MSE 4499 — Mechatronic Design Project

A Haptic Guidance System to Assist Persons with Blindness to Reach Points of Interest

By:

Ben Boyd

Aidan Bruneel

Alexander Noens

Julia Rybiak

Marina Silic

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Faculty Advisor: Dr. R. Eagleson

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Executive Summary

During project selection, we identified groups with extra difficulties or greater needs than most. This led us to investigate the day to day struggles of a person with blindness (PWB). After conducting research and interviewing Dan Maggiacomo, an expert in the field, we decided to pursue the design of an assistive device that would help a PWB to identify and locate points of interest (POIs) in their immediate vicinity; thus, the problem was defined as follows:

> *"Persons with blindness can struggle to independently locate specific points of interest in their vicinity without relying on touching their surroundings."*

To address this problem, we selected the concept of a device comprised of a vision system on the user's smartphone to detect and estimate the position of a fiducial marker and a wearable haptic system to provide directional feedback to the PWB.

Many aspects of the design were validated: the ability of the vision system to detect and determine the position of a marker, the effectiveness of using different types of actuators for haptic feedback, and the human body's ability to differentiate between different actuators. This validation informed the selection of haptic components and led to the development of a functional prototype.

The prototype was tested by three subjects to confirm the functionality of the design. The result was a 90% success rate in identifying, locating, and touching designated POIs while blindfolded. As a result, the maximum frequency of the guidance method was lowered, and a separate signal to indicate arrival was added. Furthermore, the two systems were altered to reduce the necessary amount of serial communication and load on the haptic controller.

Previous feedback has also been addressed. The method in which haptic information is being conveyed is now very clear, and the scope has been narrowed such that the use case is clear: the device assists the user only with their immediate vicinity, and not necessarily their ability to locate one POI relative to another. The problem definition was also rephrased and elaborated upon.

In summary, the prototype fully demonstrated the ability of the selected concept to fulfill the problem definition. The results of current findings were as follows: There is a learning curve to the device, and a tendency for a marker to leave camera's FOV. Further iteration would focus on testing cameras with larger FOVs, marker to marker pose estimation, and further refinement of the haptic feedback algorithm.

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Acknowledgments

Many thanks to Dan Maggiacomo, Principal of W. Ross Macdonald School for the Blind, who provided critical insights that informed and reinforced our design decisions, and to Dr. Eagleson for providing wisdom, guidance, and support along the way.

Nomenclature

2D. Two-dimensional.

3D. Three-dimensional.

ArUco. An OpenCV module that allows the generation and detection of square fiducial markers with variable grid size which encode unique identification numbers.

ArUco Marker. A single square fiducial marker which is part of an ArUco dictionary.

Blindness. The most severe category of visual impairments in which visual acuity is worse than 3/60 [1].

BOM. Bill of Materials.

Camera Axes. The x, y, and z axes of the camera which represent the camera's coordinate system; denoted by x_c, y_c, and z_c.

Camera Calibration. The process by which a camera's intrinsic parameters are calculated.

Camera Optical Axis. The z axis of the camera, aligned with the center of the image plane; denoted by z_c.

Camera Pose Estimation. The process by which a camera's intrinsic parameters are used in combination with 2-D corner points of an ArUco marker to estimate the 3-D position and orientation of the marker axes with respect to the camera axes.

ChArUco Board. A chessboard-style grid with ArUco markers placed inside each white tile; commonly used in Camera Calibration.

ChArUco Diamond. A 3×3-tile ChArUco board which can be detected as a marker with four identification numbers.

CSA. Canadian Standards Association.

DOF. Degree(s) of Freedom.

ERM. Eccentric Rotating Mass; a type of vibrational actuator.

FCC. Federal Communications Commision.

FEA. Finite Element Analysis.

Fiducial Marker. An object placed in the field of view of an imaging system which appears in the image produced, for use as a point of reference or a measure.

FOV. Field of View; the cone-shaped volume which is visible to a camera.

Frame. A custom C++ class which contains an input captured image, its grayscale, information about its detected ArUco markers, and the ArUco detection and pose estimation functions themselves.

GPS. Global Positioning System.

HTM. Homogeneous Transformation Matrix.

IDE. Integrated Development Environment.

IPS. Indoor Positioning System.

LiPo. Lithium Polymer; a type of battery.

LRA. Linear Resonant Actuator; a type of vibrational actuator.

Marker Axes. The x, y, and z axes of a marker which represent that marker's coordinate system; denoted by x_m, y_m, and z_m.

NiMH. Nickel-Metal Hybrid; a type of battery.

O&M. Orientation and Mobility; a profession which focuses on instructing persons with blindness or severe visual impairment with safe and effective travel through their environment.

OpenCV. An open-source computer vision library for C++, Python, and Java.

POI. Point of Interest; a specific point in space which is considered relevant to the user.

PWB. Person with Blindness.

RFID. Radio-frequency identification; uses electromagnetic fields to automatically identify and track tags attached to objects.

UI. User Interface.

USB. Universal Serial Bus.

WHO. World Health Organization.

Introduction

According to the WHO, “everyone … will experience at least one eye condition in their lifetime” [1]. Eye conditions are not visual impairments, but many eye conditions can lead to visual impairment [1]. The number of cases of visual impairment is expected to double by 2050 due to population ageing, recent infertility rates, and age being a principal risk factor for visual impairment [1] [2] [3]. Blindness is a distinct classification of visual impairments with extremely low visual acuity [1]. Blind persons make up a very large market - according to a 2012 report by the WHO, out of a population of 285 million people with a visual impairment, 39 million (13.7%) were classified as blind [4].

PWBs tend to struggle with mobility and manipulative tasks [5]; those who are blind depend on sighted guides, guide animals, or assistive technology to navigate through unfamiliar environments [6]. To aid in independent navigation, the field of O&M training has been developed to instruct PWBs in developing their mobility and orientation skills [7]. With regards to orientation skills, a report outlining the challenges of indoor navigation for PWBs states:

> *“Traveling inside buildings creates other difficulties since visually impaired people cannot sense and use landmarks to help move around spaces: especially walking through unfamiliar, crowded, and wide-open spaces due to limitation of their sensing environment cues (light, smell, and noise), and randomly-placed obstacles. As a result, visually impaired people may take a long time to familiarize themselves with spaces and to construct a mental map.”* [6]

Considering that existing solutions typically focus on either general indoor navigation between rooms or areas or obstacle avoidance, a technological gap is presented: guiding a PWB to a POI in their immediate vicinity without environmental contact or auditory guidance. The need to fill this gap was illustrated in an example from Dan Maggiacomo, Principal of W. Ross Macdonald School for Visually Impaired and Deafblind in Brampton, ON:

> *“Imagine a student with blindness leaving class to go to the washroom. They might be able to navigate to a washroom but might struggle to locate and use a toilet or urinal, especially since they don't want to feel around to find it. Or imagine a student trying to find their locker in a hallway. How would they know which one is theirs?”* [8]

Assisting a PWBs to locate a POI in their vicinity would result in improved spatial awareness and increased confidence. Furthermore, it would enable previously impossible tasks like finding your locker without braille. Thus, the problem for this project is defined as follows:

Persons with blindness lack a technological solution to independently locate specific points of interest in their vicinity without relying on environmental contact or auditory guidance.

Background Information

There are several technologies to assist PWBs to navigate their surroundings, determine their location, and locate points of interest. Each technology senses the environment and conveys that information to the user through various methods. Several examples of these systems include the white cane, tactile maps, *BlindSquare*, and *WeWALK*.

White canes are used by PWBs to avoid obstacles and hazards. The user will swing the cane from side to side along the ground in front of them as they walk. If the cane contacts an obstacle or change in level, the user knows to alter their trajectory [9]. The traditional white cane cannot directly guide the user to any specific POI in their vicinity and can only identify obstacles at close range.

BlindSquare is a smartphone application that can be used by PWBs to find their current location and navigate to new ones using GPS and auditory feedback. The app also allows for the PWB to filter what information they receive and set favorite locations [10]. GPS works well outdoors but has limited capability indoors [11]. *BlindSquare* also cannot be used to find specific POIs in the user's environment without use of an IPS [10]. Auditory feedback can be difficult to make out over ambient noise, and could interfere with the user's ability to hear stimuli in their environment [12].

The *WeWALK* system combines a traditional white cane with ultrasonic sensors, vibrational actuators, and a phone app to help the PWB navigate. The ultrasonics sensors use the vibrational actuators to notify the user of objects that may be in their path while they are walking, and the phone app can be used to navigate to different locations [13]. This system can provide the user with more feedback regarding their immediate surrounds, but like the *BlindSquare* app, it cannot accurately direct the user to a given location without a reliable GPS connection when indoors.

From this research, a clear technological gap is presented - there is no solution that can guide a PWB to an indoor POI without relying on auditory feedback or environmental contact. The proposed design aims to remedy this gap.

Several engineering tools were used throughout the project to evaluate the effectiveness of the solution. SolidWorks Simulation was used to conduct an FEA study on the mechanical components of the system. The IDEs used to develop the software of the system, primarily Microsoft Visual Studio, were used to evaluate the hardware and software requirements. The physical experiments to measure the accuracy of the system were verified using a measuring tape and gyroscope.

Scope, Objectives, and Constraints

Scope

Since sufficient solutions exist to guide a PWB outdoors, this project will focus on an indoor environment, specifically, the application of a student attending a school for the blind. It is believed such a school would seek to heighten the spatial awareness, confidence, and independence of its students by implementing our solution.

As per the problem definition, the project aims to develop a solution that provides guidance to a POI in a PWB's immediate vicinity, without the use auditory cues or environmental contact. This is a feasible goal as there are adequate resources to accomplish this between Dr. Eagleson's medical expertise, the team's individual strengths and the support of the faculty.

Design Objectives

Table 1. Design Objectives

Property	Criteria	Rationale
Ease of use	Maximize	Users require minimal training; intuitive design
Comfort	Maximize	Reduce negative impact on quality of life
Quality of Feedback	Maximize	Increase device effectiveness
Cost	Minimize	Product can reach a larger market
Aesthetics	Maximize	Users should not worry about how the device looks while being worn

Design Constraints

Table 2. Design Constraints

Property	Criteria	Rationale
Directional Feedback	Must provide directional feedback at range	Minimum information needed for contactless/silent guidance
Sight Independence	Use of sight must not be required	Must be usable by a PWB
Prototype cost	< $650	To meet project budget
Total System Latency	< 200 ms	To feel responsive
Wireless Operation	Required	To be feasible in a school setting
Battery Life	4 h (continuous use)	To last a full school day
Effective Range	5 m	Required to meet the project goal. Our definition of "immediate vicinity"
Successful Destination Range	0.75 m	Arm's length distance, so user can reach out to POI [14]
Battery Charge Time	8 h	Device can charge overnight while not in use
Safety	CSA and FCC regulations met	For legal sale and safe use of the product

Concept Generation and Selection

Concept Generation

Sensing Concepts

Different sensing methods were evaluated as concepts to provide guidance data; specifically, the use of computer vision, Bluetooth beacons, and RFID tags [15].

Computer vision concepts involved detecting fiducial markers in a camera's FOV. Fiducial markers considered included Vumarks, QR codes, and ArUco markers, which would require the use of the proprietary Vuforia platform or custom software utilizing the open-source computer vision library OpenCV along with a QR-decoding library such as ZBar or the ArUco module, respectively [16]. From the four corner points of a detected marker, the camera's relative orientation can be estimated by solving the perspective n-point problem.

The Bluetooth beacon and RFID tag concepts work by analyzing the signal strengths and Angle of Attack, and/or Angle of Departure of the signals to generate a position and orientation estimation [17] [18]. Using only the signal strength is cheap and simple, though it would not be able to provide angular positional data, and the signal strength can be influenced by environmental factors [19]. Systems using Angle of Attack and/or Angle of Departure with signal strength are more complex and expensive. Multiple beacons are needed to provide accurate readings.

Actuation Concepts

The concepts generated for actuation were a kinesthetic device, pressure actuators, and vibrational actuators.

A kinesthetic device would operate by controlling a small robot on the floor that is tethered to the user and rolls ahead of them to guide them in the proper direction [20].

A pressure actuator device would create pressure on the user's skin as feedback. The most precise method of pressure actuation is achieved by filling arrays of small bladders on a glove or sleeve [21].

Lastly, vibrational actuation could be achieved through motors placed along the skin that would vibrate at different intervals or intensities to indicate directional information [22].

Concept Selection

Sensing Concepts

Table 3. Decision Matrix for Sensing Concepts

Objectives	Ease of Use	Comfort	Feedback Quality	Cost	Aesthetics	Total	%	OpenCV, ArUco	OpenCV, Zbar	Vuforia	RFID	Bluetooth
Ease of use	1	5	3	3	7	19.00	36%	1	1	1	0	0
Comfort	1/5	1	1/3	1/5	1/3	2.07	4%	0	0	0	0	0
Quality of Feedback	1/3	3	1	5	7	16.33	31%	1	0	1	0	1
Cost	1/3	5	1/5	1	5	11.53	22%	1	1	0	-1	-1
Aesthetics	1/7	3	1/7	1/5	1	4.49	8%	0	0	0	1	1
						53.42	100%	**0.88**	0.57	0.66	-0.13	0.17

Bluetooth and RFID concepts were eliminated because they are costly and complex, requiring an interconnected system of powered beacons to accurately position the user and determine their orientation.

The computer vision concepts involve an inexpensive infrastructure for indoor positioning because POIs can be easily represented by a printed fiducial marker with a unique identity, allowing for easy installation and maintenance.

Decoding of QR codes presents concerns with scanning range, since the generally the scanning range is equal to 10× the side length of the QR code.

While Vuforia provides sufficient scanning distance and has impressive 3D capabilities, it relies on detecting markers as image targets and does not universally encode information into a physical marker, which would complicate the marker infrastructure. Vuforia is also designed for augmented reality applications and requires licensing for commercial use, so less control is given to the developer for real-world 3D applications.

ArUco as a marker generation and detection method provides encoding of unique integer identities into an easily detectable marker that can be scanned at 50× its side length. The ArUco module also comes with built-in functionality for pose estimation and is the only option available that integrates directly with OpenCV, which is open-source and free to use commercially.

A vision system using OpenCV and the ArUco module was selected as the sensing concept. Available programming languages for the vision system include C++, Python, and Java, but C++ was selected due to high execution speed, OpenCV and ArUco source code being written in C++, and the ability to use C++ on a wide range of devices, including smartphones.

Actuation Concepts

Table 4. Go/No-Go for Actuation Concepts

Concepts	Directional Feedback	Sight Independence	Latency less than 200ms	Battery	Wireless	Safety	Prototype Cost	GO/NO-GO
Kinesthetic	GO	GO	GO	GO	NO-GO	GO	GO	NO-GO
Pressure	GO	GO	GO	NO-GO	GO	GO	NO-GO	NO-GO
Vibration	GO	GO	GO	GO	GO	GO	GO	GO

A kinesthetic device would require the user to be tethered to another device on the floor, require substantially more power, be more expensive, and not actuate quickly enough to provide information to the user [23].

Pressure actuators were removed from consideration because they were the least cost effective, requiring the purchase and integration of pneumatics and is unsuitable for a casual wearable device.

For these reasons, the concept of vibrational actuators was selected for the prototype (Table 4).

Specific vibrational actuators needed to be selected for the prototype. Several types of vibrational actuators were identified: eccentric rotating mass vibration actuators (ERM), linear resonant actuators (LRA), and piezoelectric vibrational actuators [22].

ERMs produce vibrations by spinning an unbalanced mass using magnets. They are an older technology and are cost effective and widely available. The inertia of the mass is known to cause slow startup and shutdown times between 50 and 100 ms, which still meets the constraint of 200 ms total cycle time [22].

LRAs operate by using a magnetic coil to push a mass up and down. They provide a “cleaner feeling” output in comparison to ERM, and they have a shorter rise time [22]. However, they need to be driven by an AC signal, whereas ERMs are driven by a DC signal, complicating the circuit and driving up cost of circuit components [22].

Piezoelectric vibrational actuators are small cantilever beams that have a reaction time of 1ms and can be controlled to produce complex signals. However, they require a 200V power source and actuator development kits are too expensive [22].

Since LRA and ERM vibrational actuators are both suitable they were purchased and tested, and then selected based on empirically gathered data [22].

Overview of Selected Concept

The two systems need a platform to run on and a way to communicate. For the actuation (haptic) system, an Arduino was found to be suitable to control vibrational actuators. An Arduino has multiple PWM channels and a serial port that enables communications. These features as well as low cost and availability make the Arduino ideal.

For the sensing system, a vision system using the C++ OpenCV library and ArUco module was selected. The vision system would ideally be run on a smartphone because there is a built-in camera, UI, and Bluetooth module for communications with the Arduino. These features are all required to allow the user to interact with the device.

