illuminators, different lenses for both the camera and the illuminators, exponator, media converters and with and without a shielded window in front of the camera and flashes. The standard setup for the components was setup as it would be in the actual prototype, with the IR illuminators close to the camera, the camera connected with an Ethernet cable to a media converter and having a fiber optic cable run to the second media converter, where it was connected to the computer. The components were connected without the battery. To imitate the MRI rooms geometrical constraints, see Section 3.2.2, the subject was placed laying down in front of the camera, using a single mirror to provide the proper optical path as it would have been with a subject inside the bore, which can also be seen in Figure 14. To imitate the dimensions of the head coil mirror, a white paper was attached to it with a 50 x 150 mm cut out hole, which is illustrated in Figure 14.

Several tests were performed, mainly aimed at examining the amount of light that reaches the subject as this is a important part for a successful eye tracking. Parameters that were tested includes the distance between camera and the mirror, IR illuminators positions, number of illuminators, different camera and flash lenses and shielded windows.

A typical test round was performed by choosing the above mentioned parameters, measure the background IR radiation with a Hagner EC1 IR Digital Radiometer [28] and then record with the software. After recording, measurements of how

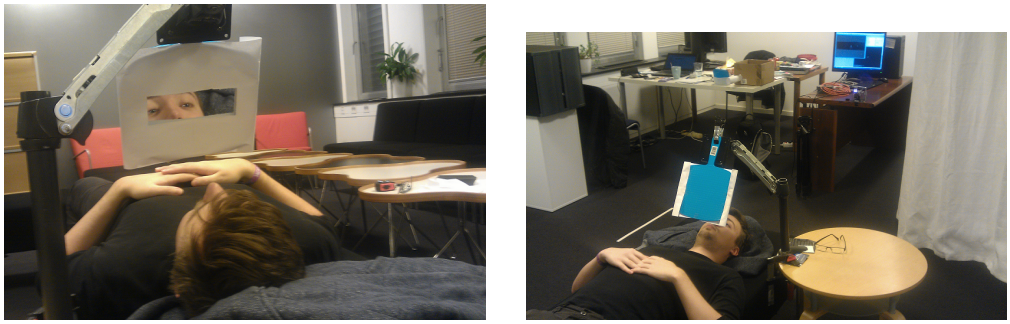


Figure 14: The images show two different angles of the setup used to imitate the optical characteristics of the MRI head coil. The mirror was covered in such a way that the visible part had the same dimensions as a real head coil mirror.

much IR radiation that reflected in the mirror was performed by pointing the radiometer's detector in the same optical path back to the illuminators. The radiation was also measured directly without the mirror from the same distance. The radiometer works in the range of 0.01 - 20,000 W/m^2 and has an accuracy of ±3%. The results of the tests can be seen in the next section.

The goal with these preliminary tests was to find a optical solution for the design suggestion that can give sufficient image quality for eye tracking.

5.4.2 IR Illuminator lens viewing angle

Table 3: Test results from investigating how the IR illuminator lens viewing angle impacts the power received where the subject is laying. The viewing angle is the angle with which all four of the IR illuminators spread their light, and the distance is the distance to where the subject is lying.

Experiment ID	Viewing Angle (deg)	Distance (m)	Power (W/m^2)
17	16	1.15	0.63 ±0.02
18	23	1.15	0.53 ±0.02
19	16	2	0.19 ±0.006
20	23	2	0.16 ±0.005

The results show that a narrower viewing angle results in more power than a wider angle, and that the increase in the amount of light is proportional between the two different distances.

5.4.3 IR illuminator quantity

Table 4: Test results from the investigation of how the number of IR illuminators as well as the distance to the subject impacts the received power.

Experiment ID	Number of illuminators	Distance (m)	Power (W/m^2)
1	4	2	0.22 ±0.007
5	4	3	0.07 ±0.002
7	4	4	0.04 ±0.001
10	6	2	0.30 ±0.009
11	6	3	0.15 ±0.005
12	6	4	0.10 ±0.003

The power naturally increases with the number of IR illuminators, and decreases roughly with the inverse-square law when the distance increases, as expected.

