ESE 519: Motorized Cranial Vault Distractor

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Abstract

Cranial vault distractor is widely used to pull the skull gradually in infants head to prevent suture fuses too early. However, the sticking out rod brings about a lot of problems. Rotation can cause much pain and high infection rate. Also, parents may not be able to precisely control the rotation. A magnetic-driven motorized cranial vault distractor embedded system is designed to cope with these problems. The magnets and distractors are enclosed completely under the skin to reduce the infection. A outside band with stepper motor, microcontroller and sensor will help precisely control the rod rotation. The system has a rapid rotation mode and a slow working mode, which will complete the rotation over a period of time to reduce babys pain. In addition, bluetooth is used to give user an easy way to control distractors.

1. Motivations

The bones of the human skull are joined together by cranial sutures. Normally the sutures gradually fuse within the first few years after birth. In infants where one or more of the sutures fuses too early, the growth of the skull is restricted, resulting in limited space for brain and abnormal head shape. In order to stop the unexpected early fuse, cranial distractors are widely used to pull the skull gradually (about 1mm each day) as Figure.1 shows. Parents would use patient screwdriver to rotate the rod of distracters to distract the skull. Distraction phase is 2 turns of 360 degrees for a total of 1mm distraction per day. The distractor is covered under skin with the head of the rod going through the skin and sticking out for operation [3].

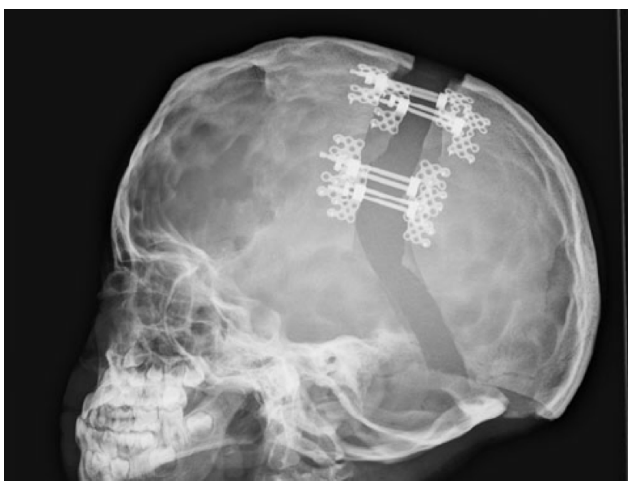

Figure 1: Existing cranial vault distractor

This sticking out rod causes a lot of problems. The rotation is painful for both the baby and the parents. And it is under high risk of infection. What makes things worse is that parents are not fully trained to conduct the rotation. They may rotate less or more than the required distance, or even turn it in wrong direction.

This project is focusing on developing a magnetic driven and motor controlled cranial distractor in labs, which will be later used in clinics, to deal with these challenges.

Figure 2: Baby with cranial vault distractors

2. Introductions

2.1. System Design

Our whole system can be divided into two sub-systems, an under-skin subsystem and an outside subsystem. The under-skin subsystem contains a distractor and a disk at the end of the rod with magnets mounting on it. The outside subsystem is a head ring fitting a stepper motor to create torque to spin, a disk with magnets to transfer torque, a power supply with power conversion and management module to provide stable and clean power, a sensor to measure the rotation of the system, a Bluetooth module to communicate with device, a microcontroller and all the other electric components for driving and control.

The system is required to provide enough torque and a high accuracy. Our first iteration is using a direct connection between inside and outside system and enclosing the motor under the skin for rotation. Then we revised our design to remove the physical connection and came up with the idea of magnetic-driven system. For distracting bones from swivel, an adequate amount of torque need to be supplied from detached arm. The torque need to be large enough to combat with the bones. One of the challenges is to transfer enough torque and indication signals between inside and outside. Magnetic force need to be specially calculated to meet the requirements. Magnets distribution is carefully designed not to draw much attraction force between inside-outside magnets to prevent from skin damage.

