CervPro

Cervical Proprioception Motion Analyzer

System Design and Project Plan

HARDING UNIVERSITY

Department of Engineering and Physics

ENGR 4201. Senior Design

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Problem Statement

According to Harding University's Physical Therapy Program, of all patients that physical therapists treat, 1 in 5 experience some sort of cervicogenic condition. Often, the first assessment the patient will undergo for diagnosis is the cervical positioning error (CPE) test. This diagnostic tests the body's sense of proprioception: the ability to sense position in space without other sensory feedback, because this can often be damaged by cervicogenic conditions. The test currently involves the patient sitting *roughly* 90 cm away from a wall with their eyes closed, and a laser pointer fixed to their head pointing at the center of a target. The patient then rotates their head across the full Range of Motion (RoM): *roughly* 80 degrees to the left or right, and then back to where they believe is the center. The differential between the laser pointer's beginning and ending location on the target is the CPE metric that the physical therapist uses to further assess the patient's condition.

The CPE test has significant room for error due to the inability to precisely place the target at a standard distance, potential shifting of the laser pointer, natural movement at a "center" position. This means that while on paper, a CPE value within 4.5° indicates healthy proprioception, the recorded metric for this test is often only ancillary to the therapist's intuition. Currently, decisions to escalate medical treatment to more intensive (and expensive) diagnostics and treatments, up to and including MRIs and surgery, are based exclusively on a therapist's educated judgement. Removing the subjectivity from the procedure has the potential to reduce the currently unknown number of mistaken diagnoses, and save patients health and money.

Customer Needs

After conducting several interviews with multiple physical therapists, needs that were expressed included the following: The device needs to be easy to use. Physical therapists may not be as technologically savvy as the engineers who create the device, so it needs to output only the necessary information. Dr. Galindo expressed, “Typically, PTs will choose tests and measures based on convenience (i.e. if the ‘best’ evaluation tool takes me 30 minutes but a ‘good’ evaluation tool that is valid/reliable takes me only 10min, I will always chose the 10min version.)” They expressed that however the device operates, comfort is very important for the patient. Additionally, the device should not inhibit the patient’s motions. The device should provide objective, clear, and accurate data. Finally, the device needs to comply with all relevant legal and industry standards in order to be usable in a medical setting.

Technical Requirements/Specifications

The time required to run a CPE test with the CervPro device will not exceed 10 minutes. This is double the time required to run the CPE test without the device. The proportion of therapists able to make a diagnosis exclusively using the device and within 40 seconds of completing the CPE test using the device shall be above 50%. Any device hardware will not inhibit the movement of the neck across an 80 degree RoM about all rotational axes. Also, the weight of any device attached to the patient will be less than 10 lbs.

The CervPro device shall measure the angular position of the head across an ideal 80° and acceptable 60° RoM in either direction with error of less than 5%. The device will measure angular velocity of the head up to an ideal 60° per second and an acceptable 50° per second with an error of less than 5%. The position of any hardware of the device (if located on the patient’s head) will not shift more than 5° during 60° per second rotational speed. Any data collected will be saved to file while immediately displaying a therapist-defined output.

The CervPro device will not require Personal Protective Equipment (PPE) for operation.It will not emit sound louder than 60 dB, and any data transmission shall comply with relevant FCC and medical device regulations.

System Description of Alternatives

There were two main design concepts that were up for consideration. The first design that was thoroughly explored was a helmet-like concept. A helmet with sensors like accelerometers, gyros, and distance measuring sensors would be placed on the patient’s head. The patient would then perform head movements specified by the physical therapist, and the device would measure angular position and velocity of the patient’s head. This data would be recorded, sent via bluetooth, and then displayed to the physical therapist in a palatable way.

A second design option was also heavily considered. Because ease of use for the physical therapist was a high priority for design choices, alternatives that didn't require the use of on-patient measurement systems were highly desirable. Current motion capture technology is capable of measuring angular velocity and position with equal, if not better, accuracy. A device concept that uses motion capture technology ultimately won the final decision. The motion capture technology would use both OpenCV and dlib, and could run in both Python and C++ programming languages. It will most likely use only one camera to track the motion of the patient's head, but may also use two depending on the outcomes of further analysis. The motion capture technology was deemed superior to the headgear device concept in every way except for the required computing power for data analysis. Motion capture would most likely require much more computational power because it will be recording and processing more data overall. This was only one disadvantage in a plethora of other advantages that motion capture had to offer.

