UNIVERSITY OF WISCONSIN-MADISON
DEPARTMENT OF BIOMEDICAL ENGINEERING
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DEVICE FOR TRACKING HEAD MOTION IN AN MRI SIMULATOR

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ABSTRACT

While performing medical procedures on patients there is often a great difference between individual subjects. Medical professionals much overcome these differences to conduct the procedure correctly and obtain accurate and reliable results. One difficulty that these professionals and researchers might encounter, as is the case with our client, deals with the difference between the abilities of their patients to hold still long enough to perform the procedure correctly. Young children have difficulty focusing and lying in one spot without moving while an MRI machine scans their brain; they must be trained to hold almost perfectly still while the scan is taking place. Using patient feedback and stopping a movie or other attractive feature for the patient when they move past a certain desirable threshold can perform this. Our device will detect very slight patient movements and stop playback when a threshold is exceeded.

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PROBLEM STATEMENT

The goal of this project is to design and build a system to track a subject's head motion in an MRI simulator and link this to a video display. When the subject moves his/her head, a displayed video (movie) is turned off; when the subject stops moving his/her head, the video resumes. Our goal is to use this device to train children to keep their head still when undergoing an MRI scan. Ideally, this device and software should be user-friendly. The system should be capable of detecting at least 0.2mm and 0.2 degree head motion at 30 Hz or better. The subject will be lying in a simulated MRI scanner, so access to the subject is somewhat spatially limited.

BACKGROUND

The client for this design project is Dr. Rasmus Birn. He is doing research on the organization of the brain during childhood development. The two main areas that his lab's research is focused on is methodological improvements for resting- state functional connectivity and changes in functional connectivity during childhood and adolescence [1]. This is done through Magnetic Resonance Imaging, MRI, of children's heads as they age.

MRI is a technique used to produce detail images of internal structures of the human body. This is done by an MRI machine producing a powerful magnetic field to cause the protons in the body to align themselves. Next, radio waves are produced and sent to the body for the protons to absorb, causing the protons to start spinning and emit energy that is picked up by the coil of time MRI machine [2]. This creates image slices of the part of the body that is being scanned which are sent to a computer that is able to produce a final three dimensional image.

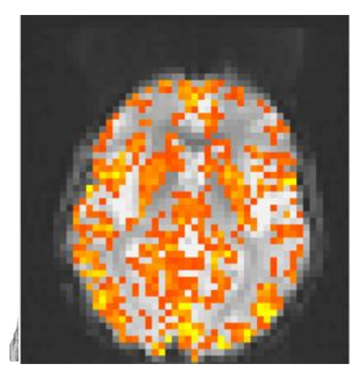

Figure 1 – An image from an fMRI during the subject taking a single deep breath [2].

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Thus, accurate brain images can be created using MRI scans. Particular brain activity can be measured using function MRI (fMRI). This is a type of MRI which detects changes in blood flow related to energy use by brain cells, also known as the hemodynamic response [3]. Figure 1 is an example of an fMRI image that could be used for research. Images of patient as they become older allow researchers to see the difference between the children and adults brains. An example of major locations being identified for comparison can be seen in Figure 2. For this research to be done, multiple scans must be taken from a large subject pool that will produce clear usable images.

MOTIVATION

For accurate scans and clear images to be created, the subject in the MRI scanner must remain still. This is because movement that occurs during scanning can result in image distortion. In fact, movement of 1 mm translational or 1˚ rotational will cause image distortion. If larger movement occurs, the image can be distorted to the point that it is no longer able to be used which wastes money and resources; therefore, an MRI simulator is used to train patients to remain still during the scanning process. The MRI simulator, Figure 3, is currently be used to try and get the patient to feel comfortable in an MRI scanner in hopes that they will then be used to remaining still during a scanning period. However, there is no way for the patient or the doctor to know if the patient is remaining still in the simulator or if small movement is occurring. Therefore, a device is need that is able to detect head motion. This device should also be able to give feedback to both the patient and the MRI operators when movement occurs. For the patient's feedback, it could be visual images or a video that is turned off if movement above a threshold occurs. The MRI

Figure 3 – A MRI simulator used to prepare patients for an MRI procedure[9].

operators' feedback could be a constant monitoring of the head in three dimensional space for movement under the threshold and an additional alert if movement occurs above the threshold.