5.4.4 Mirror influence

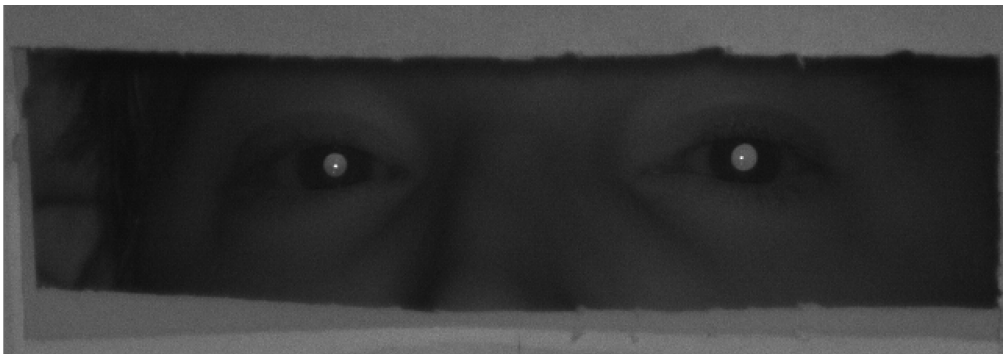
Table 5: Test results from the investigation of how the mirror influences the received power. When measuring both the light that had been reflected in the mirror and the light that had not been reflected, the sensor was aimed towards the source.

Experiment ID	Mirror	Distance (m)	Power (W/m^2)
1	Yes	2	0.22 ±0.007
2	No	2	0.24 ±0.007
5	Yes	3	0.07 ±0.002
6	No	3	0.09 ±0.003
7	Yes	4	0.04 ±0.001
8	No	4	0.05 ±0.001

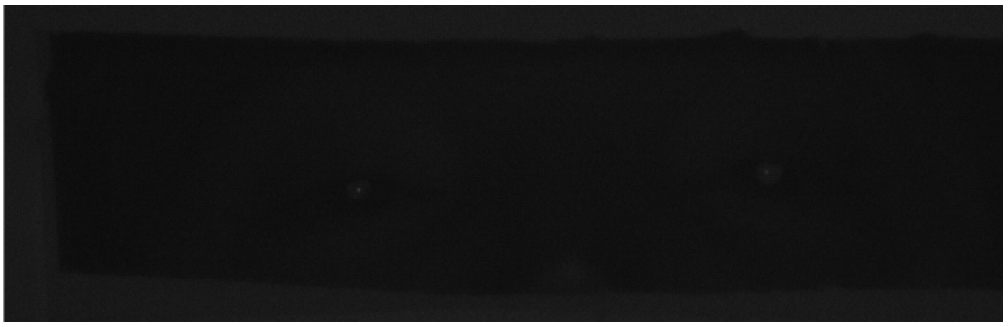
The results show that the loss in power from the reflection in the mirror seems to be constant, rather than proportional to the incoming amount of power. For these tests, only one mirror was used. The head coil in Figure 7 have two mirrors to re-invert the image, but this was managed by the software for these tests.

5.4.5 Shielding window

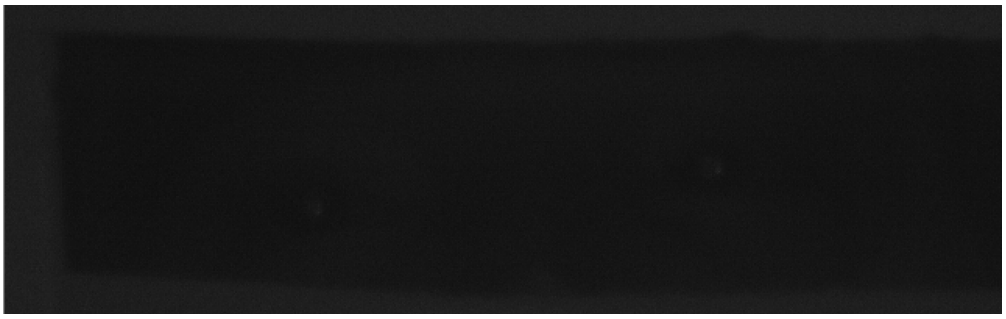
Image acquisition tests were performed without any shielded window, with the 9900 Transparent Foil and with the 9000 Mesh Foil. The test results shows that the foils reduces the amount of light in such a degree that barely any features are visible. A comparison of how much the light has been reduced, can be seen in Figure 15.



(a) Screenshot from the video recorded during test 1. The eyes are clearly visible, the pupil is bright and the corneal reflection can be seen.



(b) Screenshot from the video recorded during test 3. The light has been so much reduced that it is hard to see any features at all.



(c) Screenshot from the video recorded during test 4. The light has been so much reduced that it is hard to see any features at all.

Figure 15: Comparison of the frames recorded without any shielded window (a), with the 9900 Transparent Foil (b) and the 9000 Mesh Foil (c). All of the images were recorded at the same distance (2m), with the same gain and the same aperture settings.

6 Discussion

This section discusses the results of the project, including requirements, design, and test results, but also contains a comparison with other eye trackers for fMRI and a part on future development of the prototype.