Functional Decomposition Diagrams

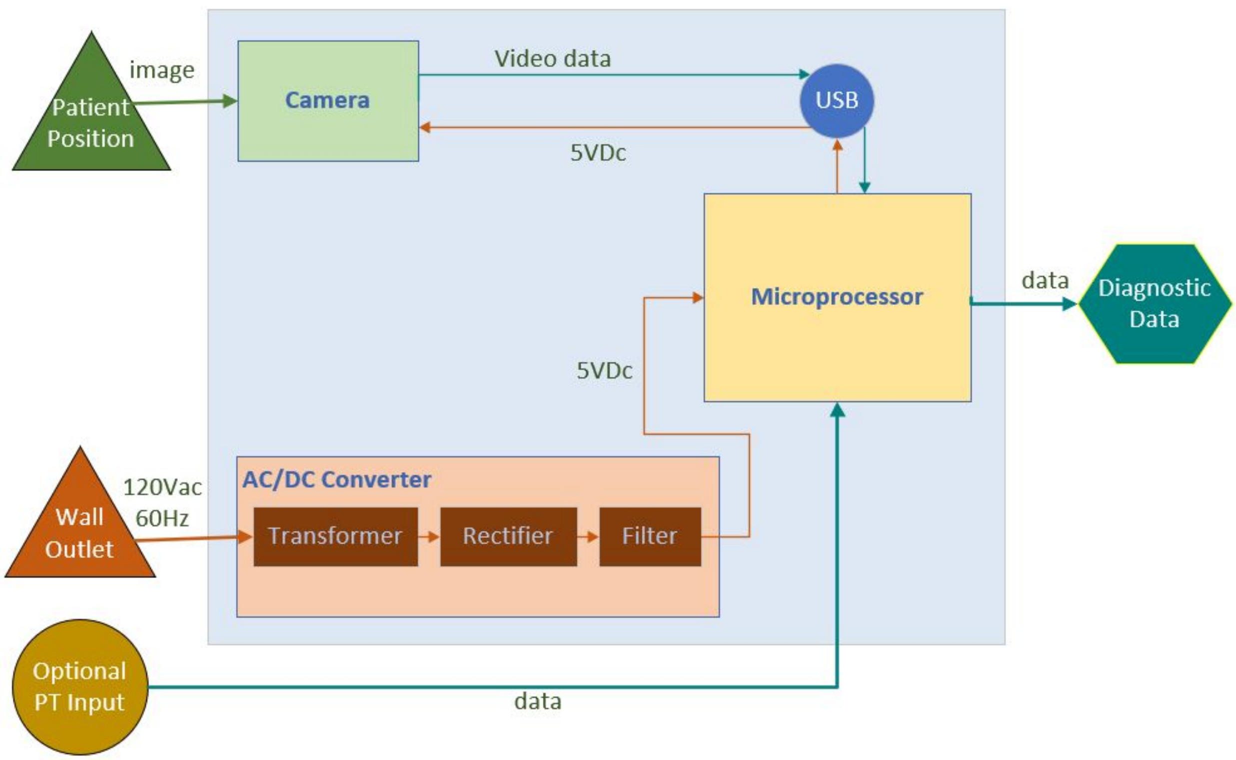

Figure 1. Functional Decomposition Diagram of the CervPro Device

Functional Descriptions

For the Functional Decomposition Diagram shown in Figure 1 above, there will be three main categories of inputs. First, there will be the optional input of the physical therapist. This is currently undecided, but the device may ultimately include some sort of user interface or functionality that allows the physical therapist to give inputs based on desired outputs. Secondly, there will be the patient's rotational head position and velocity. Third, there will be power from a standard US wall outlet. The camera shall be powered by 5Vdc and be able to convert the patient's face at 1±0.25 m into a digital image format. The power module shall convert 120Vac at 60Hz (max 1.8kW) to 5Vdc with less than 5% ripple and noise.

The microprocessor will be capable of running OpenCV or OpenCX allowing for the processing of images. It will also have the processing power to run a machine learning algorithm, such as dlib, allowing for the recognition of a face and finding key points. These are achieved by having a microprocessor that can run an operating system or one that is designed for computer vision uses. There will be a sufficient amount of RAM for the processor to store at least 2 pictures, three sets of facial points, and the running program which is a minimum of 5GB. Ultimately, the microprocessor will calculate the rotational head position and velocity of the patient's head about the x, y, and z axes and will calculate translation of the head in the x, y, and ideally z axes.

Systems Analysis

Microprocessor Selection

When selecting a microprocessor for this project we had to take into account the needs of the software packages that are needed to perform computer vision and machine learning. With this we needed a more processing power, which removed the possibility of using a microcontroller. We currently plan to use OpenCV to facilitate interaction with the camera and dlib as a machine learning system that comes with a trained system for recognizing a human face. Taking these requirements into account, we need a full microprocessor that has some amount of an operating system running on them, narrowing the selection down to Microchip's line of microprocessors and Nvidia's Jetson line. Both lines of microprocessors run a light-weight version of Unix/Linux, allowing for some of the functions in the above libraries to function.

Microprocessor Selection

		ALTERNATIVES			
Decision Model		Nvidia Jetson		Microchip	
Criteria	Weight	Rating	Score	Rating	Score
OS	0.15	9	1.35	9	1.35
Speed	0.3	9	2.7	1	0.3
RAM	0.15	9	1.35	5	0.75
Storage	0.2	5	1	5	1
Interfaces	0.1	5	0.5	9	0.9
Power Draw	0.1	5	0.5	9	0.9

Total:	1	42	7.4	38	5.2

Figure 2: Decision Making Matrix for Microprocessors

Using the above data we decided that it is best to use a Nvidia Jetson microprocessor, with a breakdown of the criteria following. Both systems had an operating system and scored equally. The Jetson is much faster and has more RAM than the Microchip processors, which is shown in more detail below. The Microchip processor would not have enough built in memory while the Jetson has many options, when it comes to memory, with many using a standard microSD card. Both systems have USB drives built into them, but more pin locations are available on the Microchip processors. The Jetson has multiple power levels for each member of the family, but both require more power than the Microchip one, but neither is a problem when it comes to using the power supplied by a wall outlet. Beyond what is shown in figure 2, the Jetson family was designed for computer vision projects and has been used and tested for years.

Camera Selection

Choosing a camera for the device largely considered 5 different criteria: cost, software support for our microcontroller, frame rate, field of view, and video/image quality. In benchmarking current technologies for similar applications, we found that many were built off of existing video game products like the Sony Eye and Microsoft Kinect series. As a result, these often beat most comparable “webcam” products for many needs.