EXISTING DEVICES

Currently, there is a device that is commercially available to work in MRI simulators that can track head motion. This technology was developed by the Psychology Software Tools, Inc. and is called Mo Trak® Head Motion Tracking System. Mo Trak is software that uses Ascension Technology's Flock of Birds sensors. These are magnetic sensors that are attached to the patient's head that can locate the position of the head in space. The Mo Trak system, Figure 4, is able to track translational and rotational movement in the MRI simulator. It is also able to give visual feedback of the patient's motion as well as auditory feedback to the participant when movement above the threshold has occurred [4]. The downfall to this device is that it is out of our client's budget as it cost approximately $8,000.

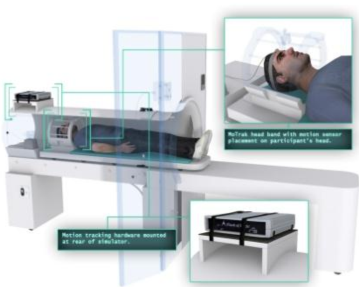


Figure 4 – Diagram of the MO Track system and how it tracks head movement in MRI simulator

CLIENT REQUIREMENTS

A number of requirements were given by the client that the system must meet. Firstly, the head tracking device must detect movement in 6 degrees of freedom: in all three planes of translational movement and rotationally around each of those three axes. The translational measurements must be accurate to 0.1 mm and the rotational measurements must be accurate to 0.1°. This precision is necessary to ensure that the image output by an MRI is not distorted or blurry. According to the clients, movement of 1 mm can significantly affect the image.

Apart from the measurements which will be taken, the size of the device also needs to be taken into consideration. After taking several measurements of the current simulator setup, a distance of 17.8 cm remains unused between the subjects face and the inner surface of the simulator. Moreover, there exists an additional round cage which is 10.2 cm from the subjects face. The device must be designed to work within these confines when considering the design alternatives.

The visual feedback to the subject must also be altered when a movement threshold of 1 mm is breached. Children have short attention spans by nature, so it is paramount to limit their movement within the simulator. By having real-time feedback, the subject will be alerted when they are not remaining still enough for the MRI to capture a clear and ultimately useful image.

It is also worth noting that we are only working with an MRI simulator which does not use actually magnetic resonance. Therefore, ferrous materials can be used in the final design.

DESIGN ALTERNATIVE: IR SYSTEM

One design alternative considered involves using LEDs and an IR camera to track head motion. The LEDs will be secured to the head of the subject in a fashion which will allow for the tracking of movement in six degrees of freedom. As the head then moves, so will the LEDs. The IR camera will take in the image projected by the LEDs onto a mirror above the subjects face and be able to triangulate the position of the head, given an initial reference point. The voltage output of the camera will then be sent through a USB microcontroller to a processing program on a computer. The program will display the six measurements described above and allow the user monitoring the subject to know how still the subject is.

IR cameras, similar to the camera used in a Wii remote, have the capabilities to track position within 0.1 mm. The rotational accuracy is more unknown, and testing would be needed to ensure its adequacy for this accuracy requirement.

A USB microcontroller, most likely Arduino, is used to allow for easy interfacing between the device and the computer. Furthermore, a programming language will need to be settled on in order to talk to the microcontroller.

Figure 5 shows the orientation of the IR camera, mirror, and the surface of the LEDs on the subject. By using a mirror to project the LEDs position, the restriction of size within the simulator is partially solved, since the camera will be place outside of the simulator.

DESIGN ALTERNATIVE: CAMERA TRACKING SYSTEM

The second design alternative is similar to the first one but instead of an IR camera this design uses a video camera. The setup will be similar to the diagram in Figure 5 with the mirror extending the field of view and allowing the camera to focus of the entire face of the subject in the MRI simulator. This system works through a web camera recording images. These images are then sent to a computer where imaging software, such as Free Track, processes the images to determine if movement occurs. Movement is detected by differences in images on a frame to frame comparison [5]. If there is a difference in the images, then movement has occurred. The images recorded by the video camera will appear similar to those in Figure 6. The image processing software will

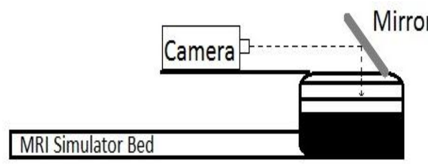


Figure 5 – Diagram of the layout of the camera tracking system.