6.1 Requirements and design

The majority of the requirements in the FRS are based on the information collected from the partner meetings, more than the other sources, due to the experience they have in third party products for fMRI. In the early stages of the project, all possible solutions to each of the design decisions required were open, as to not exclude options too early. An example of such a topic is the placement of the eye tracking system. Placement at long range, short range and inside the bore (with or without electronics inside) was considered. The choice of this placement is one of the most fundamental decisions that influence many other factors later in the design. Because of the strong recommendation from several partners that long range was superior, this approach was chosen. Having a long range system vastly reduces the risk of influencing the MRI images, and also makes the safety requirements easier to fulfil. The choice of using battery over power cables was another important decision that has an impact on later design issues. The usage of power cables in an MRI environment in some labs is not very popular and can encounter great resistance. By completely removing that requirement by choosing to use a battery, the system can more easily be used in more labs. One of the most important goals of the project is to design a prototype that is not too specialised and that can be used in as many MRI environments as possible. Our concept of being able to use the system in as many different labs as possible has been in the background for all of the design choices. This may have lead to some of the requirements in the FRS being too focused on a final finished product rather than a prototype that can just confirm if it is possible to track in an MRI environment.

Feedback from potential customers, as well as talks with partners, have shown that currently existing eye tracking systems for fMRI are very hard to use and that a lot of expensive MRI time is wasted because of this. In some cases the eye tracking system has not been used at all due to taking too much time to setup and wasting time from the MRI experiment. This issue has led to us trying to have a focus on ease of use and quick setup, which has influenced several design decisions.

There are several examples of this, such as the choice to have all components of the system be located in one unit, making it easier to setup rather than having to setup several components at different places in the MRI room. Another example is the usage of a battery, which removes the need to put down power cables, reducing the setup time.

6.2 Preliminary test results

The preliminary tests were focused on finding a good solution for image acquisition, i.e. finding a good optical solution. When it comes to designing the optical components for the prototype, the two factors that most influence the amount of light that reaches the subjects face, are the number of IR illuminators and the distance. Another factor that also impacts the amount of light is the viewing angle of the IR illuminator lenses, but definitely less than the other two previously mentioned factors. The mirror did not have a very large influence, which was unexpected but positive, since the mirrors will not cause optical problems as we first suspected they might. Combining the results of all these tests that tried to mimic the different characteristics of the MRI environment, it seems very plausible to be able to perform eye tracking from an optical stand point. Other factors that we have not tested but could affect the final quality of the image are flashes with higher power and different cameras. However, higher power flashes would lead to a higher battery consumption and hence shorter operation time, and a trade-off between image quality and battery time needs to be considered.

In the preliminary tests of the shielded windows, it was shown that these blur and reduce the intensity of light significantly in the images. That makes it unlikely for this proposed solution to work as the optical path through the enclosure. The use of a waveguide would therefore be a better option, provided that it can be sufficiently EMI gasketed, since it does not put anything in the optical path that could reduce the image quality. Preliminary testing of such a waveguide has however not been performed in this project.

6.3 Comparison with other eye trackers for fMRI

This comparison has been performed by looking at the product specification of the different products, rather than testing them in an actual MRI environment.

Both ASL's model R-LRO-XG and SMI's iViewX^{TM}MRI-LR are long range systems but with different solutions for the illumination sources. R-LRO-XG has the illumination placed inside the module, like the proposed system, while SMI uses a

mirror box that is mounted to the head coil. The advantages of having the illumination and the camera in one module are less system pieces, and the ability to have the light on the same optical axis, i.e. bright pupil technique. However, SMI's solution for the illumination makes it a lot easier to have sufficient amount of light on the subject's face, but each mirror box has to be customised for different head coils. The proposed solution with a tripod mount is easier to adapt to different MRI rooms and machines, and the camera and the illumination share the same optical path.

None of the systems uses batteries as a power source, but the SMI model has it as an option. A battery solution, as stated before, makes the system more easily used in different labs.

Some of the characteristics of our prototype are similar to R-LRO-XG, such as the placement of the illumination which gives bright eyes, while other are similar to the MRI-LR, such as the straight optical path and (probable) use of waveguide. But we have some unique features, such as a compact system solution with a standard battery power source.

6.4 Looking into the future

To put this design suggestion together into a final prototype, a few points are required to be solved. These include the mechanical design of component attachment inside the enclosure, electronics for the battery, as well as a mounting solution for placing the system in the right position. Finally, tests have to been done with an actual waveguide and a RF enclosure in an MRI environment to deduce if our solution is MR compatible.

Our system solution has a 120 Hz camera frame rate, as opposed to some existing systems that operate at a high frequency (250-2000 Hz). The partners that we have talked to, as well as ourselves, fail to see the meaning of high frequency eye tracking when combined with fMRI which has a low temporal resolution. Researchers seems most interested in simpler data signals, such as approximate gaze direction and attention of the subject. It is less common to use signals that require high frequencies such as micro-saccades. Some of the partners, however, do imply that research in these much more specialised areas might become more common further into the future. This might lead to an interest in high frequency eye tracking in fMRI, but it is not that common today. If a Smart Eye system were to be modified to be able to sample at high frequencies, the main limitations and obstacles would lie in the processing power required by the eye tracking algorithms. This would also require different cameras than those that are used by the company.