In summary, the selected concept involves a band of vibrational actuators (Figure 2) controlled by an Arduino that will receive directional information from a smartphone via Bluetooth. The smartphone will detect and estimate the camera pose relative to ArUco markers in the user's surroundings and process this 3D data into guidance information that can be sent to the Arduino (Figure 1). The safety and legality of the concept were deemed appropriate assuming the CSA and FCC constraints were met. Sustainability was not explicitly investigated but assumed to be appropriate due to the simplicity and availability of the required components.

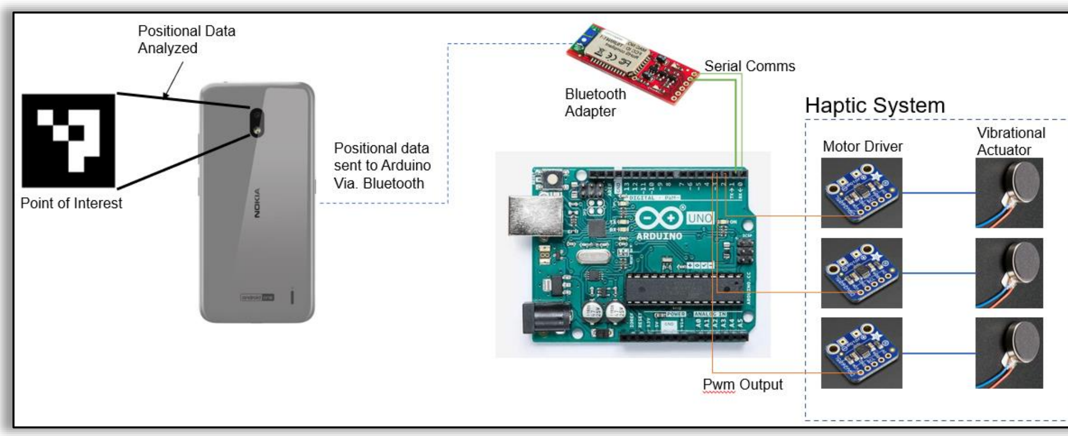


Figure 1. Overview of Selected Concept

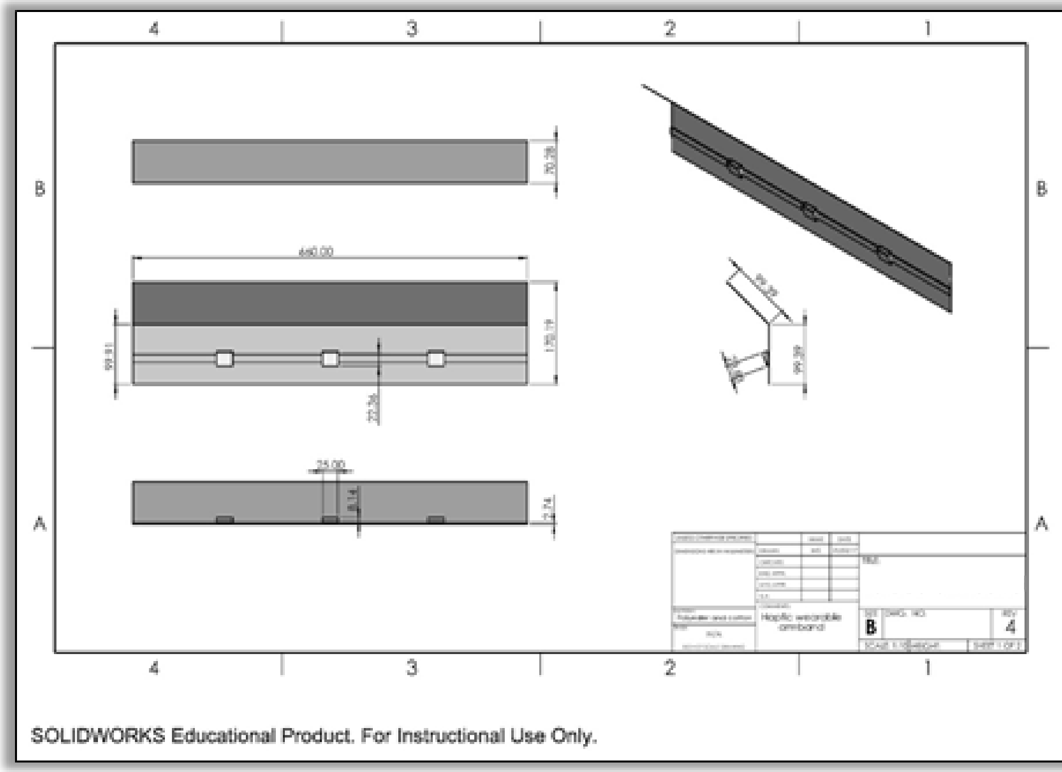


Figure 2. Drawing of Wearable Band of Vibrational Actuators

Design Validation

Vision System

Camera Calibration and the Perspective-n-Point Problem

In computer vision, a common scenario arises in which the 3D positions of n points in a 2D image are desired; this is known as the perspective-n-point problem and can be solved through camera calibration [24].

A pinhole camera's matrix of linear intrinsic parameters, $\boldsymbol{K_c}$, is used in combination with the camera's 6 DOF HTM (i.e., matrix of extrinsic parameters, $\boldsymbol{T_c^w}$), to relate a 2D image point, $\boldsymbol{p_c}$, to a 3D point in the world coordinate system, $\boldsymbol{p_w}$ (1).

$$s\boldsymbol{p_c} = \boldsymbol{K_c T_c^w p_w}$$

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} fm_x & \gamma & u_0 & 0 \\ 0 & fm_y & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & d_x \\ r_{21} & r_{22} & r_{23} & d_y \\ r_{31} & r_{32} & r_{33} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_w \\ y_w \\ z_w \\ 1 \end{bmatrix} \tag{1}$$

Where s is a scaling factor, $[u, v]^{\mathrm{T}}$ is the point in the image plane, f is the focal length of the camera, m_x and m_y are the inverse of pixel height and width in the projection plane, γ is the coefficient of skew between the camera's x and y axes, and $[u_0, v_0]^{\mathrm{T}}$ is the principal point (i.e. the center of the image plane).

By exposing a checkerboard with known size to the camera's FOV, OpenCV uses the above linear relations with corner points to solve for the camera's intrinsic parameters, $\boldsymbol{K_c}$, as well as non-linear radial and tangential distortion coefficients [25]. Using the resulting intrinsic parameters, an ArUco marker's pose can be estimated relative to the camera using its four corner points, since the inverse of the camera HTM is equal to the marker HTM (2).

$$\boldsymbol{T_m^c} = \boldsymbol{T_c^m}^{-1} \tag{2}$$

Distance Accuracy Study

A calibrated webcam was used with pose estimation to determine the system's accuracy when calculating the Euclidean distance to the relevant marker. Three different side lengths of square ArUco markers and ChArUco diamonds were used to determine optimal size: 10 cm, 15 cm, and 20 cm. Each marker was placed on a music stand of fixed height and moved in 0.5 m increments (measured using a measuring tape) from 0.5 m to 8 m away from the camera, which was placed on a fixed tripod to ensure no change in height between the marker and camera (Figure 3). The markers were set at a height where the center of the marker would line up closely with the camera's optical axis, as the actual distance is measured along it without any translation in x or y to provide accurate results (Figure 4).

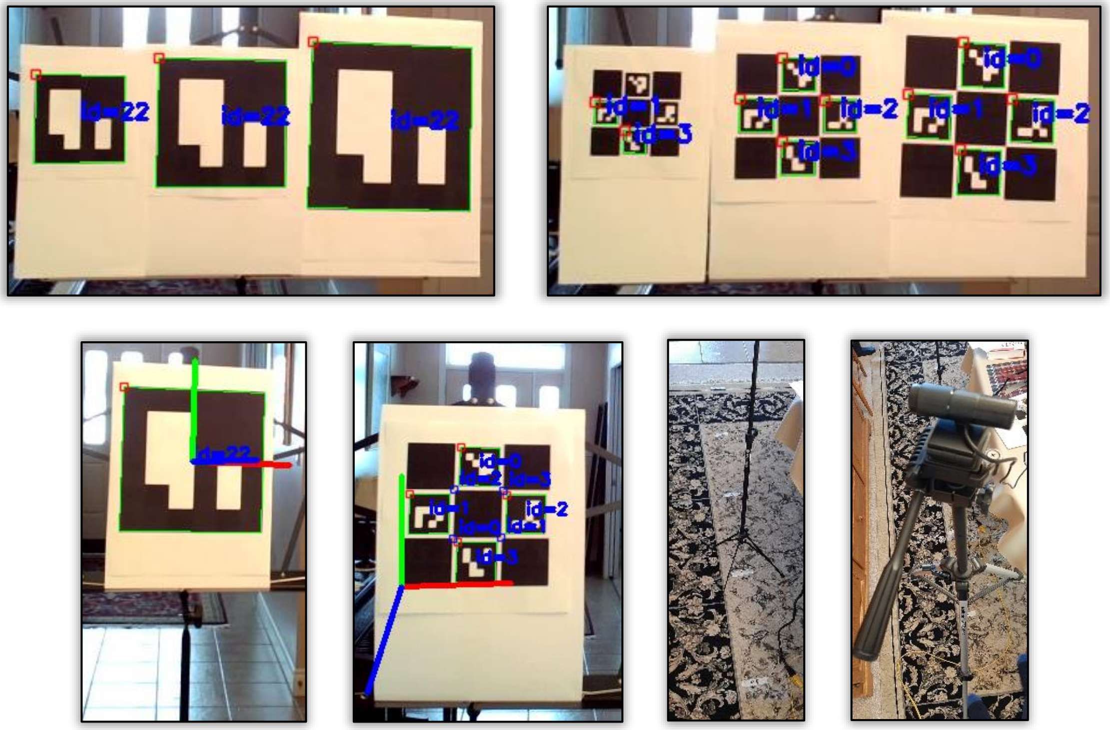
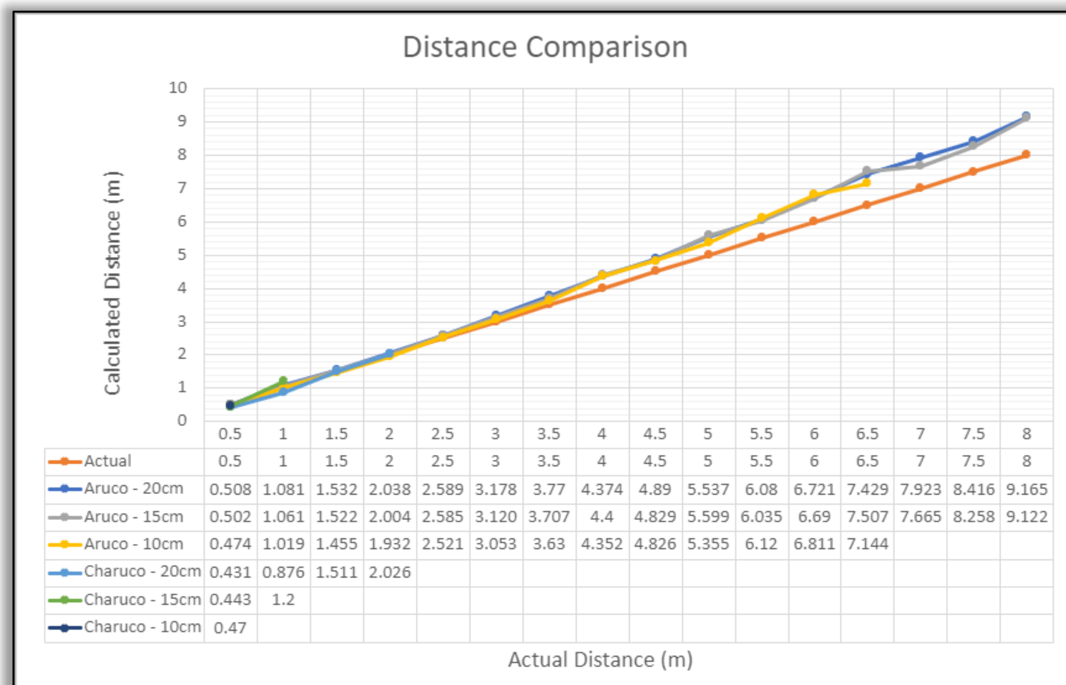


Figure 3. Distance Accuracy Testing Setup



	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Actual	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Aruco - 20cm	0.508	1.081	1.532	2.038	2.589	3.178	3.77	4.374	4.89	5.537	6.08	6.721	7.429	7.923	8.416	9.165
Aruco - 15cm	0.502	1.061	1.522	2.004	2.585	3.120	3.707	4.4	4.829	5.599	6.035	6.69	7.507	7.665	8.258	9.122
Aruco - 10cm	0.474	1.019	1.455	1.932	2.521	3.053	3.63	4.352	4.826	5.355	6.12	6.811	7.144			
Charuco - 20cm	0.431	0.876	1.511	2.026												
Charuco - 15cm	0.443	1.2														
Charuco - 10cm	0.47															

Figure 4. Distance Accuracy Data

After 2 m, the ChArUco diamonds were not detectable by the vision software. The smallest of the ArUco markers was not detectable after 6.5 m, and the 20 cm and 15 cm ArUco markers were detectable until the test limit of 8 m. At the furthest distance, the ArUco markers had an error of 15% compared to the measured value. The percent error decreased as the measured distance decreased, and the calculated distance converged to the measured value. Therefore, the system will meet the 5 m constraint for identifying and finding the position of a marker and can accurately identify when it meets the arm's-length constraint, 0.75 m.

Angle Accuracy and Limit Study

To test the accuracy of the angle measurements of the roll, pitch, and yaw of a marker relative to the camera (Figure 5), a 15 cm square ArUco marker was placed at a fixed height, level with a fixed, calibrated webcam 1 m away (Figure 6). The marker was rotated in 15° increments, measured using a smartphone gyroscope, from 0° to 75° about the marker axes to simulate changes in roll, pitch, and yaw of the camera.

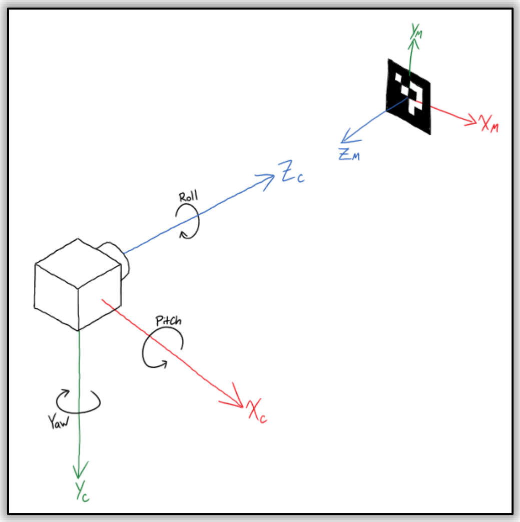


Figure 5. Camera Roll, Pitch, and Yaw Relative to Marker

Figure 6. Angle Accuracy Testing Setup

Each trial began with the marker face parallel with the lens of the camera to ensure only one variable was changed during each stage of the study and that the recorded data is controlled (Figure 7).

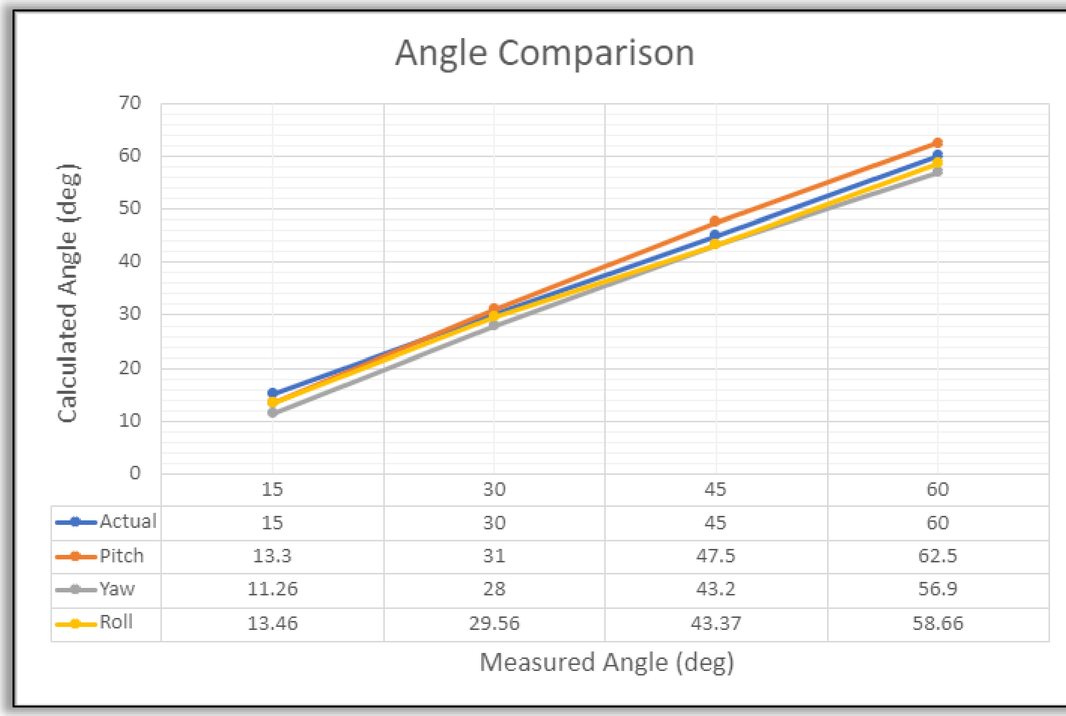


Figure 7. Angle Accuracy Data

All three rounds of the experiment resulted in similar error. The recorded difference between the actual and estimated values had a mean of 1.78° and a standard deviation of 0.71°; this means that for most of the measurements reported by the system, the maximum error will be 2.49°.