We are currently looking at using the Playstation Eye, which has been used in other computer vision projects, which runs at 640x480 at 60 frames per second. It has an alternate setting for lower quality faster video but we believe this setting to be better. This camera can be connected to through a USB port, which both lines of microprocessors have. Taking this data into account, we get an uncompressed bitrate of about 9 MB per second of footage (from the calculation of bitrate = resolution * bit depth * framerate). This can be extended to see the processor speed needed and the memory needed; when combined with OpenCV a Nvidia GeForce gtx 480 could process 480p images at about 30 frames per second with a clock speed of 700 MHz and an effective rate of 3.7 Gbps **[1]**. The lowest end Nvidia Jetson microprocessor has a memory speed of 25.6 GBps and a clock speed of 1.43 GHz with 4 GB of RAM; the lowest end Microchip microprocessor has a clock speed of 12 MHz (the other ones run at 400 MHz) with 512 MB of RAM.

	Cost	Type	Software?	Frame rate	FoV	Img Quality	alt mode
Playstation Eye	20.99	Video	Supported	120	75	320x240	60fps @ 640x480
Logitech C922x	104.99	Video	Windows	60	78	720p	
Azure Kinect DK	399	Video/Range	Supported	30	75	640x576	
Xbox Kinect	75	Video/Range	Supported	30	57	640x480	
Kinect V2	298.97	Video/Range	Supported	30	70	512x424	

Figure 3(a): Raw data from benchmarking cameras

	Cost: 20%		Type: 5%		Software: 20%		Frame rate: 20%		FoV: 10%		Img Quality: 25%		Totals
	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted	Raw	Weighted	
Playstation Eye	9.5	1.9	8	0.4	10	2	9	1.8	9.8	1.0	7.2	1.8	8.9
Logitech C922x	7.5	1.5	8	0.4	5	1	9	1.8	10.0	1.0	10.0	2.5	8.2
Azure Kinect DK	1.0	0.2	10	0.5	10	2	7	1.4	9.8	1.0	7.6	1.9	7.0
Xbox Kinect	8.1	1.6	10	0.5	8	1.6	7	1.4	8.5	0.9	7.2	1.8	7.8
Kinect V2	2.5	0.5	10	0.5	9	1.8	7	1.4	9.5	0.9	6.5	1.6	6.8

Figure 3(b): Decision Making Matrix for cameras

Z-axis Problem: One Camera vs. Two Cameras

Once the motion capture technology was selected, it became apparent that the number of cameras to be used needed to be decided on quickly. Depending on the number of cameras and their relative set-up, data collection could vary. The team knew that motion of the head would need to be analysed in all six degrees of freedom ideally, and in all degrees of freedom *but* the Z-axis translation acceptably.

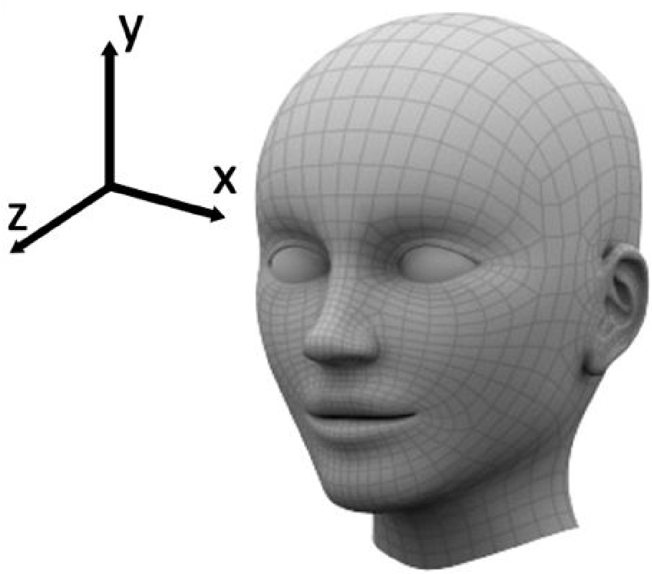

Figure 4: Description of Coordinate Axes

It became apparent that there would be a potential problem with only using one camera. The team felt confident that only using one front-facing camera would be able to accurately capture rotational motion of the head about the X, Y, and Z axes. Translational motion of the head about the X and Y axes would also be no problem for a one camera system, but translational motion on the Z axis seemed to be the challenge for the one camera system.

Assume that motion capture is only analyzing four points on the front of the patient's face. It's important to note, Δx is not the *real* distance between points 1 and 2, it's the distance between the two points that the camera *sees*. For example, if the patient starts to rotate their head about the Y axis in either direction, Δx will decrease from the camera's perspective, even though the literal distance between the points will remain the same.