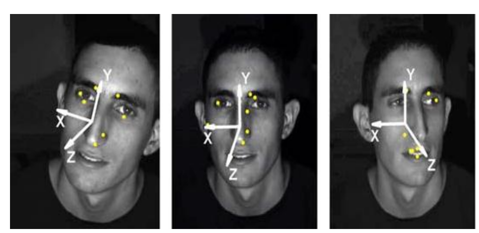


Figure 6 – Images being recorded by video camera and how they would appear before processing by software [X5]

be programmed to use the camera's pixel resolution to determine how large of a movement occurred.

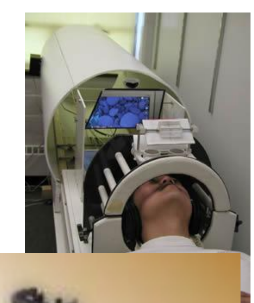
Two different camera setups can be used to allow for six degrees of freedom tracking. The first is using a single web camera like in Figure 7. This setup will need to use Light Emitting Diodes, LEDs, like how the IR Camera System did. That is, four LEDs will be used. The LEDs will be placed in the three planes making up three dimensional space [5]. The LEDs will then be placed on the subject's head to use as reference markers. The camera then records the LEDs and tracks their movement which is the same as the patient's head.

Figure 7 – A web camera that could be used in this tracking system [5].

The second camera system would use two different cameras, Figure 8 that record images simultaneously. The images are then recorded together on particular computer software that produces three dimensional images [6]. This system works similar to how humans' eyes allow them to see depth and in 3D. This system requires more complex image processing and could be affected by the use of the mirror. Further research or testing would need to be done if this system is selected to be used.

Figure 8 – DynaSight stereo- camera system [8].

The image processing software will be able to give real time feedback for the MRI operators to watch visually. A second program can be created to work alongside the imaging processing program to send feedback to the subject in the simulator when the movement threshold is reached. The subject's feedback could be a video display seen using the mirror that turns off when the movement threshold is reached. This setup would be similar to the



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one in Figure 9 that researchers at the University of Washington are trying to develop.

DESIGN ALTERNATIVE: ACCELEROMETER SYSTEM

Accelerometers measure displacement by detecting the acceleration of the sensor. It measures tilt through static acceleration, or gravity, and direction through dynamic acceleration. Accelerometers can be either analog or digital and can detect motion along one, two, or three axes. For the specifics of this design project, a three axis digital accelerometer may be the best option to reduce the amount of calibration necessary. Figure 10 shows one example of a triaxial accelerometer. By selecting a digital model a microcontroller can also be used in conjunction with the accelerometer. In addition to these differences in models, the way in which acceleration is measured varies from model to model. In some models, a hot gas bubble is located in the chip along with a number of temperature sensors around the edge. As the chip moves the bubble moves, redistributing the temperature. The temperature sensors pick up these changes and are then related to acceleration [12]. Other models contain microscopic crystal structures which forces due to acceleration stress and cause voltage generate. This changes the capacitance which is then measured. Other less common methods of measurement include use of piezoresistive effects and light [13].

Figure 10 – An example of a three axis accelerometer [11].

Interfacing the accelerometer with the subject feedback system would be accomplished with a simple circuit. At the specified threshold (i.e. 1 mm) a switch like mechanism would turn the video feed off until the subject stops moving.

DESIGN MATRICES AND EVALUATION

The design matrix was split up into 6 different categories; cost, accuracy and sensitivity, programmability, MRI compatibility, size, and manufacturability. Figure 11 illustrates the point breakdown for each of the individual categories. The first category, cost, received a ranking proportional to 18% of the total. Cost is a necessary part of the design as the clients have requested to keep the cost as minimal as possible. We have been given a budget of $500 and all of the designs should stay well within this range, leading to its average power ranking. The accelerometer received the highest score for the cost category of 18 as the accelerometer and other necessary components will be very inexpensive. The optical and infrared designs both received very similar rankings for the cost. They are slightly more expensive than the accelerometer design and therefore received slightly lower scores. The optical design requires more parts and setup and therefore received a 14 while the infrared scored 15.