All components must function well in human body, which means a lot of constraints on choosing the sensor and great effort towards minimizing the size. The stepper motor is used for precise rotation control. Stepper motor is known as an open loop device. To ensure the system is stable and precise, we close the loop by placing a hall effect sensor near outside disk to detect the rotation of magnets. The sensor acts as a wheel encoder to count the number of magnets that pass through.

Bluetooth module communicating with microcontroller ensures our system could interface with any device with a standard Bluetooth module. The user can use their device for receiving commands and sending rotation information. We placed five LEDs into our outside skin system to indicate the progress of rotation.

There are two modes of operations in our system, the fast rotation mode and slow rotation mode. The previous one has a normal motor rotation speed based on research. It allows user to finish 1mm distraction in less than a minute. The latter slow mode rotation is accomplished by entering the corresponding time period user would like to operate for finishing one 360 degree turn. Commands are sending from bluetooth electric device. Research information shows slower mode of distraction would mitigate the pain of patients. This operation would finish the distraction at a duration of time as user requested.

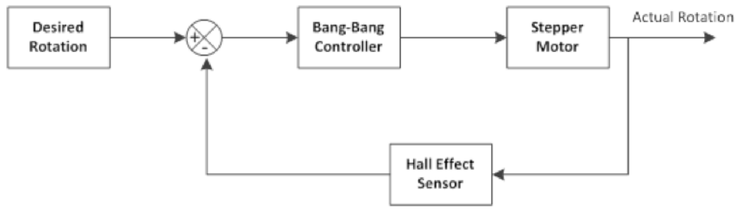

Figure 3: Block diagram

2.2. System Architecture

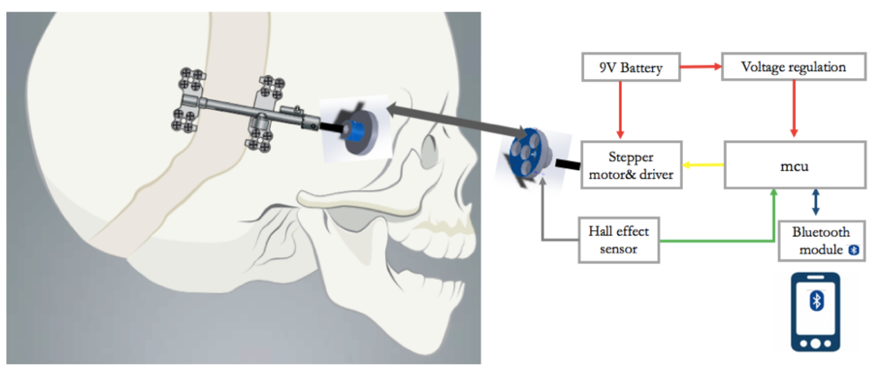

Figure 4: System architecture

3. Detailed Development Steps

3.1. Project Components

(i) Stepper motor (28BYJ-48 ULN2003 5V stepper motor)

(ii) Corresponding motor drive (ULM2003 driver board)

(iii) Batteries (Duracell Procell 9 Volt Batteries)

(iv) Corresponding battery holders

(v) Bluetooth module (HC05)

(vi) Microcontroller (Arduino micro)

(vii) 3D-printed plastic joints

(viii) 6mm diameter Nb-Fe-B magnets ()

(ix) Bluetooth electric device (Samsung phone)

3.2. Electrical/Hardware Effort

To support enough torque for the operation of stepper motor, a 9V supply is needed. In the meanwhile, 5V is the nominal voltage for Arduino micro microcontroller and its peripherals. Since we need a stable and clean supply for our system, we choose to use the 9V battery with power management module that converts supply voltage from 9V to 5V. Low dropout regulator circuit using LM340T5 is composed to step down the voltage.