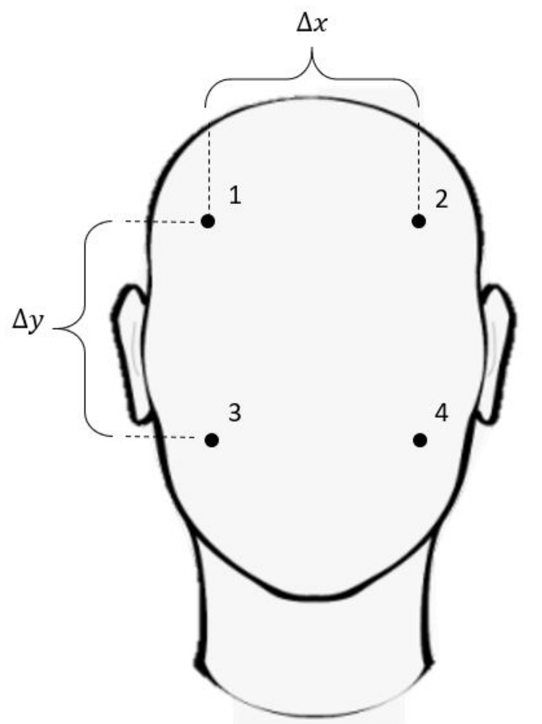

Figure 5(a): Defined theoretical points on a patient's head for analysis

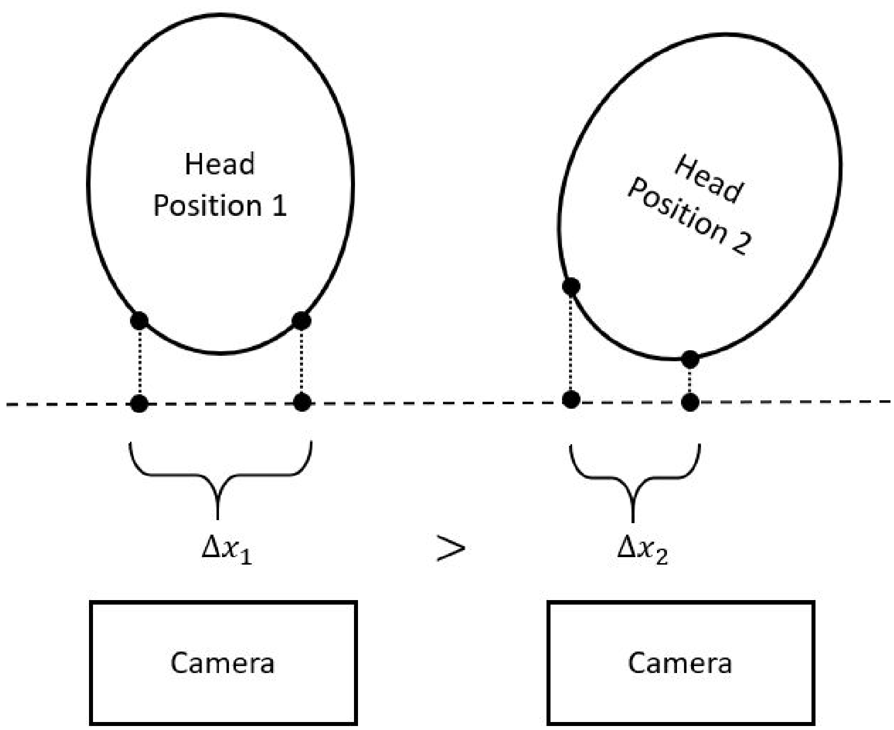

Figure 5(b): Aerial view of difference in Δx_1 vs. Δx_2 when rotating about Y axis

The same situation is present for analyzing the change in Δy when the head rotates about the X Axis. Motion in each degree of freedom would be analyzed in this way--proving that only using one camera will be sufficient for each case. The figure below shows how the four points will move in relation to each other for each case of motion in a degree of freedom. The points are being shown as the camera will see them in each case.