To test the maximum angle where the ArUco marker is detectable by the system, a series of 10 tests were performed where the ArUco marker was rotated away from the camera until it was no longer recognized. The maximum angle was recorded for each test (Table 5).

Table 5. Maximum Recognizable Angle Data

	Test Number									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Angle Measurement:	82.71177	83.74309	85.46196	82.02422	86.03492	84.88901	83.17013	81.45126	84.31605	82.59717

As shown by the average of the data, the maximum angle where the marker can be identified is 83.6° away from the lens, and applies to roll, pitch, and yaw. This means that the student must be almost perpendicular with the marker for the system not to recognize it. The probability of this occurring is small, especially considering the marker will be located on the wall above the location, and therefore the maximum recognizable angle falls within the constraints of the project.

Haptic System

Two-Point Discrimination Test

To determine the minimum actuator distance such that they are detected as individual points instead of one single point, a two-point discrimination test was conducted by gently pressing two pencils into the upper arm of a test subject [26]. The distance between the two points was measured, and the subject guessed whether one or two pencils were touching the arm. The data obtained from this test was compared to standard data available online [27].

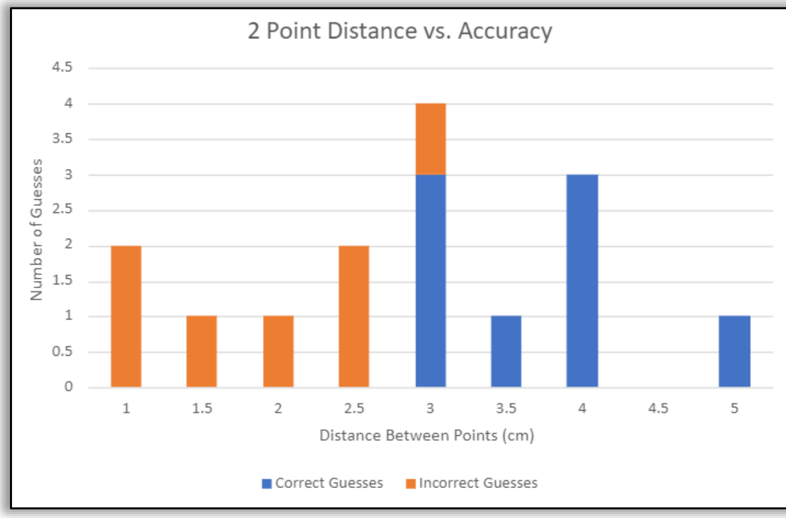


Figure 8. Two-Point Discrimination Test Results

Any distance less than 3 cm was guessed incorrectly as one point. The experimental data matches available data for two-point discrimination tests for the upper arm, which is found to be 30 mm to 40 mm [27]. Therefore, the vibrating motors on the haptic wearable will be kept at minimum 3 cm apart from one another. This must be checked by the user since the location of the actuators is customizable for different arm sizes.

While nerves do not detect pressure and vibration in the same way [28], this test served to find a minimum distance for testing. Some parts of the body were found in literature to have poorer tactile resolution than other body parts [27].

Vibrational Actuator Testing and Selection

ERMs and LRAs were purchased and tested with DRV2605L haptic breakout boards. The goal was to test the ability to feel the actuators through cloth to assess suitability for the haptic wearable. The figure below demonstrates the results after ten trials, where a 1 indicates sensation, and a 0 indicates lack of sensation.

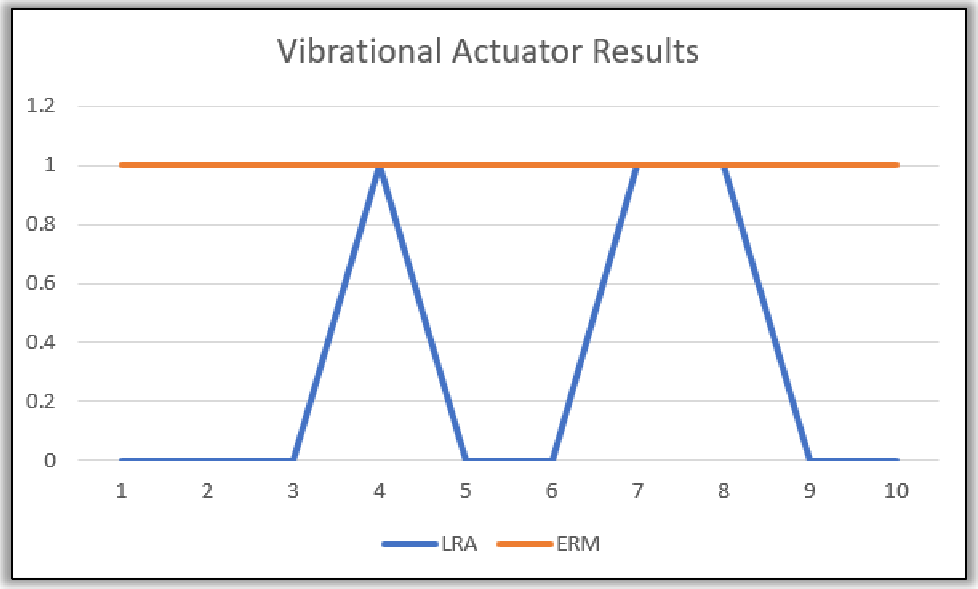


Figure 9. ERM vs. LRA Results

ERMs had a 100% success rate while LRAs had a 33% success rate, which makes sense because LRAs are typically used for smoother feeling vibration. It was found that the smooth vibration was not strong enough; therefore, ERM actuators were used in the prototype[1].

Battery Selection

Table 6. Current Draw of Haptic System Components

Component	Current Draw
Arduino Uno	50 mA [29]
Breakout Boards	5 mA [30]
Vibrating Motors (at 100% duty cycle)	100 mA [31]

When continuously vibrating at full power, the total current draw can be calculated (3).

$$I_{draw,total} = (50\text{ mA}) + (3 \times 5\text{ mA}) + (3 \times 100\text{ mA}) = 365\text{ mA} \quad (3)$$

[1] For further information on placement of the haptic vibrational actuators, see Design Refinement - Haptic System - Vibrational Actuator Placement.
For further information about haptic feedback methods, see Prototype Planning and Development - Prototype Development - Haptic System: Feedback Methods.

Table 7. Battery Type Specifications

Battery Type	Rechargeable	Voltage per Cell	Charge Capacity	Cells Required (for 7-12V Arduino)	Minimum Hours of Use (for 365mA draw)
AA Alkaline	No	1.5V	2000-3000mAh [32]	5-6	5.47h
Lithium-Ion Polymer	Yes	3.7-4.2V	2500mAh [33]	2-3	6.85h
PP3	No	9V	400-1200mAh [34]	1	1.1h
D-Cell	No	1.5V	2000-18000mAh [35]	5-6	5.47h
Nickel-Metal Hydride AA	Yes	1.25V	1900mAh [36]	6	5.2h

The intended user of this product is a secondary school student. An average school day in a secondary school lasts for 6-7 h [37]. Assuming 7 h of constant use, none of the proposed battery solutions can last the entire day (Table 7).

To estimate actual usage time in a five-period school day, it will be assumed that students have two 5 min breaks between first and second, and fourth and fifth period; that it is in use for two 15 min periods before and after classes; there is constant usage during a 1 h lunch break; and 25% usage during the four 75 min periods of class (4).

$$\begin{aligned} t_{use,total} &= 60\text{ min} + (2 \times 5\text{ min}) + (2 \times 15\text{ min}) + (4 \times 75\text{ min}) \times 0.25 \\ &= 75\text{ min} \\ &= 2.9167\text{ h} \end{aligned} \tag{4}$$

All batteries, excluding the PP3, can last for the estimated 3 h of usage during the school day. Firstly, D-Cell batteries are large, and to meet the voltage requirements for powering the Arduino Uno, five to six of these batteries would be required [35]. This is unideal for a wearable system, so they are eliminated.

LiPo batteries pose a safety hazard, because any damage done to the batteries can create fire hazards [33]. LiPo batteries purchased online are another safety risk because many online manufacturers create faulty batteries. For these reasons, LiPo are eliminated.

Remaining are AA alkaline and NiMH AA batteries. Although AA alkaline batteries last slightly longer than NiMH, NiMH batteries are rechargeable and just as easily purchased in stores as AA alkaline [36]. There are no other differences between these options, so NiMH AA-size batteries will be recommended and used for this product.

Design Refinement

Vision System

Automated Camera Calibration Process

During the validation process, it was discovered that calibrating a camera is an involved process. To make it easier for the user, an automated calibration process was devised (Figure 10), and an instruction manual was created (Appendix I: Camera Calibration Instructions).

Figure 10. Automatic Camera Calibration Process

If the measurements taken by the system after this process seem to be inaccurate, the user can repeat the process. It is also essential that the calibration board is printed to actual size; therefore, a calibration board printout with a dimensioned line was created (Figure 11).

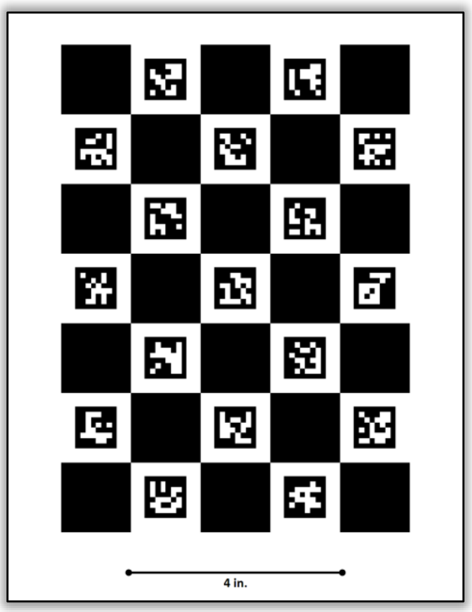


Figure 11. Calibration Board Printout

Marker Selection and Installation Considerations

In the distance accuracy study, it was determined that ChArUco diamonds could not be identified more than 2 m from the camera. ArUco markers with 15 cm and 20 cm side lengths could be identified further than 5 m. The printer settings had to be changed to produce the 20 cm marker, so the marker side length of 15 cm was selected. Similar to the calibration board, POI printouts with ArUco markers and dimensioned lines were created (Figure 12), and a set of instructions was written for installation of ArUco markers around a building (*Appendix II: Marker Installation Instructions*).

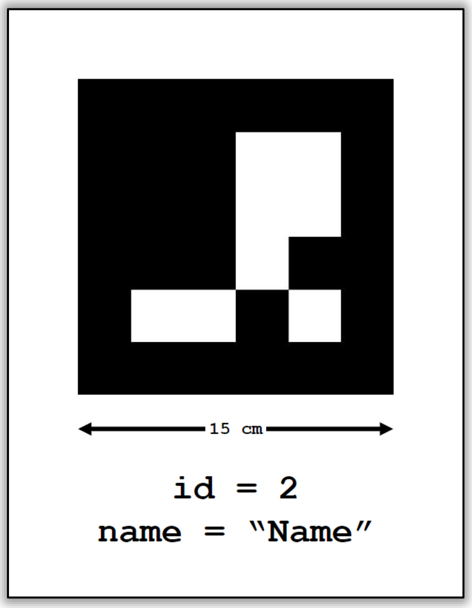


Figure 12. POI Marker Printout

Haptic System

Vibrational Actuator Placement

The concepts generated for placement of the band of vibrational actuators can be seen below with accompanying notes.

- Wrist (bracelet)
  - Concern about controller/power supply placement
  - Small surface area
  - Wrist size varies between users
- Waist (belt)
  - Power source and controller can go on the belt, may be uncomfortable
  - Belt size easily adjustable
- Torso (vest)
  - Uncomfortable to wear
  - Power supply and controller could be placed in a seam or pocket
- Feet (socks)
  - Extreme forces from weight of the person
  - Introduces safety hazard if wires exposed
- Sleeve (shirt)
  - Large surface area
  - Power supply and controller could be wired and placed on shoulder or back
- Using multiple body parts
  - Different parts of the body for different information

A decision matrix was used to determine which band placement to use for prototype development (Table 8).

Table 8. Decision Matrix for Actuator Placement

Objectives	Ease of Use	Comfort	Feedback Quality	Cost	Aesthetics	Total	%	Wrist	Waist	Torso	Feet	Sleeves	Multiple
Ease of use	1	5	3	5	3	17.00	36%	1	1	1	1	1	1
Comfort	1/5	1	1/3	3	3	7.53	16%	0	0	-1	-1	1	1
Quality of Feedback	1/3	3	1	5	7	16.33	34%	1	1	1	0	1	1
Cost	1/5	1/3	1/5	1	1/3	2.07	4%	0	1	-1	-1	0	0
Aesthetics	1/3	1/3	1/7	3	1	4.81	10%	0	0	0	-1	1	0
						47.74	100%	0.70	0.74	0.50	0.05	**0.96**	0.86

Torso and feet were eliminated because of their low comfort level and their inability to be quickly modified to fit different users. Multiple locations would more challenging because of spreading the actuators across the body, causing wires to be more dispersed. Sleeve, wrist, and waist were determined as being suitable candidates for actuator placement. Sleeve ranked the highest and therefore was selected for prototyping.

In summary, it was decided that vibrational actuators placed along the sleeve of the user's arm is the best solution. This aligns with the previous information regarding the higher tactile sensitivity of the upper arm relative to other body parts [27].

Maximum Positional Error

Using a pseudo-cardinal direction output scheme allows for the use of three directional actuators to provide the user with feedback in 6.67° increments, assuming a camera FOV of 60°. The maximum error in camera yaw found during the angle accuracy study was 3.74° (Figure 7).

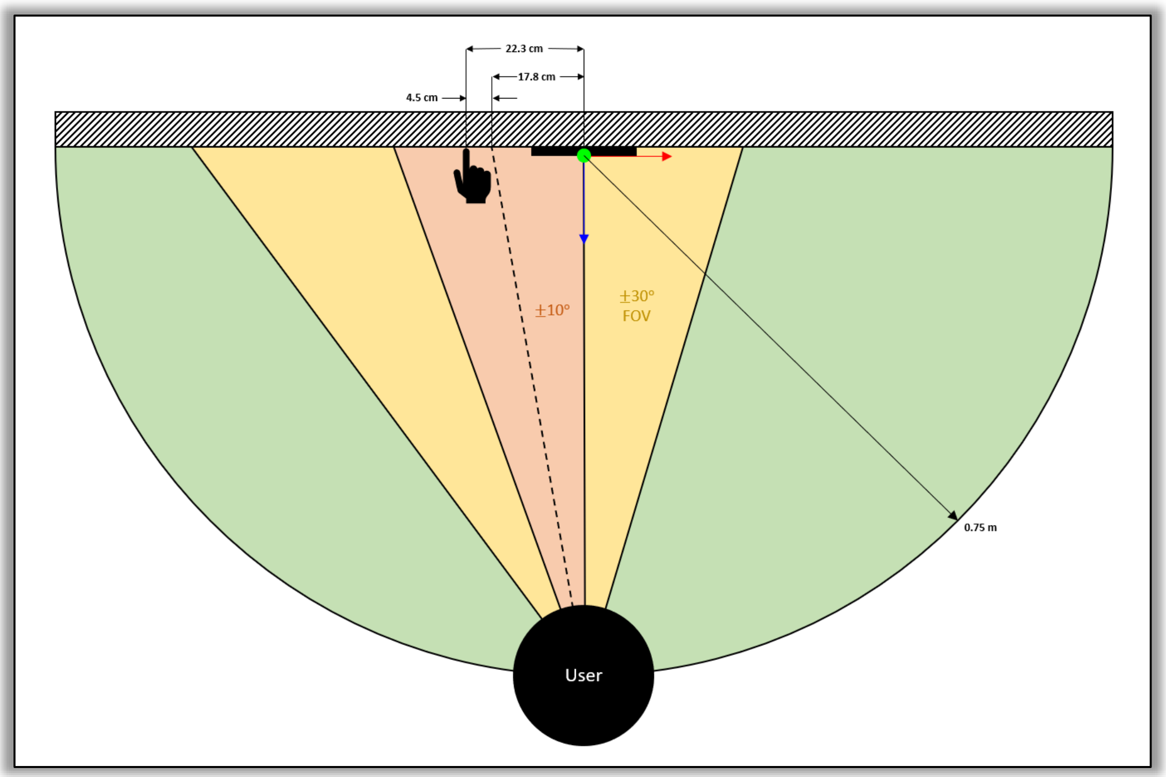


Figure 13. Maximum Positional Error with Haptic System

Assuming the system guides the user within 0.75 m of the marker and notifies them that they are directly facing the POI ($\pm 10°$)[2] the maximum theoretical positional inaccuracy along the markers x axis can be calculated (5).

$$e_{sys,max} = \pm\big((0.75\ \text{m}) \times \sin(10° + 3.74°)\big) = \pm 17.8\ \text{cm} \qquad (5)$$

Additionally, user error is of when touching the marker is accounted for by adding half the width of a hand, measured empirically as being approximately 4.5 cm (Figure 13). The maximum positional error can then be calculated (6).

$$e_{user,max} = 17.8\ \text{cm} + 4.5\ \text{cm} = 22.3\ \text{cm} \qquad (6)$$

This value is used in functional prototype testing to define successful guidance to a POI.