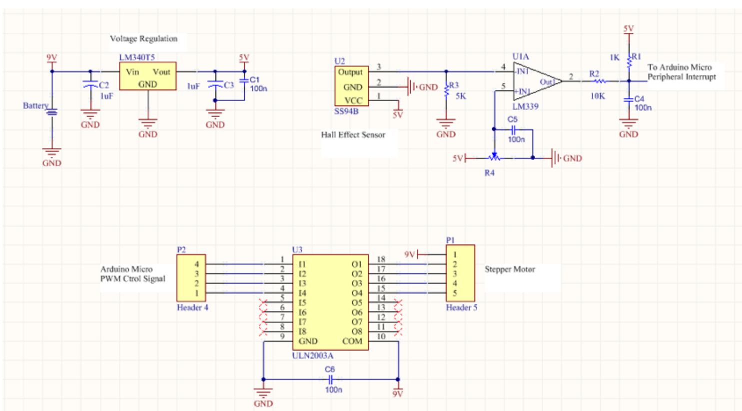

Figure 5: System hardware

For motor driver, we are using ULN2003A which are high-voltage, high-current Darlington transistor arrays.

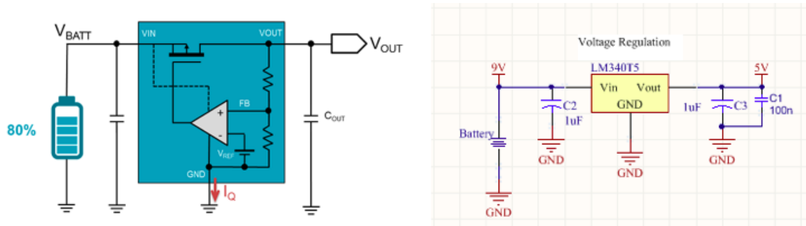

Figure 6: Low dropout regulator module for power management

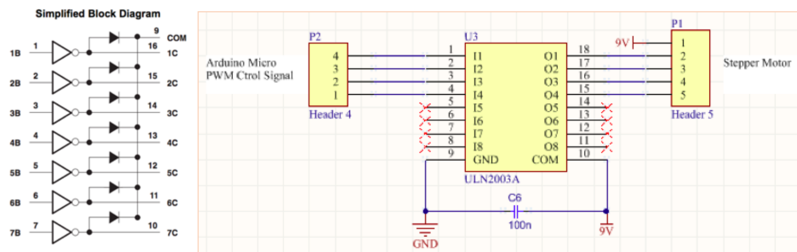

Figure 7: Motor Driver

Since the stepper motor is known as an open-loop system, we use the hall effect sensor to close the loop in case of the asynchronous operation of inside and outside disks. The magnetic disk and hall effect sensor work together as a magnetic encoder. Both two magnetic plates are designed with changing magnetic field when they rotate. A Hall effect sensor is a transducer that varies its output voltage in response to a magnetic field. The magnetic encoder uses two disks with series of magnetic poles to represent the encoder position to the hall effect sensor. The magnetic sensor reads the magnetic pole positions.

In our design (explained in detail in following mechanical part), a hall effect sensor is placed near the outside-skin magnetic disk to sense the rotation of both disks by sending up and down voltage signals back to microcontroller. The hall effect sensor will operate as an analog transducer, detect three S poles and three N poles in one rotation, corresponding to three top and three bottom voltage values. Here we are using the SS94B hall effect sensor with high perception. After calibration, we know that the hall effect sensor directly returns a voltage between about 0V and 4.5V. The voltage is feed to voltage comparator to convert to square wave signal. Also, with the noise surrounded, it would be necessary to build both hardware and software debouncing module to filter out the noise.

For hardware debouncing effort, a simple RC circuit is introduced into the module to filter out high frequency noise. In order to keep track of the rotation of inside disk, we use the interrupt capture to record the motor position when interrupt happens. This should happen every one third turn. And we use the difference between the record position and current position of the motor to determine whether the inside disk stops rotation. If the malfunction occurs, the system will send out error message and stop immediately.

The power supply of the board is feed into the ADC for checking the voltage level of battery. LEDs are connected to digital output pins as indicators for rotation.