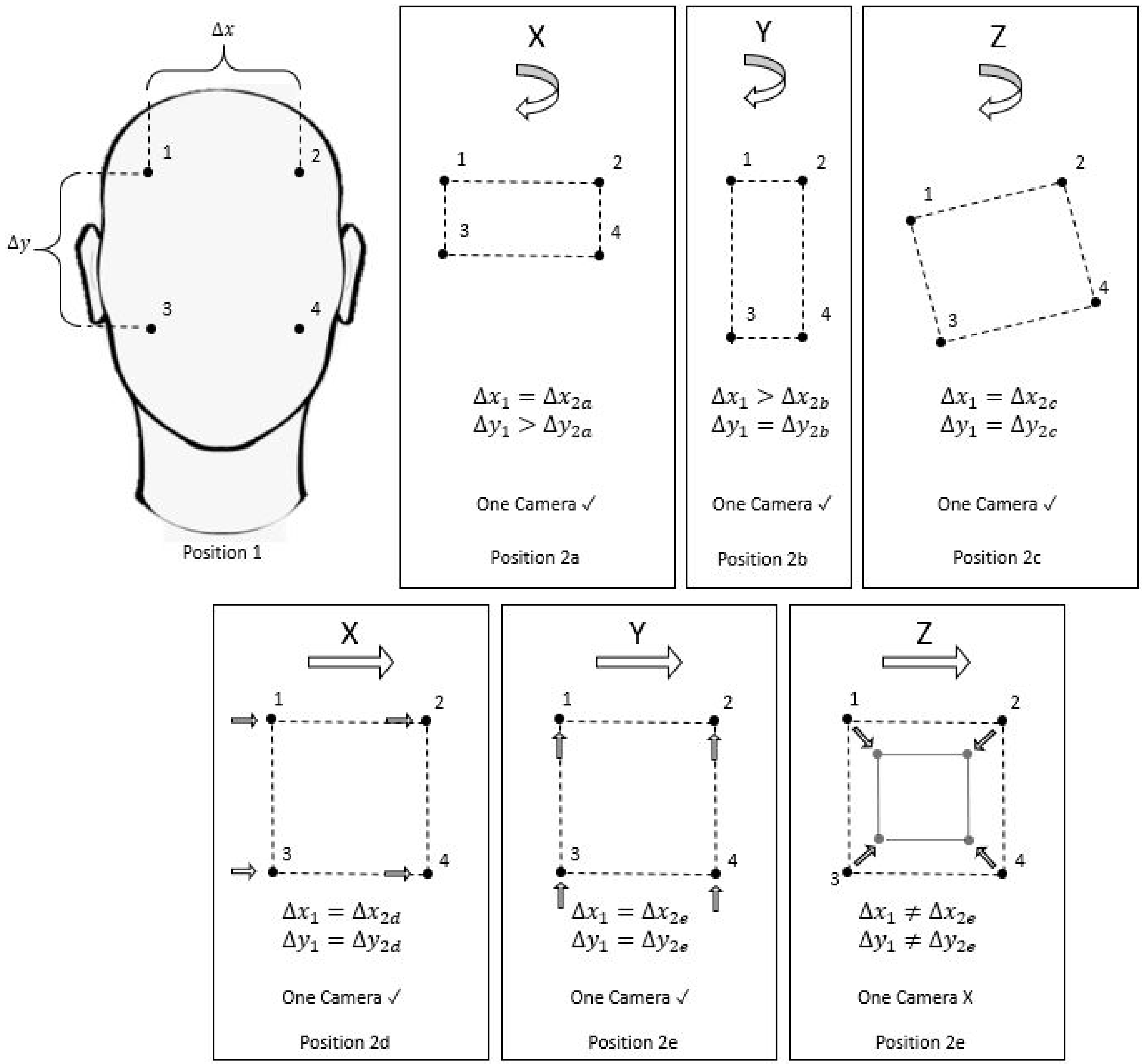

Figure 6: Analysis of camera view of all six D.O.F.

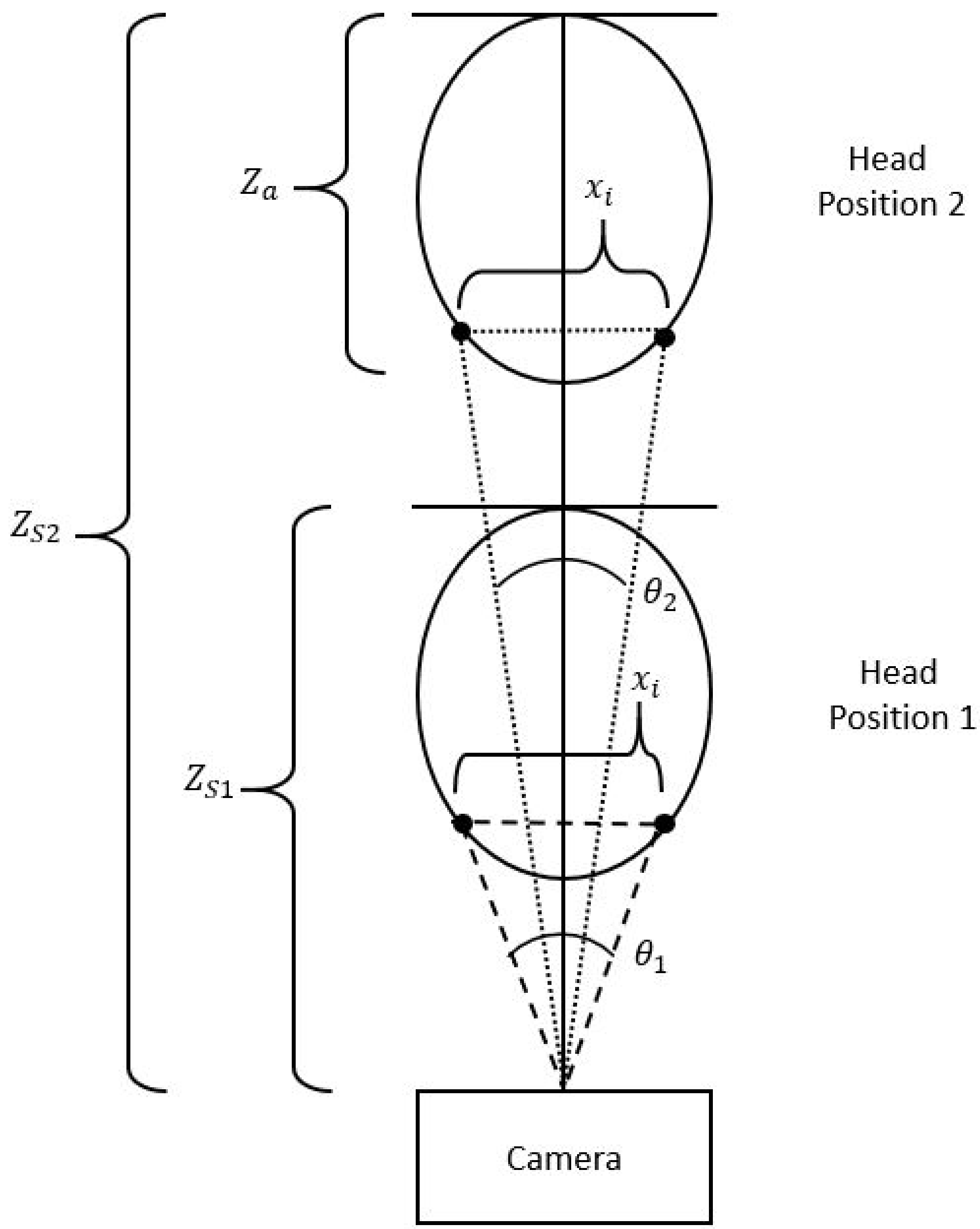

Figure 7: Head moving along Z axis with variables labeled

According to Harding University's Physical Therapy program, patients sit "roughly 90 cm" away from the wall while performing a CPE test. This is assumed to have been measured from the wall to the patient's face. For the motion capture set up, the camera will be assumed to be the same location as the wall. Z_a is the length of the patient's head, Z_{S1} is the starting distance between the back of the patient's head and the camera. Z_{S2} is the ending distance between the back of the patient's head and the camera. X_i is the width between the two points, and θ_1 and θ_2 are the angles made by the camera and the points at positions 1 and 2 respectively.

$$x_1 = 0.9(tan(\theta_1))$$

$$x_1 = (Z_{S2} - Z_a)(tan(\theta_2))$$

$$0.9(tan(\theta_1)) = (Z_{S2} - Z_a)(tan(\theta_2))$$

$$Z_{S2} = \frac{0.9(tan(\theta_1)}{(tan(\theta_2)} + Z_a$$

Figure 9. Derivation of equation to find Z distance at position 2

Therefore, the one camera set-up can capture translational motion along the Z axis. With this case satisfied, a one camera set-up can capture motion in all six degrees of freedom. This is why the team chose to go with one camera instead of two or more.