Charging Board

Repeatedly opening and closing the case of the product to change the batteries when they have run out of power can lead to fatigue in the joints of the case, leaving the inner components vulnerable to damage. To eliminate this, the MAX712 battery charger control board from Maxim Integrated was selected and paired with six NiMH AA batteries to power the haptic system (Figure 14, Figure 15). A 10 V DC wall adapter is plugged into the board, which charges the batteries over 135 min, which fits within the charging time constraint of 8 h. This board connects to both the microcontroller and the batteries (Figure 16).

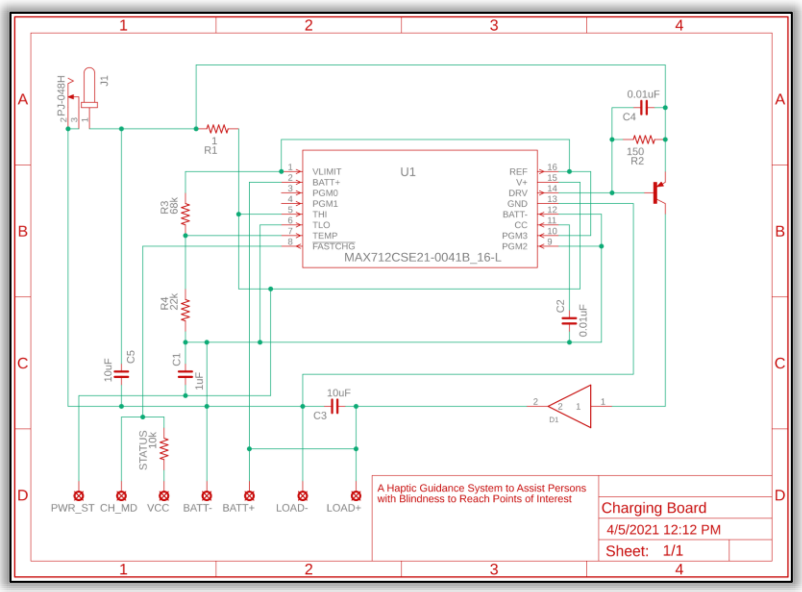


Figure 14. Charging Board Schematic

[2] This range is taken from a prototype iteration; every actuator will pulse simultaneously when the guidance angle falls within one of the three center "compass" regions for the haptic pattern, as seen in Prototype Modifications and Improvements – Haptics – Notification of Arrival.

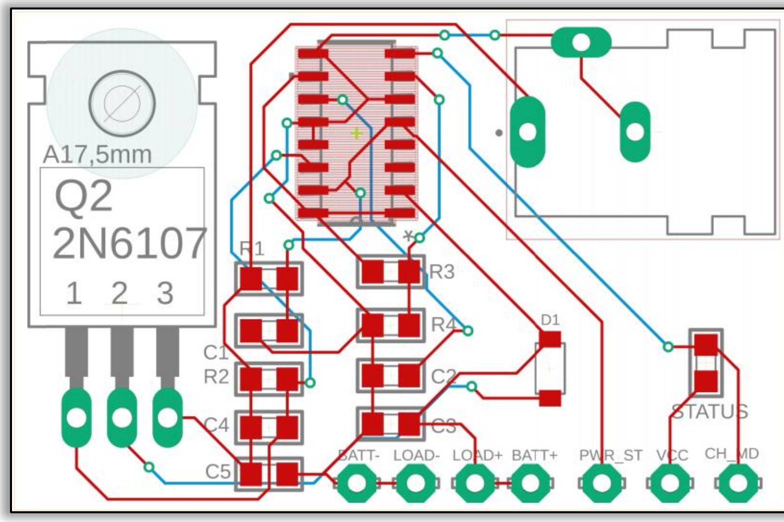


Figure 15. Charging Board PCB Layout

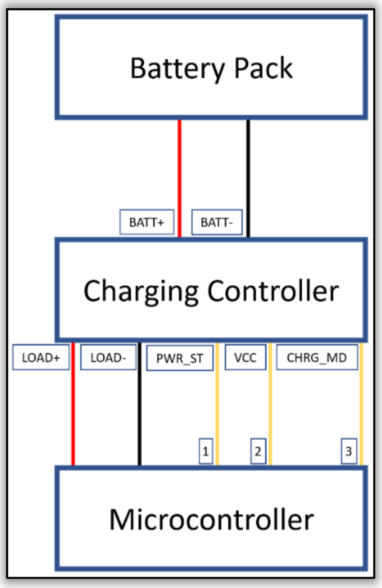


Figure 16. Power Supply Routing

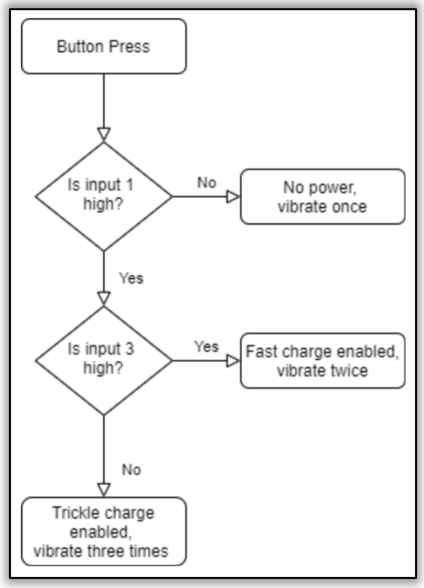


Figure 17. Charging Status Program Flowchart

While charging, a button connected to the Arduino can be pressed to check the status of the charging board (Figure 17).

Overview of Final Design

The following diagram displays the process flow of the entire design (excluding power supply), after refinement due to design validation. Confidence that this process flow would result in an effective prototype was high.

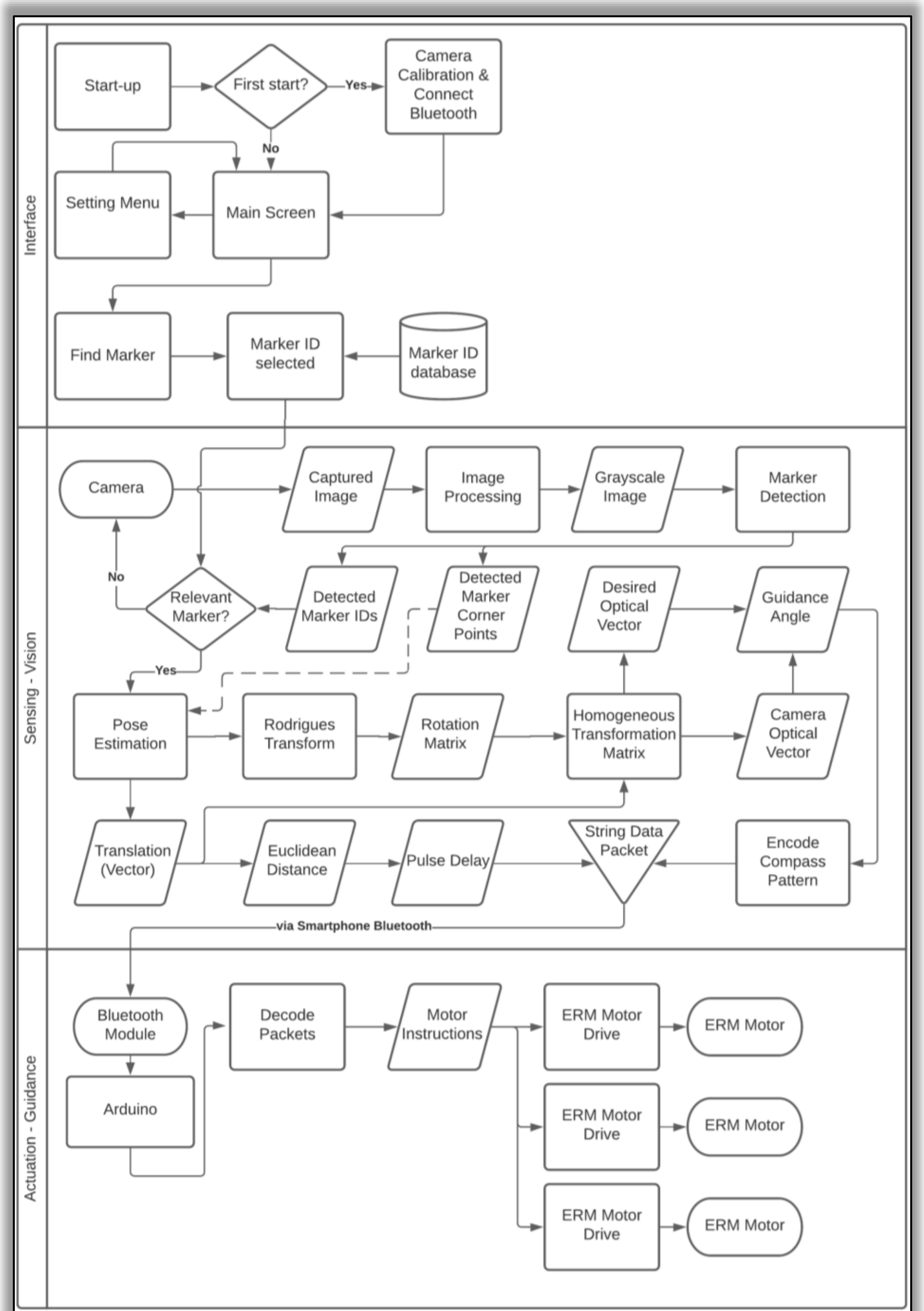


Figure 18. System Flowchart

Prototype Planning and Development

Prototype Planning

A contingency plan was made regarding the various states of lockdown, such that the development of the prototype would not be impacted by the COVID-19 pandemic. For the duration of this project, the team practiced social distancing and minimized contact between team members. To create the prototype, the team split the project into three different parts, each having specified team members. The haptic system required more than one person to construct, and the team delegated the task to members who were living together.

The vision system was software based, so this part of the project was completed remotely. Creating the smartphone application and testing the Bluetooth communications was also completed remotely. Most of the components for this project were ordered online and delivered without contact. Prototype testing was completed using items available in team members' homes and with minimal test subjects due to restrictions. Once the vision and haptic systems were completed, the functional prototype was assembled and tested.

Table 9. Design Components Included in Functional Prototype

Final Design Component	Novel to Design	Physical Testing Required	Prototype
Battery Charging Circuit	No	No	No
Enclosures	Yes	No	No
Haptic wearable	Yes	Yes	Yes
Arduino Receiver/Decoder	Yes	Yes	Yes
Android Application	Yes	No	No
Bluetooth Communications	No	Yes	Yes
ArUco	Yes	Yes	Yes

A fully functional prototype was developed; however, a 1:1 prototype of the final design was not pursued. In line with the contingency plan, any design component not required to test the functionality of the design was not fully integrated into the prototype, and was instead tested independently, if required. Table 9 indicates which components of the design are novel to the design, and whether physical testing and prototyping were required to validate the design.

The battery charging circuit and enclosure were not prototyped because they are not novel to the design and do not impact functionality of the prototype.

The Android application's primary purpose is to facilitate user interaction but does not impact functionality of the prototype.

Additionally, although Bluetooth communication between an Android device and Arduino was achieved with acceptable latency, the functional prototype utilizes a USB connection for serial communications between the vision system and haptic system. This is due to obstacles compiling OpenCV with ArUco into the Android Environment and calling them from C++. Android application prototype testing will seek to validate that utilizing a smartphone's Bluetooth connection – as is the case in the final design – will result in similar latency as serial communications over a USB connection.

Despite any compromises, the prototype was expected to fully demonstrate the effectiveness of the design.

Prototype Development

Haptic System: Feedback Methods

The haptic wearable uses three vibrational actuators to convey distance and orientation information. Two different methods of conveying directional information through the haptic wearable to the user were programmed and tested. The two methods are called "vector" and "compass".

Note that the vibrators will be referred to as the front, left, and right vibrators. 0° is directly ahead of the user, and the amplitude of vibration ranges from 0% to 100%. It will be assumed that the camera has a FOV of 60.0°.

The vector method operates by turning on the motors in a combination that represents the angle. For example, if the front and right vibrators turn on at equal strength, that would indicate a -30.0° angle. Alternatively, with the front vibrator at 90% strength, and the left vibrator was on at 10% strength, that would indicate an angle of ~7.0°. There is no indication of distance from the POI in this mode.

The compass method operates by giving three pulses, followed by a rest pulse, to indicate direction. Amplitude of the vibration is not relevant in this mode. The pattern of the pulses encodes the direction of the POI and the frequency of pattern repetition encodes the distance. A higher frequency corresponds to a shorter distance, with limits of 300 bpm and 60 bpm for maximum and minimum tempo, respectively.

A test subject closed their eyes while wearing the haptic wearable and provided feedback as if the system detected a marker. They reported which actuators they felt were on, and if possible, the direction indicated by them. Due to COVID-19 restrictions, minimal trials were conducted with a few test subjects.

Angle	Front	Left	Right	Guess F	Guess L	Guess R	
45	50	0	50	0	1	0	INCORRECT
130	56	44	0	1	1	0	CORRECT
190	0	94	6	1	1	0	INCORRECT
220	0	78	22	0	0	1	INCORRECT
20	22	0	78	1	1	0	INCORRECT
100	89	11	0	1	1	0	CORRECT
							33.3333333
adding 100ms delay between different vibrators pulsing							
45	50	0	50	1	0	1	CORRECT
120	67	33	0	1	1	0	CORRECT
80	89	0	11	1	0	1	CORRECT
190	0	94	6	0	1	0	CORRECT
220	0	78	22	0	1	1	CORRECT
20	22	0	78	1	0	1	CORRECT
75	83	0	17	1	0	1	CORRECT
150	33	67	0	1	1	0	CORRECT
							100
reducing delay from 100ms to 50ms							
45	50	0	50	1	0	1	CORRECT
80	89	0	11	0	1	1	INCORRECT
220	0	78	22	1	1	0	INCORRECT
75	83	0	17	1	0	1	CORRECT
150	33	67	0	1	1	0	CORRECT
							60
added delay between changing angles (off for 2.5s in between trials)							
20	22	0	78	1	0	1	CORRECT
190	0	94	6	0	1	0	CORRECT
120	67	33	0	1	1	0	CORRECT
89	99	0	1	1	0	0	CORRECT
250	0	61	39	0	1	1	CORRECT
							100
subject is now listening to music as a distraction							
89	99	0	1	1	1	0	INCORRECT
45	50	0	50	0	1	1	INCORRECT
80	89	0	11	1	1	0	INCORRECT
250	0	61	39	0	0	1	INCORRECT
120	67	33	0	1	1	0	CORRECT
150	33	67	0	1	1	0	CORRECT
75	83	0	17	0	1	1	INCORRECT
							25

Figure 19 . Vector Mode Testing Results

The success rate of vector mode was 64% and decreased as the subject became distracted by music (Figure 19). The subjects were not able guess resulting direction and could only report which actuators they thought were on.

Note that in the results for compass mode (Figure 20), that “Correct D?” means correct identification of an altered frequency, and “Correct O?” means correct identification of the compass pattern. In these results, the front vibrator is referred to as the north vibrator, right is east, and left is west.