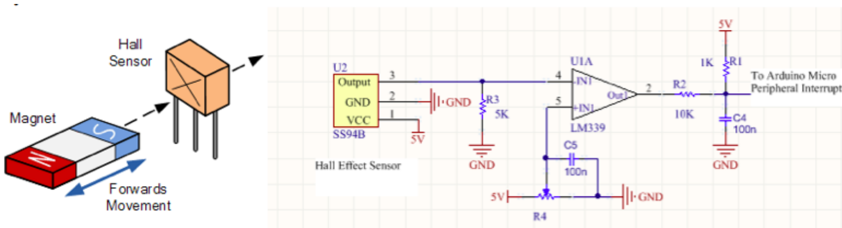

Figure 8: Hall effect sensor

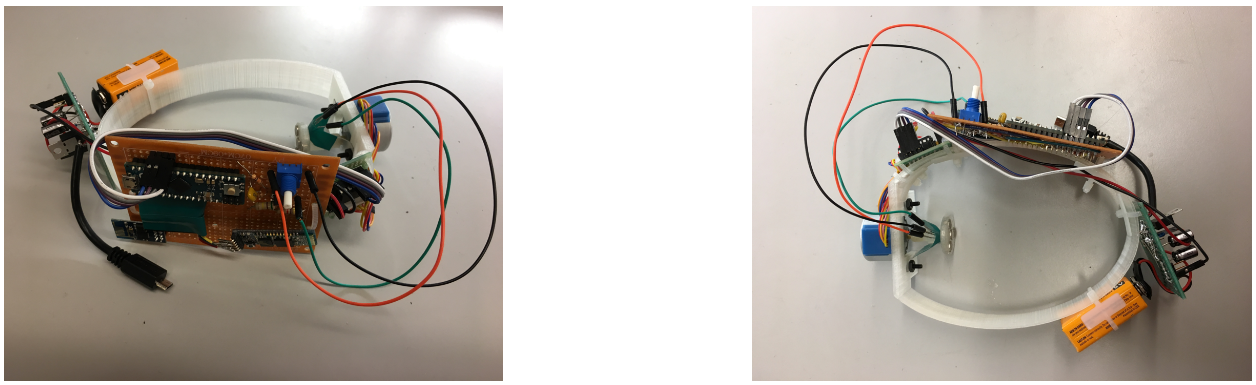

Figure 9: Crude prototype of motorized cranial vault distractor

Figure 10: Second prototype of motorized cranial vault distractor

3.3. Software Effort

Microcontroller has four main tasks to handle: Bluetooth communication, motor control, hall effect sensor control and LEDs lightning control. To simplify and clarify the operation of microcontroller. A finite state machine model is built in Figure 12.