Organization and Plan to Proceed

		Core Team			
	Role\Person	Nathan	Ethan	George	Keneth
Mechanical	Device Housing	I	R	I	S
Computer	Microprocessor	C	I	R	I
	Programming	C	I	R	I
Electrical	Sensors	R	I	C	I
	Power	R	I	C	I
Reports	A3	A	R	S	S
	Proposal	A	R	S	S
Misc	Budget	R	C	I	I
Gov Cup	Prep	A	S		
Legal	IP	A	C		
	Compliance	A	C		

Figure 8: R.A.S.I.C.

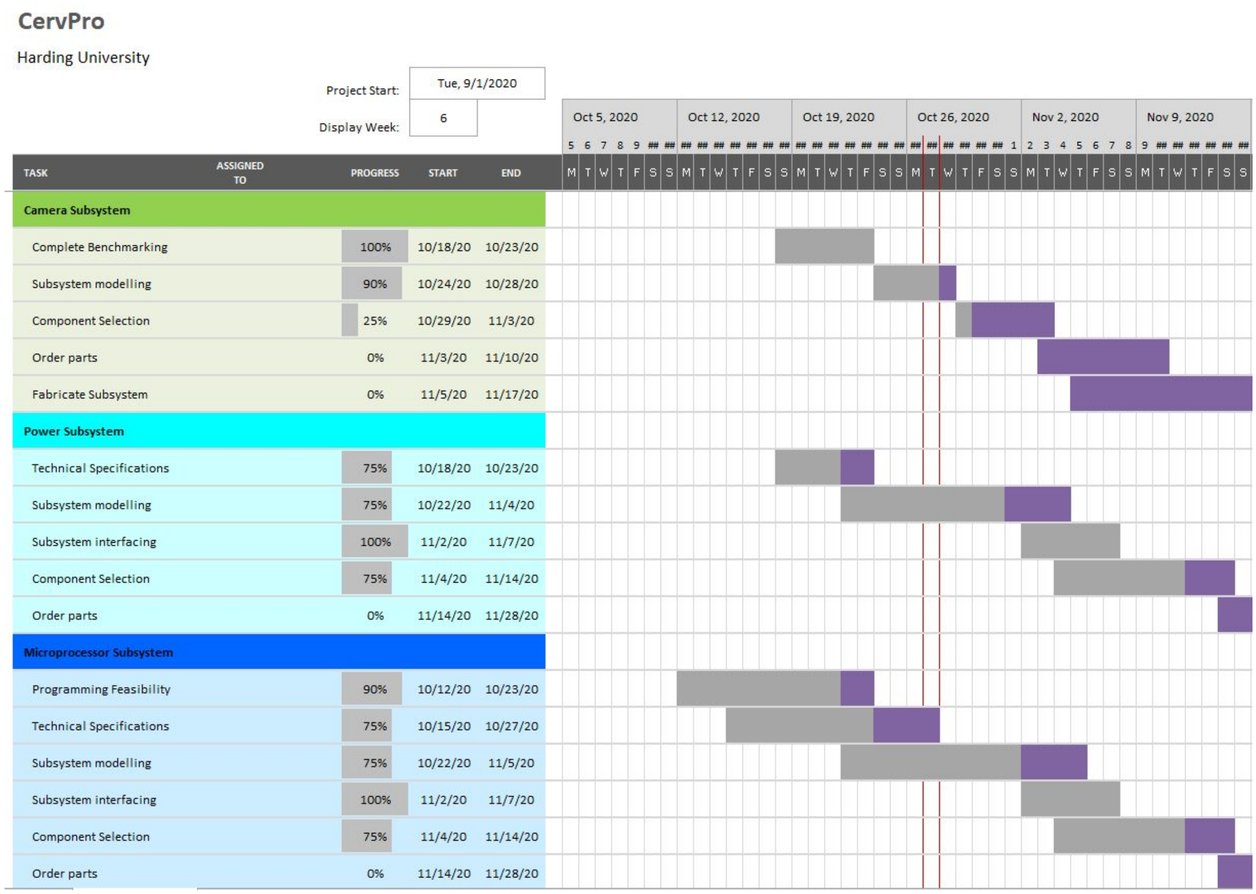

Figure 9: Gantt chart showing current development progress of CervPro device

As can be seen from Figure 3, the team is currently on schedule for the development and design of the subsystems. While still in early stages, the team hopes to have all of the benchmarking, specifications generation, and program feasibility checking completed by October 23rd, 2020. Additionally, the team plans to have all of the subsystem designs completed and parts ordered by the beginning of December 2020.