Compass Mode Testing
Using BenHapticCodeV1

Intensity	BPM	Angle	Pattern	Guess	Correct?
100	500	102.7439	NNW	NNW	Y
100	500	198.2278	WWW	WWW	Y
100	500	357.5561	EEE	EEE	Y
100	500	321.7935	EEE	EEE	Y
100	500	63.94497	NNE	NNE	Y
100	500	228.2986	WWW	WWW	Y
100	500	170.2108	WWW	WWW	Y
100	500	146.7919	NW	NW	Y
100	500	331.7263	EEE	EEE	Y
100	500	192.2447	WWW	WWW	Y
100	500	17.77541	EEN	EEN	Y
100	500	172.6597	WWW	WWW	Y
100	500	179.0818	WWW	WWW	Y
100	500	64.43235	NNE	NNE	Y
100	500	63.23144	NNE	NNE	Y
100	500	178.5063	WWW	WWW	Y
100	500	125.2197	NW	NW	Y
100	500	28.81846	EEN	EEN	Y
100	500	69.9252	NNE	NNE	Y
100	500	4.697562	EEE	EEE	Y
50	500	256.7258	WWW	WWW	Y
50	500	83.67669	NNN	NNN	Y
50	500	262.2727	WWW	WWW	Y
50	500	133.5025	NW	NW	Y
50	500	201.0022	WWW	WWW	Y
50	500	49.28118	NE	NE	Y
50	500	172.4357	WWW	WWW	Y
50	500	290.4723	EEE	EEE	Y
50	500	156.4497	WWN	WWN	Y
50	500	77.14779	NNE	NNE	Y
50	500	85.43026	NNN	NNN	Y
50	500	163.8599	WWN	WWN	Y
50	500	171.8346	WWW	WWW	Y
50	500	43.25872	NE	NE	Y
50	500	177.1338	WWW	WWW	Y
50	500	85.57621	NNN	NNN	Y
50	500	10.05703	EEE	EEE	Y
50	500	70.63314	NNE	NNE	Y
50	500	159.4993	WWN	WWN	Y
50	500	148.1756	WWN	WWN	Y
50	500	138.7396	NW	NW	Y

NEW TEST SUBJECT

100	100	122.4955	NNW	NNW	Y
100	100	150.9427	WWN	WWN	Y
100	100	116.5288	NNW	NNW	Y
100	100	25.87333	EEN	EEN	Y
100	100	85.47622	NNN	NNN	Y
100	100	118.2837	NNW	NNW	Y
100	100	147.3926	WWN	WWN	Y
100	100	122.8351	NNW	NNW	Y
100	100	178.1839	WWW	WWW	Y
100	100	75.81921	NNE	NNE	Y
100	100	156.0555	WWN	WWN	Y
100	100	162.6112	WWN	WWN	Y
100	100	40.50468	NE	NE	Y
100	100	35.67699	NE	NE	Y
100	100	150.0881	WWN	WWN	Y
100	100	13.30237	EEN	EEN	Y
100	100	20.21618	EEN	EEN	Y
100	100	76.87615	NNE	NNE	Y
100	100	57.85762	NNE	NNE	Y
100	100	119.2117	NNW	NNW	Y

Adding in Distance Determination

Intensity	BPM	Distance	Angle	Pattern	Faster/Slower?	Guess	Correct D?	Correct O?
100	100	2	81.00521	NNN	N/A	NNN	Y	N/A
100	100	3	78.97264	NNE	slower	NNE	Y	Y
100	100	1	78.13101	NNE	faster	NNE	Y	Y
100	100	4	2.90704	EEE	slower	EEE	Y	Y
100	100	4	169.3755	WWW	same	WWW	Y	Y
100	100	3	102.9924	NNW	faster	NNW	Y	Y
100	100	2	5.76591	EEE	faster	EEE	Y	Y
100	100	1	21.35795	EEN	faster	EEN	Y	Y
100	100	2	110.4602	NNW	faster	NNW	N	Y
100	100	1	89.91502	NNN	same	NNN	N	Y

New Test Subject

Intensity	BPM	Angle	Pattern	Guess	Correct?
100	100	73.3408	NNE	NNE	Y
100	100	33.29624	EEN	EEN	Y
100	100	21.54163	EEN	EEN	Y
100	100	137.2694	NW	NW	Y
100	100	31.88136	EEN	EEN	Y
100	100	5	EEE	EEE	Y
100	100	94.86891	NNN	NNN	Y
100	100	148.4266	WWN	WWN	Y
100	100	20.97045	EEN	EEN	Y
100	100	138.0658	NW	NW	Y
100	100	76.61814	NNE	NNE	Y
100	100	89.16998	NNN	NNN	Y
100	100	101.3351	NNN	NNN	Y
100	100	83.41898	NNN	NNN	Y
100	100	138.9938	NW	NW	Y

Intensity	BPM	Distance	Angle	Pattern	Faster/Slower?	Guess	Correct D?	Correct O?
100	100	2	110.323	NNW	N/A	NNW	Y	N/A
100	100	3	179.5759	WWW	slower	WWW	Y	Y
100	100	2	93.31999	NNN	faster	NNN	Y	Y
100	100	5	92.58766	NNN	slower	NNN	Y	Y
100	100	1	134.8491	NW	faster	NW	Y	Y
100	100	2	128.8954	NW	slower	NW	Y	Y
100	100	3	76.12817	NNE	faster	NNE	N	Y
100	100	4	120.9532	NNW	slower	NNW	Y	Y
100	100	4	131.6001	NW	slower	NW	N	Y
100	100	3	117.1074	NNW	faster	NNW	Y	Y
100	100	5	109.5829	NNW	same	NNW	N	Y
100	100	4	62.05845	NNE	faster	NNE	Y	Y
100	100	1	40.72234	NE	faster	NE	Y	Y
100	100	3	9.556283	EEE	same	EEE	N	Y
100	100	2	117.613	NNW	slower	NNW	N	Y

Figure 20. Compass Mode Test Results

The “compass mode” results were successful. Users were able to identify the pulse pattern and encoded direction. Furthermore, the change in distance was also correctly identified in 66.67% of trials. Incorrect answers were typically a result of the change in frequency being difficult to discern. Overall, this mode was found to be easy to use, and test subjects only needed a few trials to understand the information conveyed by the pattern.

The compass method was selected for use in the final design.

Vision System: Computing Euclidean Distance and Guidance Angle

Before functional prototype testing began, the vision system operated by taking an image input from the camera and populating a Frame object with all marker information pertaining to that single image. The output of the vision system was the Euclidean distance to the marker and a guidance angle, which was calculated by comparing the camera's optical axis z_c and desired axis z_d from the marker-to-camera HTM (7) (8) (9) (10).

$$\boldsymbol{T_c^m} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & d_x \\ r_{21} & r_{22} & r_{23} & d_y \\ r_{31} & r_{32} & r_{33} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

$$d_{Euclidian} = \sqrt{d_x^2 + d_y^2 + d_z^2} \tag{8}$$

$$\boldsymbol{z_c} = \begin{bmatrix} r_{13} \\ r_{23} \\ r_{33} \end{bmatrix} \tag{9}$$

$$\boldsymbol{z_d} = \begin{bmatrix} -d_x \\ -d_y \\ -d_z \end{bmatrix} \tag{10}$$

z_c and z_d were then projected as unit vectors onto the marker's x-z plane to compute a guidance angle accounting only for the person's facing direction on the horizontal plane (11) (12).

$$\boldsymbol{z_{c_{xz}}} = \begin{bmatrix} z_{c_{xz_x}} \\ z_{c_{xz_z}} \end{bmatrix} = \frac{1}{\sqrt{r_{13}^2 + r_{33}^2}} \begin{bmatrix} r_{13} \\ r_{33} \end{bmatrix} \tag{11}$$

$$\boldsymbol{z_{d_{xz}}} = \begin{bmatrix} z_{d_{xz_x}} \\ z_{d_{xz_z}} \end{bmatrix} = \frac{1}{\sqrt{(-d_x)^2 + (-d_z)^2}} \begin{bmatrix} -d_x \\ -d_z \end{bmatrix} \tag{12}$$

The angles of both vectors were found in the marker's x-z plane by utilizing the $\mathrm{atan2}$ function, and the difference in angles from the camera's optical axis to desired axis (projected on the marker's x-z plane) was used as the guidance angle which would be utilized in the haptic system (13).

$$\theta_{guidance} = \mathrm{atan2}\left(z_{d_{xz_x}}, z_{d_{xz_z}}\right) - \mathrm{atan2}\left(z_{c_{xz_x}}, z_{c_{xz_z}}\right) \tag{13}$$

It should be noted that in cases where the computed guidance angle was higher in magnitude than 180°, it was converted into a complimentary angle by adding or subtracting $360°$.

Integration of the Vision System and Haptic System

To provide the guidance information to the haptic system, the vision system transforms the distance and guidance angle into pulsing instructions.

First, the Euclidean distance was converted into a pulse delay in ms for the haptic actuators (14). This results in a rational square root function (Figure 21).

$$
\begin{aligned}
t_{pulse\ delay} &= \frac{60000\ \text{ms}}{\cancel{1\ \text{min}}} \cdot \frac{\cancel{1\ \text{min}}}{300\ \cancel{\text{beats}}} \cdot \left(\frac{1}{2}\ \cancel{\text{beats}}\right) \cdot \sqrt{d_{Euclidean}} \\
&= (100\ \text{ms}) \cdot \sqrt{d_{Euclidean}}
\end{aligned}
\qquad (14)
$$

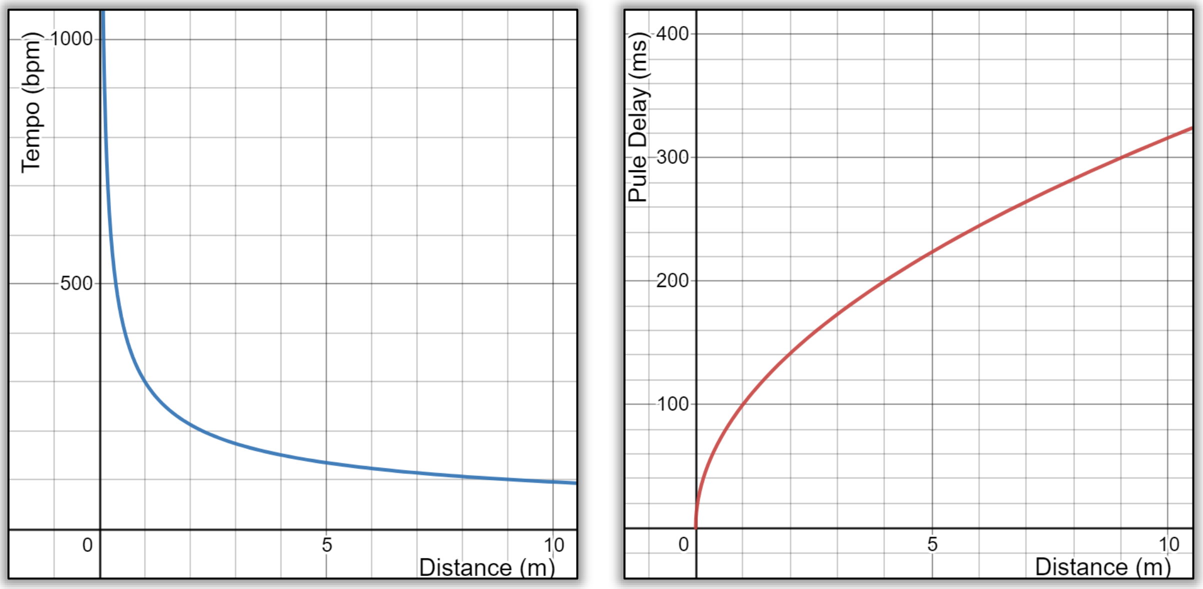


Figure 21. Plots of Tempo and Pulse Delay vs. Distance

Similarly, the guidance angle was converted into a pulsing pattern according to the haptic system's "compass method", where the camera's 60° FOV was split into nine regions in the marker's x-z plane (Figure 22) to produce a pattern corresponding to which region the guidance angle falls into (15).

$$
\text{Pattern}(\theta_{guidance}) = \begin{cases}
\text{"EEE\_"}, & -30.00° \le \theta_{guidance} \le -23.33° \\
\text{"EEN\_"}, & -23.33° < \theta_{guidance} \le -16.67° \\
\text{"NE\_\_"}, & -16.67° < \theta_{guidance} \le -10.00° \\
\text{"NNE\_"}, & -10.00° < \theta_{guidance} \le -3.33° \\
\text{"NNN\_"}, & -3.33° < \theta_{guidance} \le 3.33° \\
\text{"NNW\_"}, & 3.33° < \theta_{guidance} \le 10.00° \\
\text{"NW\_\_"}, & -10.00° < \theta_{guidance} \le 16.67° \\
\text{"WWN\_"}, & 16.67° < \theta_{guidance} \le 23.33° \\
\text{"WWW\_"}, & 23.33° < \theta_{guidance} \le 30.00°
\end{cases}
\qquad (15)
$$

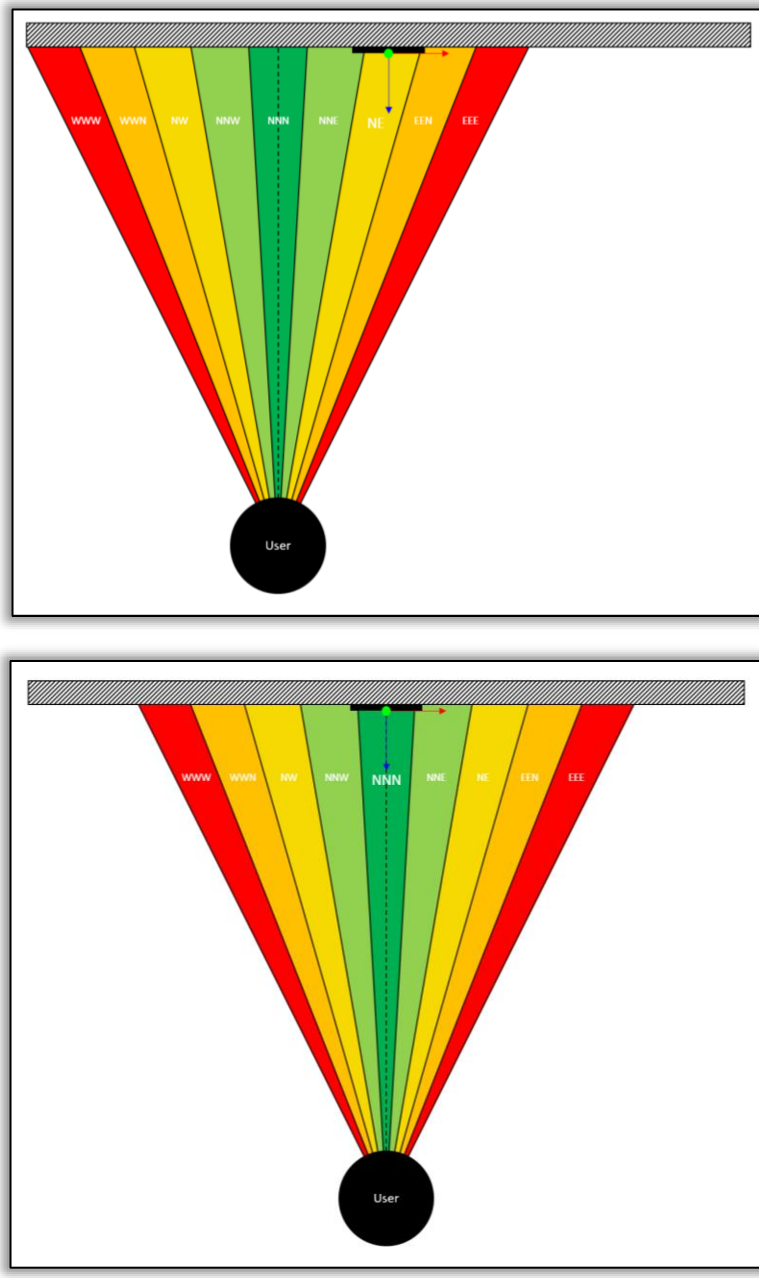


Figure 22. Guidance Angle to Pulsing Pattern

This information was combined into a string data packet to be sent to the Arduino, which took the form of a 10-character string "`MSEppppddd`" where:

- `MSE` is the 3-character header to initialize the receiving of information
- `pppp` is the 4-character string which describes the pulsing pattern (15)
- `ddd` is the 3-character string representing an integer for pulse delay in ms (14)
- For example, a marker detected 2 m away and 20° clockwise from the user's facing direction, the data packet is `MSEEEN_141`, which pulses EEN_ at 141 ms delay.

Prototype Testing and Evaluation

Functional Prototype Testing

Test Design

A testing environment was constructed using a blank room with unique ArUco markers distributed along three walls. The centre point of the room was measured and marked by tape on the floor (Figure 23).


Figure 23. Functional Prototype Testing Environment

The final prototype was tested by having a test subject don the haptic wearable while blindfolded. A webcam was connected to a laptop running the vision system ArUco identifying program which would send data via USB serial communications to the Arduino attached to the haptic wearable. One team member would follow the test subject with the laptop while they navigate the environment in an attempt to identify the POI (Figure 24).

For each trial run, an ArUco marker ID was randomly selected and the subject would begin standing in the centre of the test area, facing in a random direction of the subject's choice with the camera covered until the start of the test.