For the moment, the main market seems to be research rather than clinical usage. If a diagnostic method dependant on eye tracking together with MRI was developed however, the potential in such a system would be very large, since that would lead to much larger quantities of products required than is the case for just research. This would lead to a much bigger market, but also more requirements and regulations.

7 Conclusion

In this thesis, the conclusion has been reached that it is plausible to adapt a Smart Eye system to be used in an MRI. This can be achieved by using a long range system, with optical components suited for use outside the 3 mT field line. The system must also be EMI sealed, constructed using minimum amounts of ferromagnetic materials, and utilise fiber optics for data transfer and a battery as power source. However, to verify our suggested design, tests with an actual RF enclosure and waveguide will need to be done in an MRI environment.

The requirements were investigated, answering the six research questions posed in the problem statement, and was used to create a requirements specification outlining the most important points to consider in the design of an MRI adapted eye tracking system.

A design of the system was suggested, and preliminary testing was performed. This preliminary testing was focused on the optical components of the system, and the conclusion of them is that it is plausible to put together a system that can achieve images of sufficient quality for eye tracking.

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A Questionnaire for eye-tracking in MRI

1. In what field are you working / conducting research?

2. Have you used an eye tracker before?

3. What would you like to improve to accomplish your goals and align more with your research?

4. What other systems would need to work in cooperation with the eye tracker, and what models?
(MRI, MRI head coil model, EEG, MEG, TMS, data logger, stimuli generators, response box, other...)

5. What kind of visual stimuli are you using, if any?
(computer screen, screen position relative to bore, goggles, system model, stimuli other than visual, ...)

6. What other software do you need to work in cooperation with an eye tracker, both during the experiment and in the analysis phase?
(E-prime, LabVIEW, MATLAB, Presentation, Superlab, other...)

7. Do you have any requirements when it comes to spatial and temporal resolution (sampling rate), accuracy or synchronization with other equipment?

8. Roughly describe a typical / desired setup for your institution / company.

9. What signals would you like to get out of an eye tracking system for your research?
(E.g: Pupillometry, gaze target location, eye rotation state, eyelid state, blink event, fixation/saccade classification, detection of test subjects (in)attention, other...)

10. What kind of geometrical positioning of the cameras would fit the best into your working routine?
(In headcoil, at rear end of bore, remote mounted at feet, remote mounted across the room, ...)

B Preliminary testing results

This appendix contains the results from the preliminary testing, and they have been divided into three separate tables for easier overview. The three categories are tests with 4 LEDs, 6 LEDs, and with shielding windows. More detailed descriptions of the test setup and way it was conducted can be found in the main text.

Table 6: Tests using 4 LEDs, that were all performed using 23° LED lenses and a 50 mm Tamron camera lens.

ID	Distance (m)	Mirror	Power (W/m^2)	Background radiation (W/m^2)
1	2	Yes	0.22 ±0.007	0.02
2	2	No	0.53 ±0.02	0.02
5	3	Yes	0.07 ±0.002	0.02
6	3	No	0.09 ±0.003	0.02
7	4	Yes	0.04 ±0.001	0.02
8	4	No	0.05 ±0.002	

Table 7: Tests for the shielded windows were performed at a distance of 2 meters with 4 LEDs using 23° LED lenses and a 50 mm Tamron camera lens.

ID	Window	Power with mirror (W/m^2)	Power without mirror (W/m^2)	Background radiation (W/m^2)
3	9900 Transparent Foil	0.09 ±0.03	0.11 ±0.03	0.02
4	9000 Mesh Foil	0.11 ±0.03	0.13 ±0.04	0.02

Table 8: Tests using 6 LEDs, that were all performed with the mirror and 6 LEDs using different configurations of LED lenses

ID	LED lens composition	Camera lens	Distance (m)	Power (W/m^2)	Background radiation (W/m^2)
9	2x 16° (centered), 4x 23°	50mm	2	0.32 ±0.01	0.01
10	4x 16°, 2x 23° (centered)	50mm	2	0.30 ±0.01	0.02
11	4x 16°, 2x 23° (centered)	50mm	3	0.15 ±0.005	0.02
12	4x 16°, 2x 23° (centered)	50mm	4	0.10 ±0.003	0.02
13	4x 16°, 2x 23° (centered)	25mm	2	0.30 ±0.009	0.02
14	4x 16°, 2x 23° (centered)	25mm	3	0.15 ±0.005	0.02
15	4x 16°, 2x 23° (centered)	25mm	2	0.15 ±0.005	0.02
16	4x 16°, 2x 23° (centered)	25mm	2	0.15 ±0.005	0.02