	Qty	Price per each	Total Real Cost	Total Actual Cost
Power Subsystem				
Transformer	1	$10.00	$10.00	$13.00
1N4004	4	$0.00	$0.00	$0.12
2N3904	1	$0.50	$0.50	$0.50
TP31	1	$1.00	$1.00	$1.00
Resistor	3	$0.00	$0.00	$0.05
Capacitor	2	$0.00	$0.00	$0.05
Potentiometer	1	$1.50	$1.50	$1.50
subtotal:			$13.00	$16.22

Camera Subsystem				
Camera	1	$20.99	$20.99	$20.99
subtotal:			$20.99	$20.99
Microprocessor Subsystem				
Microprocessor (main)	1	$100.00	$0.00	$100.00
Microprocessor (Bluetooth)	1	$60.00	$0.00	$60.00
64 GB microSD card	1	$15.00	$0.00	$15.00
subtotal:			$0.00	$175.00
Total				$212.21

Figure 10: Anticipated Budget

References

[1] J. Fund, “Computer Vision on the GPU with OpenCV - Nvidia,” *Computer Vision on the GPU with OpenCV*. [Online]. Available: http://developer.download.nvidia.com/GTC/PDF/1085_Fung.pdf. [Accessed: 27-Oct-2020].

[2] J. C. Martinez, “Detecting Face Features with Python,” *Medium*, 04-Jul-2020. [Online]. Available: https://towardsdatascience.com/detecting-face-features-with-python-30385aee4a8e. [Accessed: 27-Oct-2020].

Appendices

Appendix A: Testing Plan

Technical Specification	Weight	100	80	60	30	0
Mean time for new therapists to run Cervical Position Error (CPE) test shall not exceed 10 minutes (double standard CPE time)	0.05					
Proportion of therapists able to make diagnosis exclusively using the device and within 40s of completing device cycle shall exceed 50%	0.05					
Hardware shall not significantly impede movements across an 80 degree Range of Motion (RoM) of the neck about all rotational axes.	0.05					
Weight of any device attached to the patient will be less than 10 lbs.	0.05					
Device shall measure angular head position across an ideal 80° and acceptable 60° RoM in either direction with error of less than 5%.	0.25					

Devices shall measure angular velocity up to an ideal 60° per second and an acceptable 50° per second with an error of less than 5%.	0.25					
Hardware (if present) position shall shift less than 5° on the patient's head during 60° per second rotational speed.	0.05					
Data shall be saved to file while immediately displaying therapist-defined output	0.1					
Device shall not require Personal Protective Equipment (PPE) for operation	0.05					
Shall not emit sound louder than 60 dB	0.05					
Any data transmission shall comply with relevant FCC and medical device regulations	0.05					
Total	1.00					