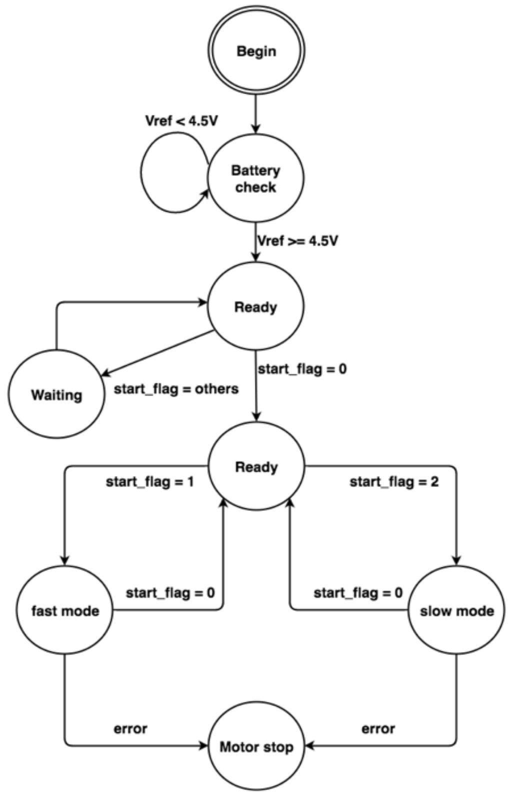

Figure 11: Finite state machine model

The system begins after snapping battery on. At first, it starts with checking battery capacity, LEDs and Bluetooth communication. ADC is used to check the voltage level of the power supply. The system goes to ready condition and wait for instruction if every module is functioning well. The system will ask the user for mode selection first. If the user goes with fast mode, the user is required to set the rotation distance (in millimeter). Under this mode, rotation is at fixed speed. If in the slow mode, the user can set both the rotation distance and rotation period. This allows the user to leave the band at babys head and let the system complete the rotation automatically. After setting the distance and speed, the system will perform rotation operation until it completes. Then it comes back to the ready state and wait for next instruction.

While the rotating, the sensor will keep tracking of the position of magnets on inside disk with interrupt. This is accomplished by recording the motor position when the interrupt occurs. If the current position of the motor is leading the position recorded more than 240 degrees, we assume that inside disk is stuck and the system fails. The system will stop immediately as well as send out an error instruction to the user. This can prevent the malfunction of the system from hurting the baby.

3.4. Mechanical Effort

Considering the application of this project, big torque and slow rotation from motor are very important to distract the skull and reduce the pain of patients at the same time. Most stepper motor on market cannot satisfy the requirement. 28BYJ-48 stepper motor has reduction gears with ratio of 64:1 inside to produce enough torque, slow the rotation, and improve the motor rotation precision [1][2].

Another challenge is how to transfer the torque from outside motor to inside distractor with magnets. Nb-Be-B magnets, the strongest type of permanent magnet commercially available, are adopted to minimize the size of distractor system [4]. On each side, four small magnets are fixed on the rotating disc and the distribution of them is shown in fig 12. The diameter of the each magnet is 6mm. The two center magnets with opposite polarity are attracting each other and it helps to keep the relative position of discs in rotation. Other magnets with same polarity (N in fig 13) are pushing each other. When the outside disc is rotating, the yellow magnets push the white the magnets fixed on the inside disc and inside disc will rotate accordingly. After testing different magnets distribution on disc, fig 12 is the best one for trading off size and torque.