The time required for the subject to successfully identify the correct POI was recorded for each trial run, and the error was recorded if applicable. Any trial where the subject touched within 22.3 cm of the target was a success as defined by the previously determined error.

Figure 24. Functional Prototype Testing Process

Test Results

The run times for each test subject fell within the range of 15 s to 2 min, with an average of 47.9 s across all trials (Figure 25, Figure 26, Figure 27). Subjects adapted to the system over time, indicating a learning curve to use of the device.

Comments recorded from 31 trial runs with three different test subjects (Figure 28) led to some prototype improvements; a notification of arrival was added for the user to discern once they have crossed the threshold of being within 0.75 m of the POI to better adhere to design constraints, as will be discussed in Prototype Modifications and Improvements - Haptic System - Notification of Arrival. Additionally, after the first trial, the elevation of the ArUco markers in the testing environment was lowered, as will be discussed in Prototype Modifications and Improvements - Vision System - Marker Elevation.

Subject	Run No	Pol ID	Time (s)	Failure Distance (cm)	Result	Notes
Ben	1	5	26.94	0	y	
V2	2	4	31.68	0	y	
	3	6	37.66	0	y	
	4	5	32.04	48	n	false signal
	5	2	20.96	0	y	
	6	1	14.5	0	y	
	7	2	21.3	0	y	
	8	5	26.49	0	y	
	9	10	16.5	23	n	close, slightly to left
	10	8	65.61	0	y	rotated too quickly and missed marker
	11	3	27.62	0	y	vibrators get weaker over time
Chris	1	4	85	20	y	
V3	2	1	106	0	y	
	3	7	120	0	y	
	4	10	44.61	20	y	
	5	6	33.43	0	y	
	6	4	57	27	n	
	7	5	114	0	y	
	8	0	45.92	0	y	
	9	3	84.32	0	y	
	10	2	19.93	0	y	
Aidan	1	5	101	0	y	
V3	2	7	38.31	0	y	
	3	9	50	22	y	
	4	8	52	11	y	
	5	1	39.44	18	y	touched ID 2 instead of 1, but technically still in range
	6	2	45	0	y	
	7	9	11.25	4	y	
	8	3	18.9	0	y	
	9	5	60	13	y	touched ID 4 instead of 5, but technically still in range
	10	8	31.08	0	y	

Figure 25. Functional Prorotype Test Data

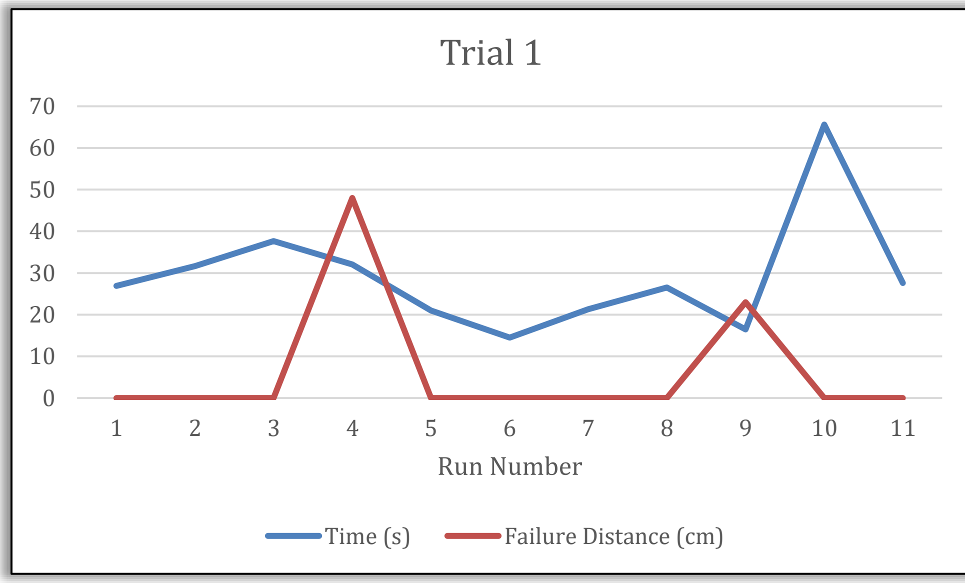


Figure 26. Functional Prototype Testing Trial 1 Results

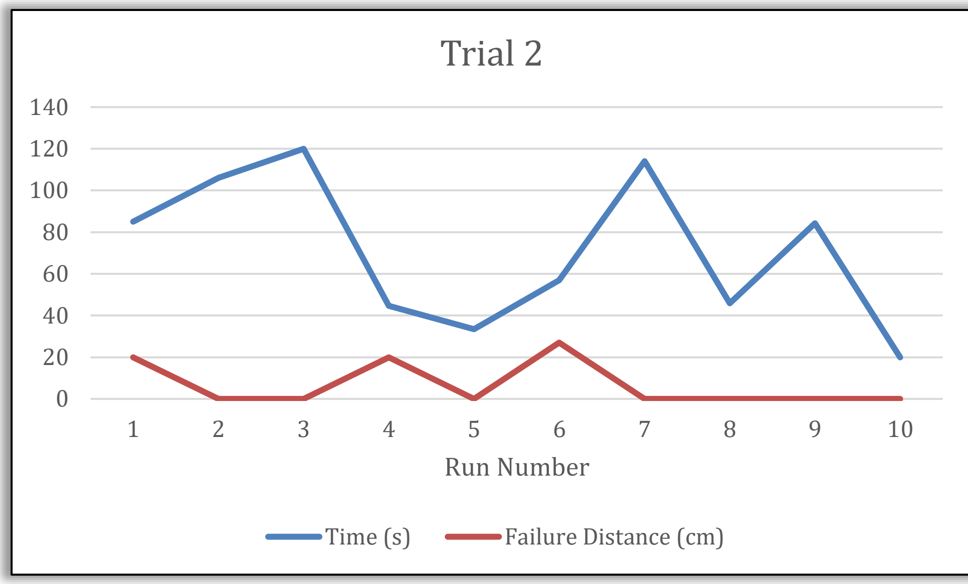


Figure 27. Functional Prototype Testing Trial 2 Results

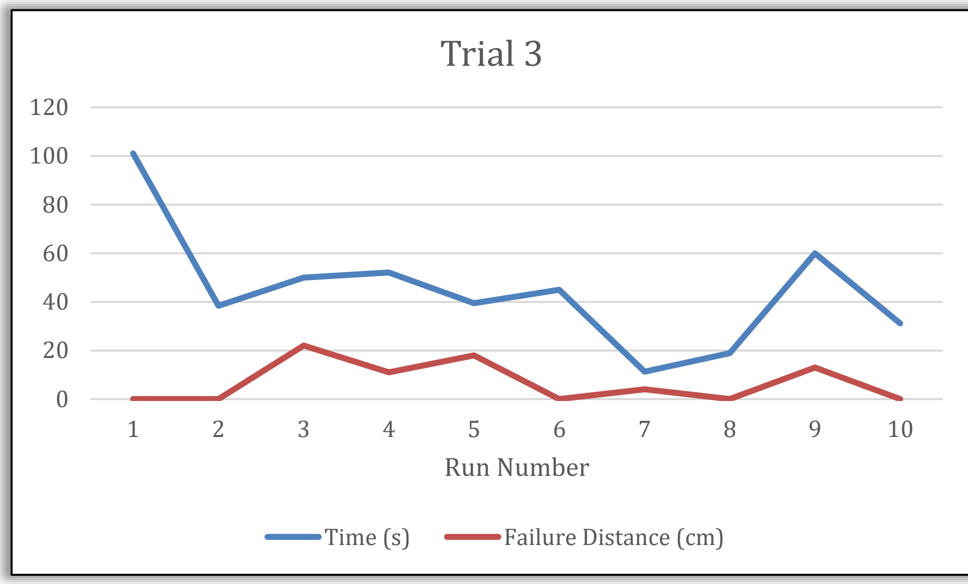


Figure 28. Functional Prototype Testing Trial 3 Results

The overall failure distance for most trial runs was within the 22.3 cm constraint, indicating that only 3 of 31 trial runs were considered failures, resulting in a 90% success rate. Additionally, the time of each trial was 2 minutes or less, indicating that the user could find the desired POI quickly and without having to physically feel the environment.

Although the trials were a success in both positional accuracy and required time, several suggestions for modifications and complaints by the test subjects were noted and will be discussed further.

Android Application Testing

Test Design

An Android application was developed to benchmark the message delay times and processing times of the ArUco system (Figure 29). This simple application counts the number of markers in a frame and sends the number, along with the message latency and processing time.

```
@Override
public Mat onCameraFrame(CameraBridgeViewBase.CvCameraViewFrame inputFrame) {
    if(Count >= 10) {
        StartTime = System.currentTimeMillis();
        java.util.List<Mat> corners = new ArrayList<>();
        Mat ids = new Mat();
        Mat im = inputFrame.gray();
        Aruco.detectMarkers(im, getPredefinedDictionary(DICT_4X4_50), corners, ids);
        Aruco.drawDetectedMarkers(im,corners);
        ProcessTime = System.currentTimeMillis() - StartTime;
         diff = StartTime - LastTime;
        SendMsg = message + diff + ", Process:, "+ ProcessTime + ", Markers:, " + corner
         BtXfer.write(SendMsg.getBytes());
         LastTime = StartTime;

         return im;
     }
     ++Count;
     return null;
}
```

Figure 29. Code for Android Benchmarking

Test Results

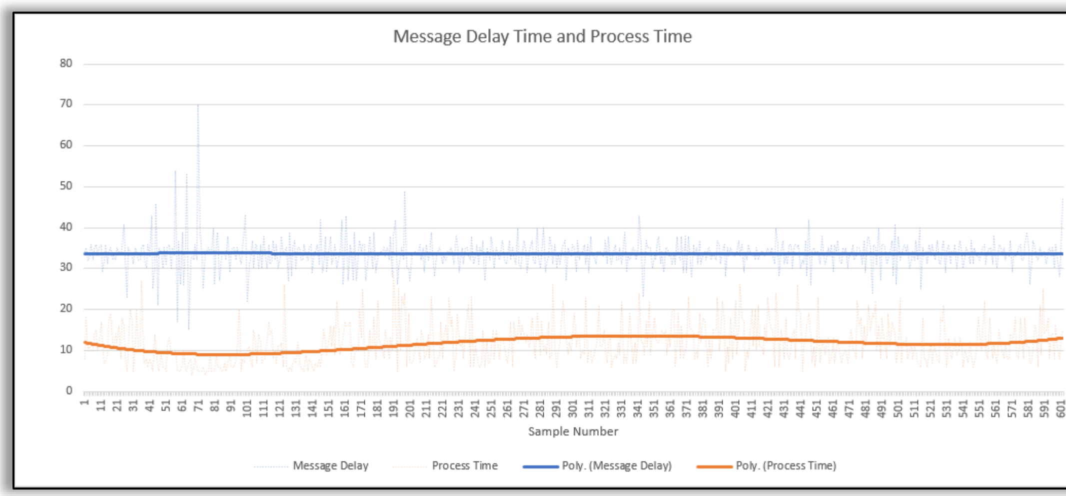


Figure 30. Message Delay Time and Process Time Results

From the Android application test results (Figure 30), processing time does not appear to have a significant effect on the message latency. This is because the Android kernel oversees scheduling the tasks, making the message latency slightly unpredictable.

Table 10. Android Benchmarking Summary

Row Labels	Average of Message Latency (ms):	Average of Process (ms):
0	33.7	11.7
1	33.3	10.3
2	33.9	13.0
3	33.4	11.5
Grand Total	**33.6**	**11.7**

The summary of the results (Table 10) also indicates that the number of markers in an image does not affect the message delay or process time.

The results show that an Android device can analyze images using ArUco marker detection and send messages via Bluetooth within 34ms on average, with a peak latency of about 70ms. Furthermore, the increase in processing time required to estimate the pose of detected markers is unlikely to have a large impact on the message latency. In conclusion, the Android application can send messages quickly enough to meet the maximum total system latency constraint of 200ms.

Although the functional prototype utilizes a USB connection for serial communications, it is clear that running the vision system on a smartphone would function correctly with comparable latency, since the latency seems to be bottlenecked by Baud rate rather than by the wireless nature of the Bluetooth connection itself. This confirms that the functional prototype is a valid demonstration of the final design, even without smartphone integration.

Prototype Modifications and Improvements

Vision System

Marker Elevation

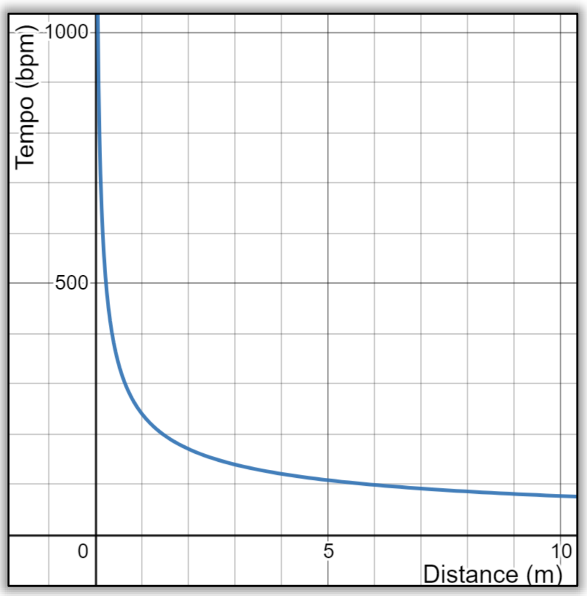
Through testing of the functional prototype, it was found that marker elevation plays a role in keeping the markers within the camera's FOV as the user approaches. An elevation of 150 cm was first attempted but was found to be a bit too high, and an elevation of 110 cm was found to be a bit too low. Thus, 130 cm is the ideal marker elevation for use of the prototype.

Haptic System

Tempo Upper Limit Change

Users reported the tempo to be too fast to recognize the pattern when close to the marker. This was due to too short of a pulse to allow a full rotation of each eccentric mass in the ERM motors, so the equation from (14) was altered to accommodate an upper limit of 240 bpm, instead of 300 bpm (16). In the resulting plot of pulse delay (Figure 31), an increase in pulse delay is seen at higher distances to support the alteration. Note that any delays greater than 500ms or less than 109ms were rounded accordingly.

$$\begin{aligned} t_{pulse\ delay} &= \frac{60000\ \text{ms}}{\cancel{1\ \text{min}}} \cdot \frac{\cancel{1\ \text{min}}}{240\ \cancel{\text{beats}}} \cdot \left(\frac{1}{2}\ \cancel{\text{beats}}\right) \cdot \sqrt{d_{Euclidean}} \\ &= (125\ \text{ms}) \cdot \sqrt{d_{Euclidean}} \end{aligned} \tag{16}$$



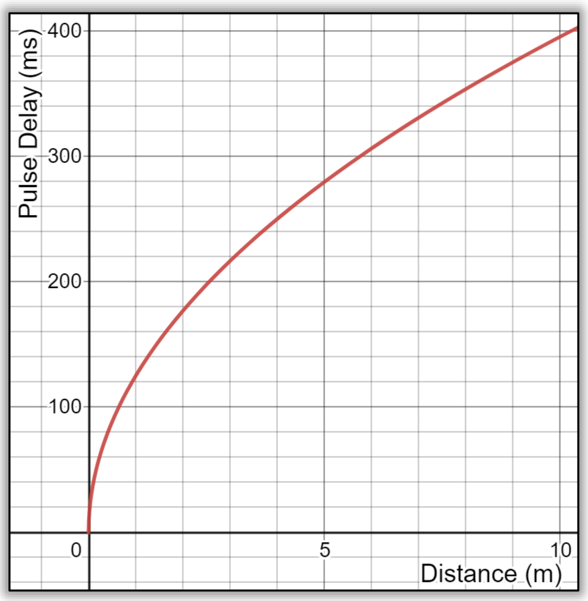


Figure 31. Plots of Tempo and Pulse Delay vs. Distance After Change

Notification of Arrival

A new pattern was implemented to notify the user that they have arrived at the POI. This occurs once the delay is less than 109 ms - meaning user is within 0.75 m (i.e., an arm's length) of the POI while also facing ± 10° towards the POI (i.e., NNE, NNN, or NNW directions for an FOV of 60), which became the success criteria of 22.3 cm allowable user positional error during functional prototype testing. The notification pattern is unique and consists of pulsing all the actuators together at the maximum tempo. It is believed that this would greatly help the user know when to stop moving forwards.

Resources and Budget

Team Resources

The team members contributed skills in project management, software development, firmware development, PCB design, electronic circuit design, electronic wearables, finite element analysis, computer vision, enclosure design, and prototype design. The faculty advisor, Dr. R. Eagleson, had expertise in computer vision for augmented and virtual reality applications.

The team had access to equipment such as a multimeter, soldering iron, hot glue gun, sewing machine, Arduino, cameras, Android phone, and computers. The team spent approximately 400 h each working on the capstone project over the course of the year.