Figure 11: Prototype Demonstration Rubric

Appendix B: Power Supply Diagrams

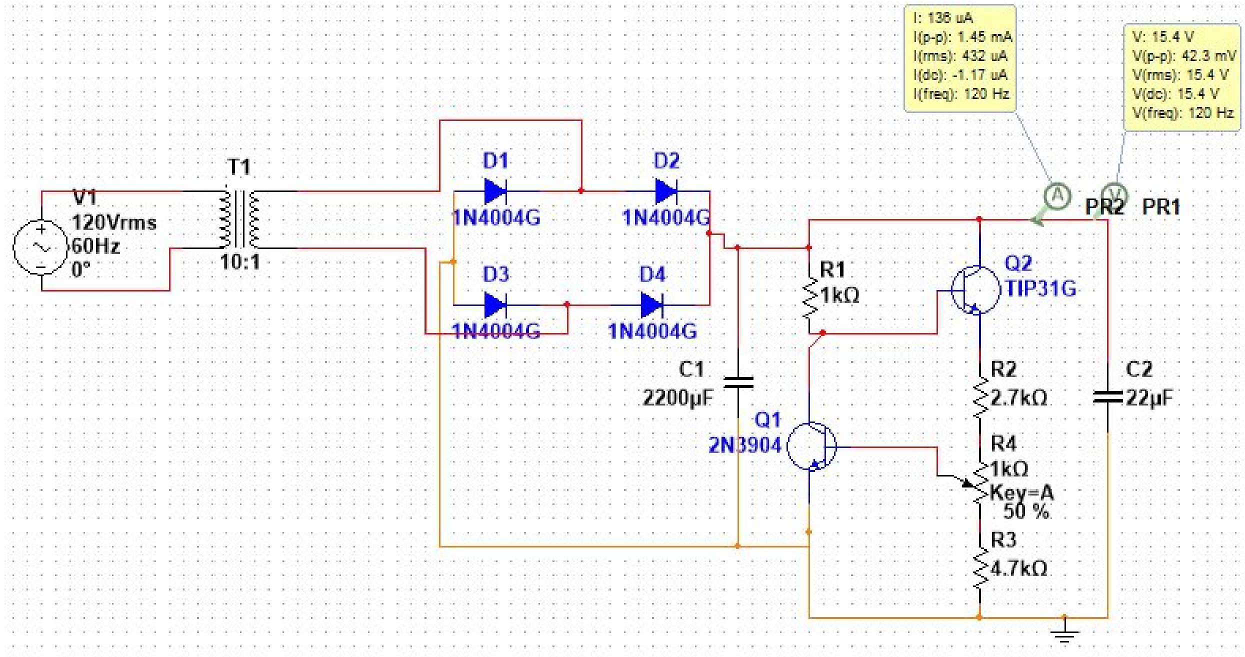

Figure 12(a): Multisim Simulation of Power Supply

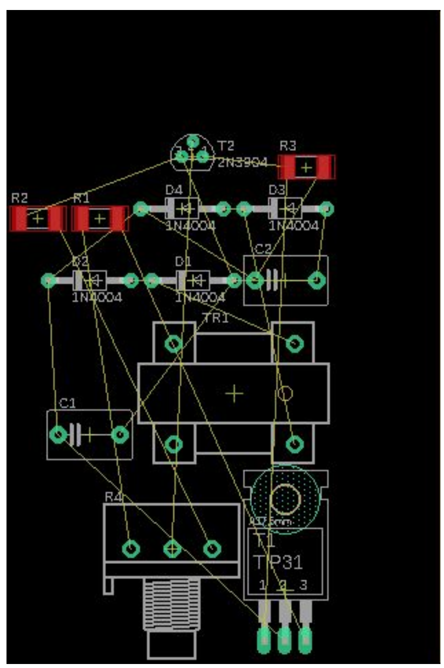

Figure 12(b): Eagle CAD PCB Footprint of Power Supply

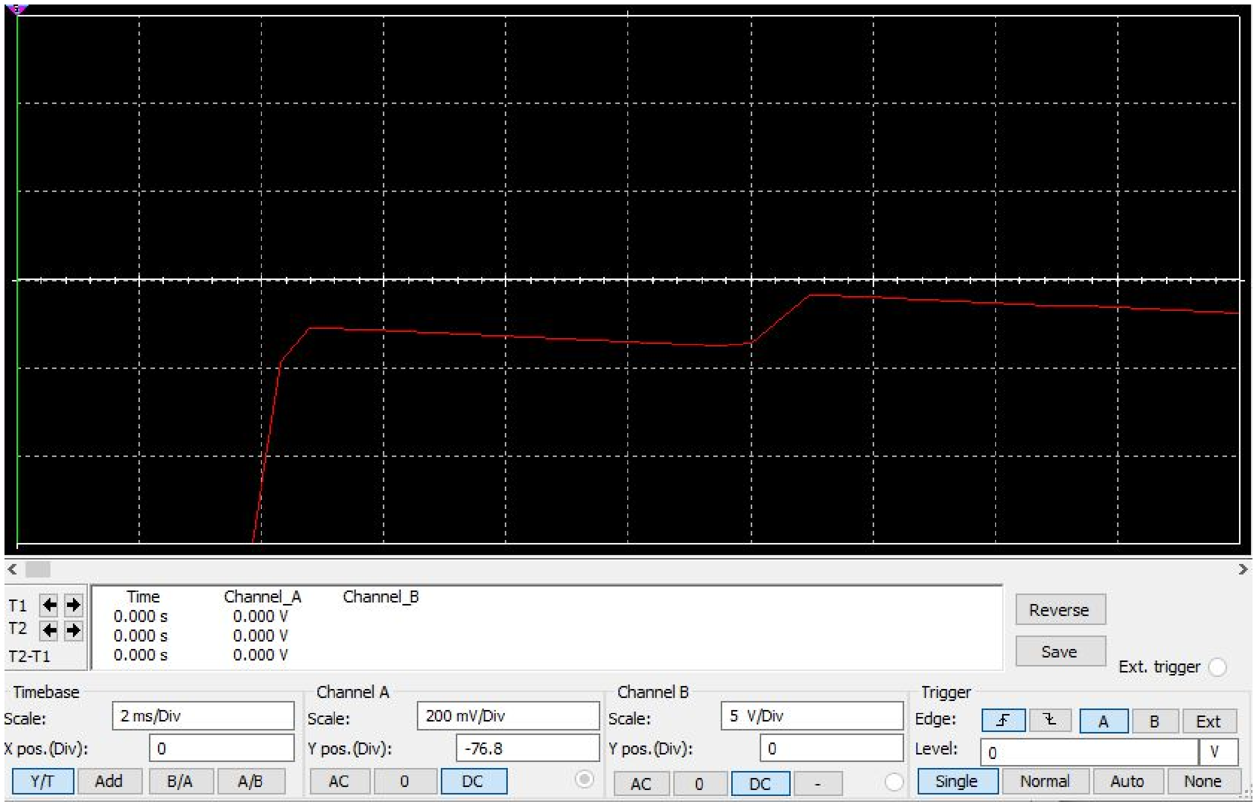

Figure 12(c): Output ripple from power supply

Appendix C: Example Program with OpenCV and dlib [2]

```
import cv2
import dlib

# Load the detector
detector = dlib.get_frontal_face_detector()

# Load the predictor
predictor =
dlib.shape_predictor("shape_predictor_68_face_landmarks.dat")

# read the image
cap = cv2.VideoCapture(0)

while True:
   _, frame = cap.read()
   # Convert image into grayscale
   gray = cv2.cvtColor(src=frame, code=cv2.COLOR_BGR2GRAY)

   # Use detector to find landmarks
   faces = detector(gray)

   for face in faces:
       x1 = face.left()  # left point
       y1 = face.top()  # top point
       x2 = face.right()  # right point
       y2 = face.bottom()  # bottom point

       # Create landmark object
       landmarks = predictor(image=gray, box=face)

       # Loop through all the points
       for n in range(0, 68):
           x = landmarks.part(n).x
           y = landmarks.part(n).y

           # Draw a circle
           cv2.circle(img=frame, center=(x, y), radius=3,
color=(0, 255, 0), thickness=-1)

   # show the image
   cv2.imshow(winname="Face", mat=frame)
```

```
    # Exit when escape is pressed
    if cv2.waitKey(delay=1) == 27:
        break

# When everything done, release the video capture and video
write objects
cap.release()

# Close all windows
cv2.destroyAllWindows()
```

Appendix D: Report R.A.S.I.C.

	Core Team			
Role\Person	Nathan	Ethan	George	Keneth
Problem Statement	I	R	I	I
Customer Needs	C	R	I	I
Technical Specs	I	R	I	I
System Desc. of Alts.	I	R	I	I
FDD	R	A	C	I
Functional Descriptions	C	R	C	I
Systems Analysis	C	R	C	I
Organization	R	R	I	I
References	I	S	R	I
Appendices	S	R	S	I