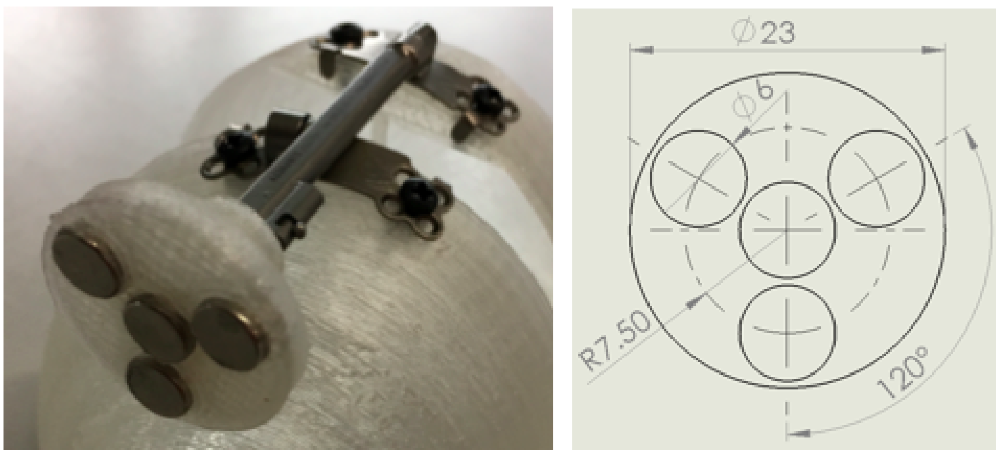

Figure 12: Distractor and rotating disc with Nb-Fe-B magnets physical model

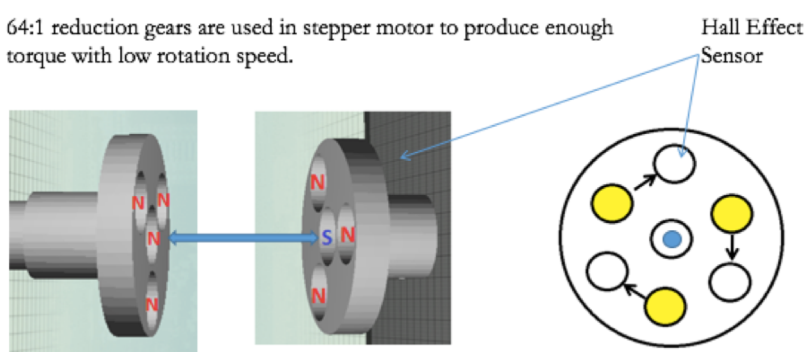

Figure 13: Polarization of magnets and hall effect sensor position

Hall effect sensor is fixed on the backside of the rotating disc outside as fig 9 shows. When the discs are rotating the sensor will see N and S alternately to detect the rotation of discs both inside and outside and provide information for closed loop control.

4. Further Implementation

One of the challenge for this project is the size of inside system. Later research can adopt smaller magnets with higher magnetic density, or maybe refined magnets distribution design. Outside system would be optimized in size as well by using printed circuit board. Smaller components can be used, like micro stepper motor. Also, since the stepper motor is open-loop components, other types of motors with closed-loop functionalities can be utilized in further implementation for complex control.

References

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[2] R. C. Robinson, P. J. ONeal, and G. H. Robinson, "Mandibular distraction force: Laboratory data and clinical correlation," Journal of Oral and Maxillofacial Surgery, vol. 59, no. 5, pp. 539544, May 2001.

[3] S. Daokar, G. Agrawal, S. Junaid, and R. Rajput, "Distraction Osteogenesis," Annals of International medical and Dental Research, vol. 2, no. 6, Oct. 2016.

[4] J. Boisson, H. Strozyk, P. Diner, A. Picard, and N. Kadlub, "Feasibility of magnetic activation of a maxillofacial distraction osteogenesis, design of a new device," Journal of Cranio-Maxillofacial Surgery, vol. 44, no. 6, pp. 684688, Jun. 2016.

Appendix

Baseline demo: https://www.youtube.com/watch?v=HlDqCCFK9PE
Reach goal demo: https://www.youtube.com/watch?v=EzjZjozG55c

Figure 14: Distractor fitting and rotating disc on teeth model I

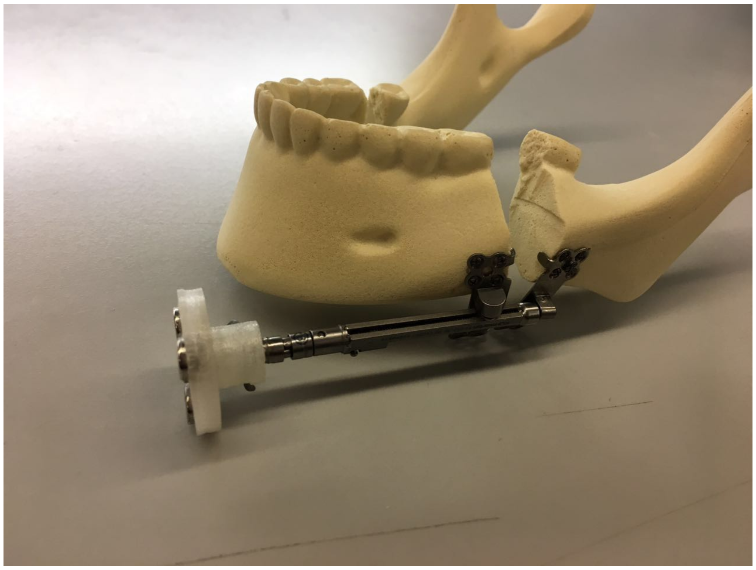

Figure 15: Distractor fitting and rotating disc on teeth model II