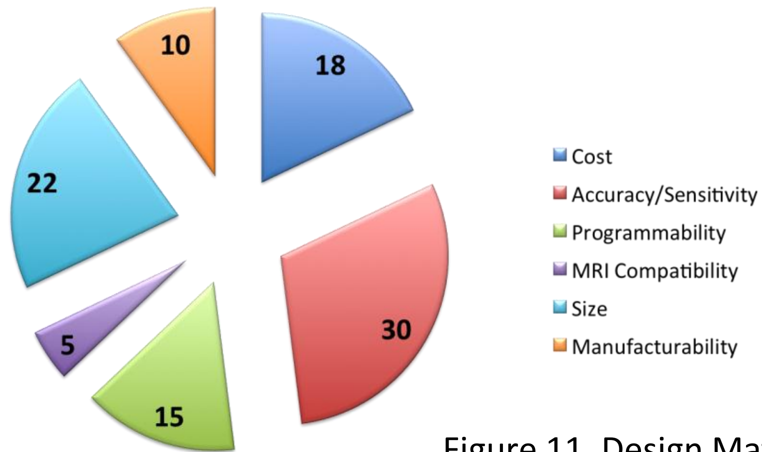

Figure 11. Design Matrix

Manufacturability is the next variable that was evaluated and received a total of 10% of the total weight. All of the designs will be relatively simple to manufacture so the scores are fairly similar with the accelerometer scoring the highest. The accelerometer will have wires attached to it that pose some manufacturing problems that prevent it from receiving a perfect score but it still comes in at an 8 out of 10. The optical and infrared designs will both require the use of mirrors to reflect the image of the subject in the MRI simulator back to them as there is not enough room in the imaging tube for the lenses and reading devices to focus in their optimal range. The optical design requires more precise mirror placement and will be more difficult to pick up the image variation than the LED position so it received a 4 while the infrared received a 5.

The size of the design and its fit into the imaging tube was the next category to be looked at. As the ability of the design to fit into the tube and perform its necessary operations must occur for the device to be functional it received a slightly heavier weighted value of 22% of the whole. In this category the accelerometer received a perfect score. There are no worries about the ability of the accelerometer to fit in the necessary space, as it will simply be attached to the subject with cords to transmit the signal to a processing unit. The infrared unit received a slightly lower score of 20, as it requires the use of one camera, a mirror, and LED lights attached to the subject. The optical design received an even lower score of 17, as it requires two cameras for six degrees of freedom, and a mirror to transmit the image to the cameras.

The category that received the highest ranking was the accuracy and sensitivity of the design. The project is meant to help train small children to hold still in an MRI simulator in order to train them for actual imaging in an MRI machine. If the children move more than 1 mm in any direction it will skew the results and render them useless. To prevent this from happening our device must have a much smaller detection value.

The accelerometer will be the most accurate of the devices, as it will detect very slight movements as long as they occur in a relatively rapid manner. This works well for the kids being trained as they are much more likely to move fast than they are to move very slowly. The optical device will also work quite well as it simply records the difference between the images it is receiving and has the ability to detect very small differences in the picture such as orientation, shadow and size. The infrared model received the lowest score in this area as the detection of the LED's attached to the subject will not give nearly as accurate of results compared to the other models. It cannot detect changes on as small of scale and also requires the most amount of objects to be attached to the test subject.

MRI compatibility is another area that was examined for each of the designs., yet it only received a ranking of 5% of the total available points. It received such a small ranking due to the fact that our client has not included it in the design requirements. The device we will produce will only be used in an MRI simulator and not an actual MRI device, but it would be beneficial to have the ability to use it in the actual machines. This led to its inclusion in the design matrix with its very small value. The accelerometer received a rank of 0 as there are many ferrous components to the device that prevent it from ever becoming MRI compatible. The infrared design received a score of 1 as if LED's can be produced using non-ferrous material it might be possible to manufacture a design that is MRI compatible. The optical design received a score of 3 as the cameras will be placed outside the actual MRI and look into the tube through a series of mirrors.

The fact that it is removed from the actual imaging tube gives it the opportunity to function without interfering with the imaging equipment.

The programmability of the devices was the last section that came under scrutiny for our design. This area was weighted for 15% of our total points available. The accelerometer will be the easiest design to work with and received a value of 12 as it utilizes a microcontroller and digital or analog input that could easily be interpreted and converted into a useful output. The optical system received a ranking of 8 as it would come with the necessary software for reading the input from the device. The software language would have to be manipulated with thresholds and recoding to help it perform the necessary functions. The infrared design received the lowest value of 6 as there would be extensive coding and programming necessary to interpret the input from all three LED's. The input from all three units would have to be combined and used as a whole to determine the orientation and movement of the individual.

Final Design

After the design matrix was completed the points each design had accrued were totaled. The accelerometer was the clear winner of the process with the optical and infrared designs scoring relatively close to each other. Each design had desirable attributes but the accelerometer scored the highest in important areas such as cost, size, and accuracy/sensitivity that were worth a majority of the total points. The design will fit in the available space without using mirrors, the necessary parts are much cheaper than the other two designs, it requires less programming and will be the easiest to manufacture. It falls behind in the MRI compatibility section but as this was not especially important to the client it still emerged as the best option to solve the problem.