Project Budget

The BOM for the final design includes all components used in the design process, including components which were not prototyped (Figure 32).

The BOM for the realized prototype (Figure 33) only includes components used in the construction and validation of the functional prototype and Android application.

The total cost of the prototype, excluding the cost of available equipment and including components not used in the final design/prototype, is $278.15 (Table 11). The references for these costs can be found in the BOM, and if not included in the BOM, are otherwise referenced.

Table 11. Prototype Material and Equipment Costs

Part Description	Part Number	Qty	Individual Cost (CAD)	Total
Fabric		1	$20.00	$20.00
Bluetooth Adapter	WRL-12580 (SparkFun)	1	$37.00	$37.00
ERM Device	1528-1177-ND	12	$2.70	$32.40
Haptic Motor Driver	1528-1346-ND	12	$11.00	$132.00
LRA Device	1670-1034-ND	8	$4.38 [17]	$35.04
I2C Mux	1528-1363-ND	1	$9.61 [38]	$9.61
2-pin connector cable	R9332	3	$1.10	$3.30
3x7cm tinned PCB	S2029	1	$1.55	$1.55
De-solder pump		1	$7.25	$7.25
				$278.15

Quantity	Part Number	Part Name	Manufacturer
1	A000066	Arduino Uno R3 ATmega328P Eval	Arduino
3	DRV2605L	Haptic Driver for ERM/LRA	Adafruit Industries LLC
3	1201	Vibrating Disc Motor	Adafruit Industries LLC
1	PRT-12795	Jumper Wire Male to Male 6" 20 per Pkg	SparkFun Electronics
2		cotton & polyester cloth	Fabricland
1		velcro	Fabricland
1	7365013141	Coats & Clark All Purpose Polyester Thread (123m)	Coats & Clark
3	R9332	22AWG 2pin connector cable 15cm0	Electrical & Electronic Supply Inc
1	S2030	5x7cm tinned PCB double sided	Electrical & Electronic Supply Inc
1	S2029	3x7cm tinned PCB double sided	Electrical & Electronic Supply Inc
1	1528-2182	Solderless Breadboard Terminal Strip	Adafruit Industries LLC
1	M000006	USB 2.0 Cable Type A/B	Arduino
1	BH26AASF	Battery Holder (Open) AA 6 Cell 9 Volt Snap Fasteners	Memory Protection Devices
1	MAX712CSE+TTR-ND	Controller MAX712CSE+T	Maxim Integrated
1	A129236TR-ND	1 Ohms ±5% 0.5W, 1/2W Chip Resistor 0805	TE Connectivity Passive Product
1	A126421TR-ND	150 Ohms ±1% 0.333W, 1/3W Chip Resistor 0805	TE Connectivity Passive Product
1	A103234TR-ND	68 kOhms ±0.1% 0.1W, 1/10W Chip Resistor 0805	TE Connectivity Passive Product
1	A103178TR-ND	22 kOhms ±0.1% 0.1W, 1/10W Chip Resistor 0805	TE Connectivity Passive Product
1	A103142TR-ND	10 kOhms ±0.1% 0.1W, 1/10W Chip Resistor 0805	TE Connectivity Passive Product
1	490-8043-2-ND	1µF ±10% 16V Ceramic Capacitor X7R 0805	Murata Electronics
2	587-1114-2-ND	10000pF ±10% 50V Ceramic Capacitor 0805	Taiyo Yuden
1	478-0805YC106KAT2ATR-ND	10µF ±10% 16V Ceramic Capacitor X7R 0805	AVX Corporation
1	478-7800-2-ND	Diode Schottky 20V 1A (DC) Surface Mount 0805	AVX Corporation
1	2N6107GOS-ND	Bipolar (BJT) Transistor PNP 70V 7A 10MHz 40W Through Hole TO-220AB	ON Semiconductor
1	CP-048H-ND	Power Barrel Connector Jack 3.00mm ID (0.118"), 6.50mm OD (0.256") Through Hole, Right Angle	CUI Devices
1	PA-30150W-ZMX	Outtag 12W Universal AC Adapter 3V 4.5V 5V 6V 7.5V 9V 12V Multi Voltage Switching Power Supply Cord	Outtag
5		PCBs 43mm x 28mm	PCBway
1	B3F-1020	SWITCH TACTILE SPST-NO 0.05A 24V	Omron Electronics
4	91698A713	Pack of 25 Black-Oxide 18-8 Stainless Steel Phillips Flat Head Screws M2x0.4mm Thread, 20mm long	McMaster-Carr
4	93738A263	Pack of 10 Barbed Inserts for Plastic Brass M2x0.40mm Thread, 3.9mm Installed Length	McMaster-Carr
1	WRL-12580	Bluetooth adapter	SparkFun Electronics
Equipment			
1	052-0052-2	Autoranging digital multimeter	Mastercraft
1		60/100W hot glue gun with 15pcs white glue sticks	SOONAN
1	JX1420	Brother JX1420 Mechanical Sewing Machine	Brother
1	058-6305-4	Mastercraft 25W Soldering Iron	Mastercraft
1	S1030	De-soldering pump	Electrical & Electronic Supply Inc
1		MARTISAN Sheet Music Stand Holder/Portable Folding Music Stand Super Sturdy Adjustable Height Tripod Base Metal Music Stand, Lightweight & Compact for Storage	Martisan
1	B07NWC3L95	Selfie Stick Tripod, UBeesize 51" Extendable Tripod Stand with Bluetooth Remote for Cell Phones and Cameras, Heavy Duty Aluminum, Lightweight	UBeesize
1	PW313	AVerMedia Live Streamer CAM 313 1080p HD Webcam	Avermedia
1	11200	Westcott 6-Inch Plastic 180 Degree Protractor, Clear	Westcott
1			
1	1	Etekcity Lasergrip 1080 Laser Thermometer Digital Infrared Thermometer Temperature Gun for Kitchen Cooking BBQ Grill and Bath Water, -58℉~1022℉ (-50℃～550	Etekcity

Cost per item	Description	Reference
$30.43	Microcontroller	https://www.digikey.ca/en/products/detail/arduino/A000066/2784006
$11	Breakout board	https://www.digikey.ca/en/products/detail/adafruit-industries-llc/2305/5356831
$2.70	ERM	https://www.digikey.ca/en/products/detail/adafruit-industries-llc/1201/5353637?s=N4IgTCBcDaIIYBM4DMBOBXAlgFwAQD
$2.70	jumpers	https://www.digikey.ca/en/products/detail/sparkfun-electronics/PRT-12795/5993860
$15	cloth	
$5	velcro	
$1.87	spool of thread	https://www.walmart.ca/en/ip/coats-clark-all-purpose-polyester-thread-white/6000197237011?cmpid=sem_google_en_pla
$1.10	clips (between breakout board and vibrators)	
$2.35	tinned PCB	
$1.55	tinned PCB	
$7.36	breadboard	https://www.digikey.ca/en/products/detail/adafruit-industries-llc/64/7241427?utm_adgroup=General&utm_source=google
$3.95	Arduino cable	https://store.arduino.cc/usa/usb-2-0-cable-type-a-b
$2.88	battery pack	https://www.digikey.ca/en/products/detail/mpd-memory-protection-devices/BH26AASF/470766
$9.21	controller	MAX712CSE+T Maxim Integrated | Integrated Circuits (ICs) | DigiKey
$0.54	resistor	CRGS0805J1R0 TE Connectivity AMP Connectors | Resistors | DigiKey
$0.16	resistor	CRGH0805F150R TE Connectivity Passive Product | Resistors | DigiKey
$0.87	resistor	CPF0805B68KE1 TE Connectivity Passive Product | Resistors | DigiKey
$0.87	resistor	CPF0805B22KE1 TE Connectivity Passive Product | Resistors | DigiKey
$0.87	resistor	CPF0805B10KE1 TE Connectivity Passive Product | Resistors | DigiKey
$0.37	capacitor	GCM219R71C105KA37D Murata Electronics | Capacitors | DigiKey
$0.50	capacitor	UMK212SD103KD-T Taiyo Yuden | Capacitors | DigiKey
$1.44	capacitor	0805YC106KAT2A AVX Corporation | Capacitors | DigiKey
$0.51	diode	SD0805S020S1R0 AVX Corporation | Discrete Semiconductor Products | DigiKey
$1.26	transistor	2N6107G ON Semiconductor | Discrete Semiconductor Products | DigiKey
$1.20	power jack	N4IgjCBcoEwJxVAYygMwIYBsDOBTANCAPZQDaIAzAOxhgAsVIAuoQA4AuUIAyuwE4BLAHYBzEAF9CYOAFY6iECkgYcBYmRB0A
$18.99	power plug	Smartphone/dp/B07VBKPWQL/ref=sr_1_4?dchild=1&keywords=AC+wall+adapter+10V+3mm&qid=1614476458&s=industri
$31.20	PCB	https://www.pcbway.com/orderonline.aspx
$0.40	push button	B3F-1020 Omron Electronics Inc-EMC Div | Switches | DigiKey
$0.39	screws	https://www.mcmaster.com/91698A713/
$0.71	inserts	https://www.mcmaster.com/93738A263/
$37.00	Arduino module	https://www.sparkfun.com/products/12580
$69.99	multimeter	https://www.canadiantire.ca/en/pdp/autoranging-digital-multimeter-0520052p.0520052.html?ds_rl=1283573&ds_rl=12835
$21.99	hot glue gun	https://www.amazon.ca/Sticks-Professional-Repairs-Festival-Decoration/dp/B07P46J49B/ref=sr_1_9?dchild=1&keywords=
$86.97	sewing machine	https://www.walmart.ca/en/ip/brother-jx1420-sewing-machine/6000198888634
$24.99	soldering iron	https://www.canadiantire.ca/en/pdp/mastercraft-25w-soldering-iron-0586305p.0586305.html?gclid=Cj0KCQiApsiBBhCKARI
$7.25	desolder pump	
$21.00	Music Stand	Carrying/dp/B083ZFMZRN/ref=sr_1_2_sspa?dchild=1&gclid=Cj0KCQiA-
$33.00	Tripod - Webcam	Lightweight/dp/B07NWC3L95/ref=sr_1_7?dchild=1&gclid=Cj0KCQiA-OeBBhDiARIsADyBcE7Tu7JF9iAGCxuoQ0SB-
100	Webcam	AVerMedia Live Streamer CAM 313 1080p HD Webcam (PW313) | Best Buy Canada
0.88	Protractor	https://www.amazon.ca/Westcott-6-Inch-Plastic-Degree-Protractor/dp/B000F8MFSW
8	Wall trim tool	
48.44	Thermometer	and Bath Water, -58°F~1022°F (-50°C～550°C), Yellow and Black: Amazon.ca: Home & Kitchen

Figure 32. Final Design BOM

Resources and Budget

Quantity	Part Number	Part Name	Manufacturer
1	A000066	Arduino Uno R3 ATmega328P Eval	Arduino
3	DRV2605L	Haptic Driver for ERM/LRA	Adafruit Industries LLC
3	1201	Vibrating Disc Motor	Adafruit Industries LLC
1	PRT-12795	Jumper Wire Male to Male 6" 20 per Pkg	SparkFun Electronics
2		cotton & polyester cloth	Fabricland
1		velcro	Fabricland
1	7365013141	Coats & Clark All Purpose Polyester Thread (123m)	Coats & Clark
3	R9332	22AWG 2pin connector cable 15cm0	Electrical & Electronic Supply Inc
1	S2030	5x7cm tinned PCB double sided	Electrical & Electronic Supply Inc
1	S2029	3x7cm tinned PCB double sided	Electrical & Electronic Supply Inc
1	1528-2182	Solderless Breadboard Terminal Strip	Adafruit Industries LLC
1	M000006	USB 2.0 Cable Type A/B	Arduino
1	WRL-12580	Bluetooth adapter	SparkFun Electronics
Equipment			
1	052-0052-2	Autoranging digital multimeter	Mastercraft
1		60/100W hot glue gun with 15pcs white glue sticks	SOONAN
1	JX1420	Brother JX1420 Mechanical Sewing Machine	Brother
1	058-6305-4	Mastercraft 25W Soldering Iron	Mastercraft
1	S1030	De-soldering pump	Electrical & Electronic Supply Inc
1		MARTISAN Sheet Music Stand Holder/Portable Folding Music Stand Super Sturdy Adjustable Height Tripod Base Metal Music Stand, Lightweight & Compact for	Martisan
1	B07NWC3L95	Selfie Stick Tripod, UBeesize 51" Extendable Tripod Stand with Bluetooth Remote for Cell Phones and Cameras, Heavy Duty Aluminum, Lightweight	UBeesize
1	PW313	AVerMedia Live Streamer CAM 313 1080p HD Webcam	Avermedia
1	11200	Westcott 6-Inch Plastic 180 Degree Protractor, Clear	Westcott
1			
1	1	Etekcity Lasergrip 1080 Laser Thermometer Digital Infrared Thermometer Temperature Gun for Kitchen Cooking BBQ Grill and Bath Water, -58°F~1022°F (-50°	Etekcity

Cost per item	Description	Reference
$30.43	Microcontroller	https://www.digikey.ca/en/products/detail/arduino/A000066/2784006
$11	Breakout board	https://www.digikey.ca/en/products/detail/adafruit-industries-llc/2305/5356831
$2.70	ERM	https://www.digikey.ca/en/products/detail/adafruit-industries-llc/1201/5353637?s=N4IgTCBcDallYBM4DMBOBXAlgFwAQDdMAJVObTAOwHNcBbAe23tRAF0BfIA
$2.70	jumpers	https://www.digikey.ca/en/products/detail/sparkfun-electronics/PRT-12795/5993860
$15	cloth	
$5	velcro	
$1.87	spool of thread	https://www.walmart.ca/en/ip/coats-clark-all-purpose-polyester-thread-white/6000197237011?cmpid=sem_google_en_pla_none_868545292_40527268781_None&gclsrc=aw.ds&&gclid=Cj0KCQiApsiBBhCKARIsAN8o_
$1.10	clips (between breakout board and vibrators)	
$2.35	tinned PCB	
$1.55	tinned PCB	
$7.36	breadboard	https://www.digikey.ca/en/products/detail/adafruit-industries-llc/64/7241427?utm_adgroup=General&utm_source=google&utm_medium=cpc&utm_campaign=Smart%20Shopping_Product_Zombie%20SKUS&utm_term=
$3.95	Arduino cable	https://store.arduino.cc/usa/usb-2-0-cable-type-a-b
$37.00	Arduino module	https://www.sparkfun.com/products/12580
$69.99	multimeter	https://www.canadiantire.ca/en/pdp/autoranging-digital-multimeter-0520052p.0520052.html?ds_rl=1283573&ds_rl=1283573&gclid=Cj0KCQiApsiBBhCKARIsAN8o_4iyVWQMetDiYA6dlIO1PC12T_5vwBHNmCLzQBHTDSl
$21.99	hot glue gun	https://www.amazon.ca/Sticks-Professional-Repairs-Festival-Decoration/dp/B07P46J49B/ref=sr_1_9?dchild=1&keywords=hot+glue+gun&link_code=qs&qid=1613946595&sr=8-9&tag=operasoft-20
$86.97	sewing machine	https://www.walmart.ca/en/ip/brother-jx1420-sewing-machine/6000198888634
$24.99	soldering iron	https://www.canadiantire.ca/en/pdp/mastercraft-25w-soldering-iron-0586305p.0586305.html?gclid=Cj0KCQiApsiBBhCKARIsAN8o_4hkJoXjrcvyeor9YsBOaLaUF2_ulzycuQRAylnmjuF8mo4CC4_bAdUaAkcUEALw_wcB&gcls
$7.25	desolder pump	
$21.00	Music Stand	OeBBhDiARIsADyBcE654H5F1jjSZndYEl5kLKz96aIbOfZScn2HFGZ8Z6jdQo80fyTOB4YaAnjpEALw_wcB&hvadid=221344373720&hvdev=c&hvlocphy=9001074&hvnetw=g&hvqmt=e&hvrand=9336531430173939605&hvtargi
$33.00	Tripod - Webcam	Uszm_aFkFNFrs8jlWq_aM_lvH7KwDrgUY0aAkRUEALw_wcB&hvadid=208335638623&hvdev=c&hvlocphy=9001074&hvnetw=g&hvqmt=e&hvrand=3044694439085994767&hvtargid=kwd-301592109294&hydadcr=840_94
100	Webcam	AVerMedia Live Streamer CAM 313 1080p HD Webcam (PW313) | Best Buy Canada
0.88	Protractor	https://www.amazon.ca/Westcott-6-Inch-Plastic-Degree-Protractor/dp/B000F8MFSW
8	Wall trim tool	
48.44	Thermometer	Etekcity Lasergrip 1080 Laser Thermometer Digital Infrared Thermometer Temperature Gun for Kitchen Cooking BBQ Grill and Bath Water, -58°F~1022°F (-50°C~550°C), Yellow and Black: Amazon.ca: Home & Kitchen

Figure 33. Prototype BOM

Conclusions and Recommendations

Conclusions

Summarily, the team's achievements, struggles, and future recommendations were highlighted. The vision system was able to identify and locate ArUco markers using a camera. The haptic system was able to receive positional data via the serial port, and consistently provided haptic feedback to direct the user toward the chosen marker.