Ethical Considerations

Since part of the system will be in contact with the subject in the MRI simulator, the device will need to be safe for the subject. The method of attachment to the subject must be comfortable when worn for a significant amount of time. Lastly, the device will not need to be tested using human subjects and therefore the team does not need to be certified for human subjects testing.

Future Work

Now that the accelerometer has been selected as the final design the device construction can begin. We have accurate measurements of the space available to work with, the necessary detection variables and the threshold necessary to give patient feedback. An appropriate accelerometer must be obtained that will fulfill all the requirements and programming can commence. The necessary feedback loops and data conversions can be calculated after the accelerometer has been tested. The placement of the device on the patient and hookups to the feedback device need to be investigated in order to ensure patient safety and reliability. Finally device testing can be performed using machines set to move certain distances at predetermined speeds in order to gauge accuracy and threshold values.

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Appendix: Product Design Specifications

Device for tracking head motion in an MRI simulator

February 8th, 2012

Darren Klaty , Jeff Groskopf, Sara Schmitz, Spencer Strand

Problem Statement

The goal of this project is to design and build a system to track a subject's head motion in an MRI simulator and link this to a video display. When the subject moves his/her head, a displayed video (movie) is turned off; when the subject stops moving his/her head, the video resumes. Our goal is to use this device to train children to keep their head still when undergoing an MRI scan. Ideally, this device and software should be user-friendly. The system should be capable of detecting at least 0.2mm and 0.2 degree head motion at 30 Hz or better. The subject will be lying in a simulated MRI scanner, so access to the subject is somewhat spatially limited.

Client Requirements

- Have the ability to detect movement in 6 degrees of freedom
- Fit into the MRI simulator, approximately 4 cm size restrictions
- If the project does eventually end up being used in an actual MRI scanner non-ferrous materials must be used
- Accuracy of detection as small as .1 mm or a tenth of a degree of rotation
- Feedback to the patient so they can tell when they are moving and need to stay still

Design Requirements

1. Physical and Operational Characteristics

   a. Performance Requirements: Device should be capable of withstanding repeated use without breaking, It needs to fit with the patient inside the MRI scanning simulator.

   b. Safety: The device will be used on human subjects so precautions must be taken to ensure nobody is harmed from using the device. Also it must not harm the other medical equipment or devices that are to be used in conjunction with it.

c. Accuracy and Reliability: A high level of accuracy is required from the design as very slight movements on the part of the subject can greatly alter the image the MRI is producing. Movement detection should be as precise as .1 mm or one tenth of a degree of head rotation.

d. Life in Service: The device should be able to withstand repetitive use and last for an extended period of time while still operating correctly. It should last for thousands of uses if necessary.

e. Shelf Life: The shelf life of the phantom should be an indefinite amount of time. All components should maintain working order; only objects such as batteries should have to be replaced in the design.

f. Operating Environment: The device will be placed on the exterior of the patient's body or held above their body and used to monitor their movement. It will be used indoors in a stable environment. There should be very little human contact to cut down on possible breakage of the device or its components.

g. Ergonomics: The device should experience very little human contact; only minimal forces should be applied for slight adjustments for positioning.

h. Size: The device needs to be able to fit inside the MRI simulator along with the human test subject. It will be stationary and does not need to be mobile or moved around large distances.

i. Weight: The total device should not exceed 20 Kg. The sensor or the part of the design that is placed on the human subject should be less than 2 Kg.

j. Materials: The materials used in the design that come into human contact must be hypoallergenic. If the device is ever to be used in an actual MRI machine non-ferrous materials must be used.

k. Aesthetics, Appearance, and Finish: Functionality is more important than appearance in this project. If the device works correctly the appearance of the device should be made as professional as possible.

2. Production Characteristics

a. Quantity: Only one device is needed at this time.

b. Target Product Cost: Target cost is approximately $500. This is flexible based on necessary components.

3. Miscellaneous

a. Standards and Specifications: Device must comply with OSHA regulations.

b. Customer: Client prefers that current MRI simulator set up remain unaltered, however nonessential components can be altered if necessary.

c. Patient-related concerns: The sensor must be easily sterilized and should be comfortable during extended use of the system. All materials used must be hypoallergenic.

d. Competition: There currently exists a head tracking device (MoTrak) used in MRI simulators made by Psychology Software Tools, Inc.