Some challenges were encountered while achieving this level of functionality. Due to COVID-19 restrictions and the Android application being unnecessary to demonstrate functionality, the Android application was not integrated into the functional prototype. There were some difficulties with the FOV of the camera as the markers were not entirely in the frame when the user was very close to the marker. Additionally, the device has a manageable learning curve, and different individuals may prefer different feedback parameters.

Challenges aside, the team was highly satisfied with the prototype's ability to demonstrate the concept, and the concepts capacity to fulfill the problem definition. A novel solution was designed that guides a PWB to a POI in their immediate vicinity; a task that would have previously been extremely difficult or impossible. The prototype enabled every blindfolded test subject to accomplish this task without visual cues, auditory cues, assistance from a sighted person, or environmental contact.

Recommendations

With these conclusions in mind, the following recommendations are made:

A higher-FOV camera would keep markers in frame at shorter distances as the user approaches the POI. Although the camera from the user's smartphone can be utilized, a dedicated camera could be included in the final design to ensure sufficiently high FOV. This would also eliminate the need user camera calibration.

Another solution would be to use marker-to-marker pose estimation. This would require the markers' positions relative to each other to be known, but it would enable guidance to any marker in the system provided that any other marker is in the camera's FOV.

A training module would also be useful, allowing individuals to practice in a known environment with support staff on standby. Finally, further refinement of the haptic feedback system could be done to reduce the learning curve and increase feelings of precision and responsiveness. This could go as far as customizable haptic feedback profiles designed to suit each PWB's individual preferences.

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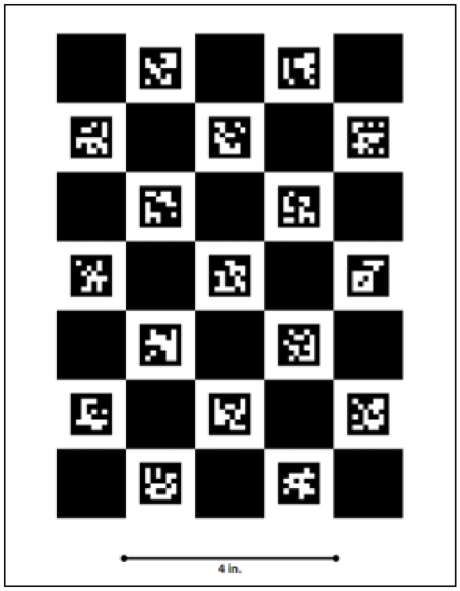
Appendix I: Camera Calibration Instructions

Getting Started: Camera Calibration

This is the ChArUco board used to calibrate the camera. It must be printed and the length at the bottom checked to ensure it is the proper size to correctly calibrate the camera for the system.



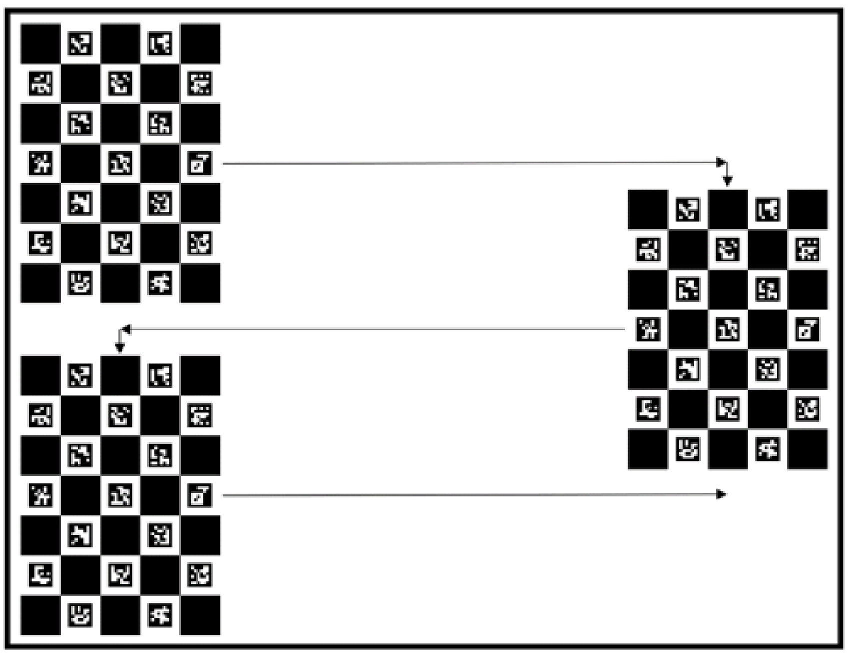
When the system is first installed, it will ask to calibrate the camera. When the prompt appears, please print the document titled "Calibration_Printout.pdf" and ensure that the bar at the bottom of the page is 4 inches. If not, please ensure the print settings are set to scale the file at 100% before printing again.

Once this file has been printed, attach it to a rigid, flat object. This will be used to move the pattern in front of the camera and calibrate it. At the end of each step of calibration, a prompt will ask if you believe you were able to complete the motions described below. If not, you may select "Retry" to record the step again. If you believe you were able to successfully capture the movement outlined in the given step, please select "Continue". At the end of the calibration process, it will ask if you wish to complete the calibration. Select "Retry" to redo the previous step or select "Continue to complete calibration. Please note that this may take several minutes.

Phase 1: Parallel ChArUco Board

Hold the board parallel to the lens of the camera and slowly move in the pattern below:

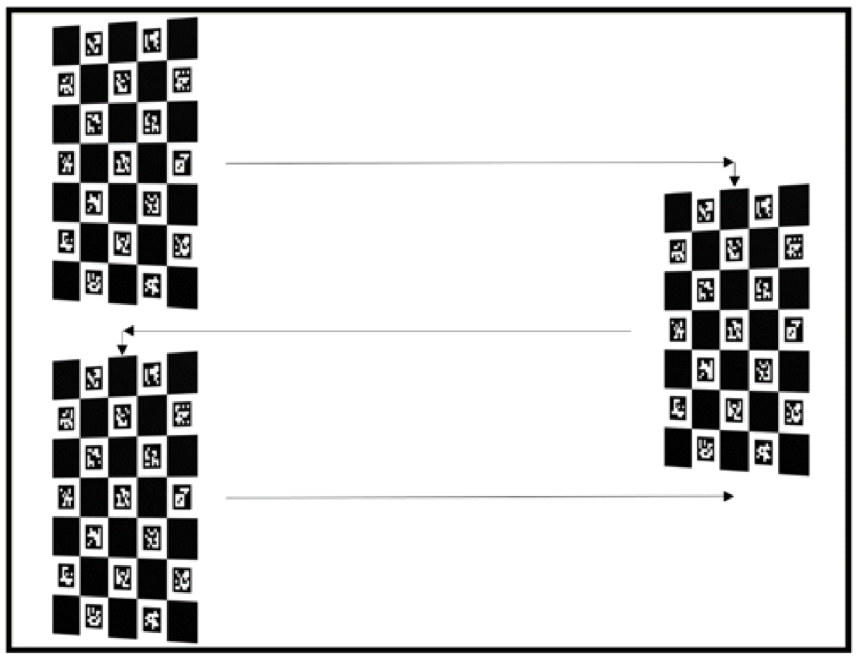
Top View:



Phase 2: Positive Yaw

Next hold the board at a 45-degree angle to the camera and move the board around the camera's field of view as seen below:

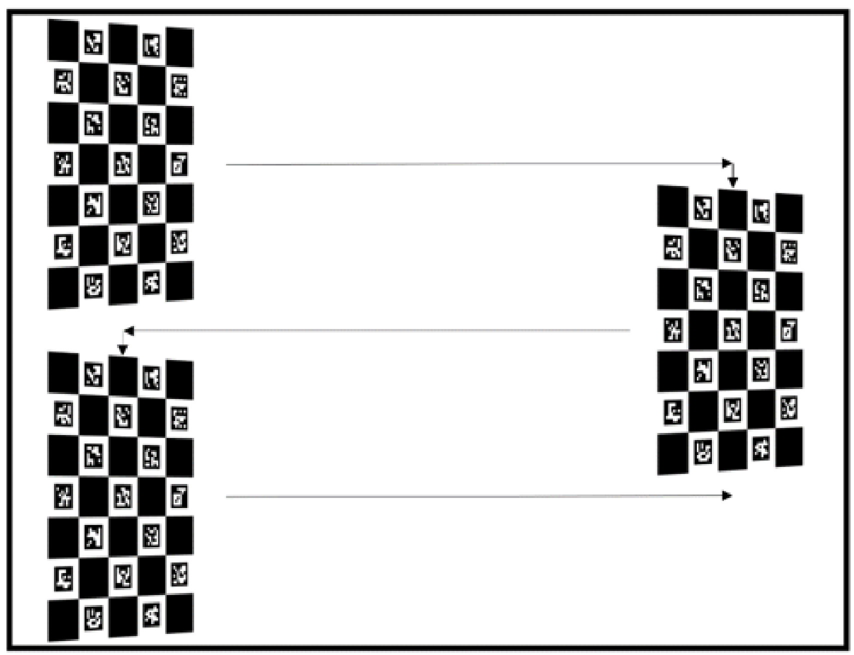
Top View:



Phase 3: Negative Yaw

Shift the board so it has about a 45-degree angle such as in the diagram below, and repeat the process of moving it through the camera's field of view:

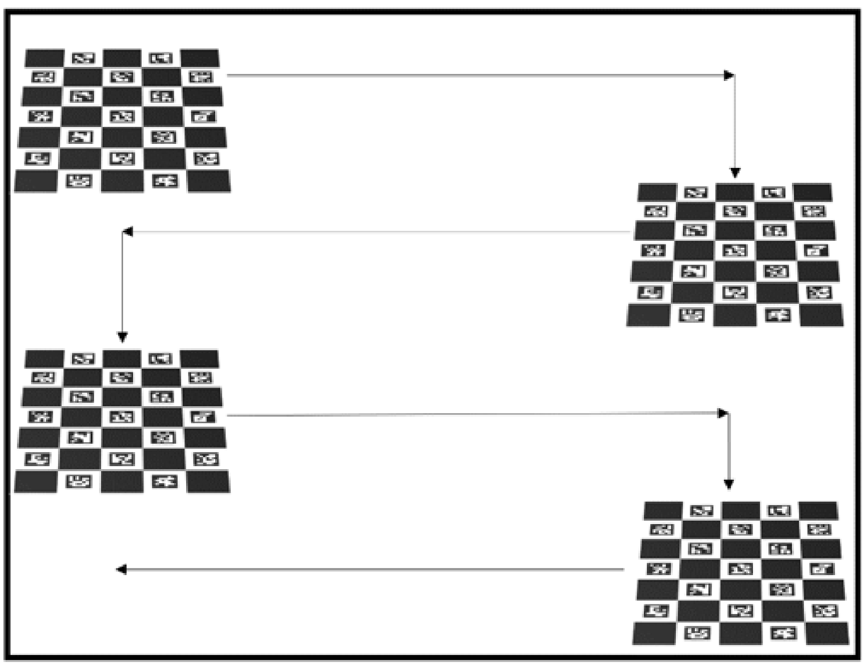
Top View:



Phase 3: Positive Pitch

Shift the board so that it forms a 45-degree angle to the camera as shown below, and move it in the indicated pattern:

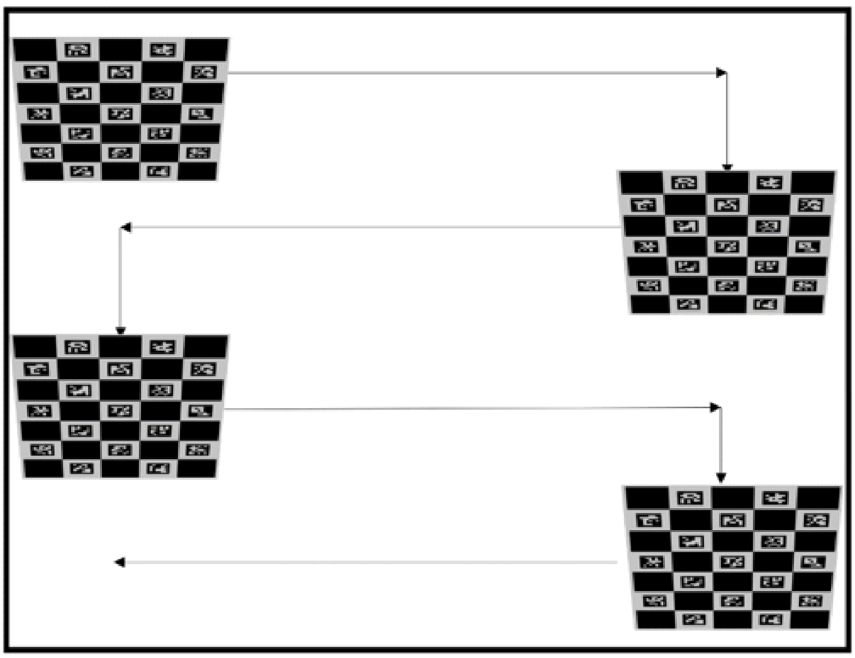
Side View:



Phase 4: Negative Pitch

Shift the board once more to form a 45-degree angle as shown below, and move it in the indicated pattern:

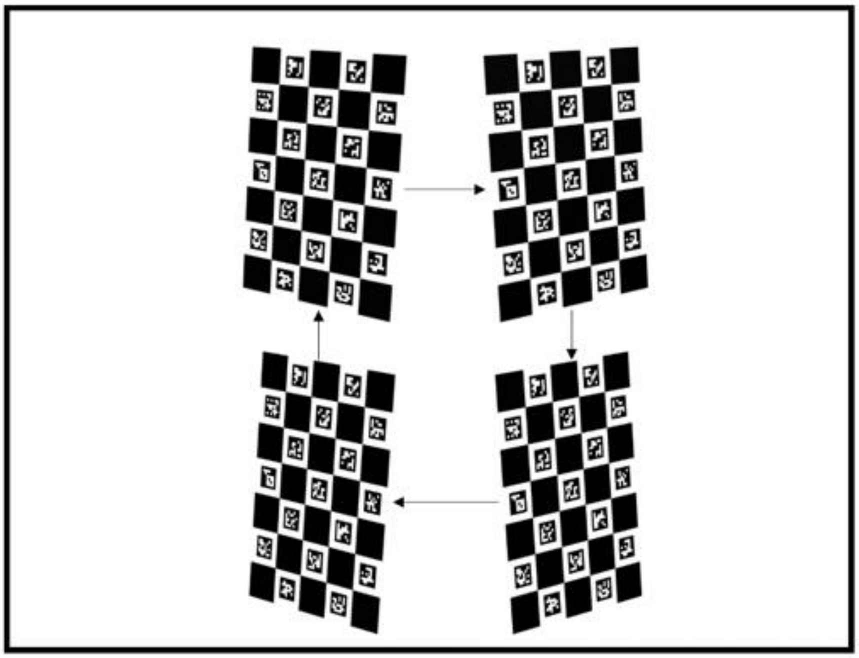
Side View:



Phase 5: Maximum Perspective

Move the board so that one corner is closest the screen and the opposite corner is furthest from the camera. Repeat this process for all four corners.

NOTE: If not enough images have been captured at this point, continue moving the board as described above until the system automatically finishes the calibration process.



Appendix II: Marker Installation Instructions

Marker Installation Instructions

To set up this system for your school, you must first assign names to some of the markers you will be posting around your school. There is a pre-set library that you may edit to accommodate the needs of your school, but you may create your own. There are 1000 markers available to identify objects within your school, and all you need to do is name them within your school's database. An example of markers that have been assigned labels are in *Table 3: Marker Naming Scheme*.

Table 3: Marker Naming Scheme

ID#	Label
1	Sink
2	Toilet
3	Urinal
4	Water Fountain

An example marker database that demonstrates how the marker dictionary's IDs can be assigned to locations and facilities within a school are in *Table 4: Example Marker Database for School*.

Table 4: Example Marker Database for School

ID# Range	Labels
0-199	Common Objects and Locations (Bathroom door, water fountain, etc.)
200-499	Classroom doors
500-999	Locker Numbers

The specific name of each label can be viewed and changed as needed through your school's administrative account. To print any given marker, please ensure the scale of the page is set to 100% and it is printed on standard 8.5" × 11" paper. To check the marker is the correct size, measure the bar located at the bottom of the page. If it is the same length as labeled, you have printed it correctly. If not, you will need to adjust your printer's settings and try again.

When the marker is placed within the building, make sure the arrow is pointing up and the marker is level on the wall. This will prevent any problems that may occur when finding the marker with the vision system.