

CIS Software Manual

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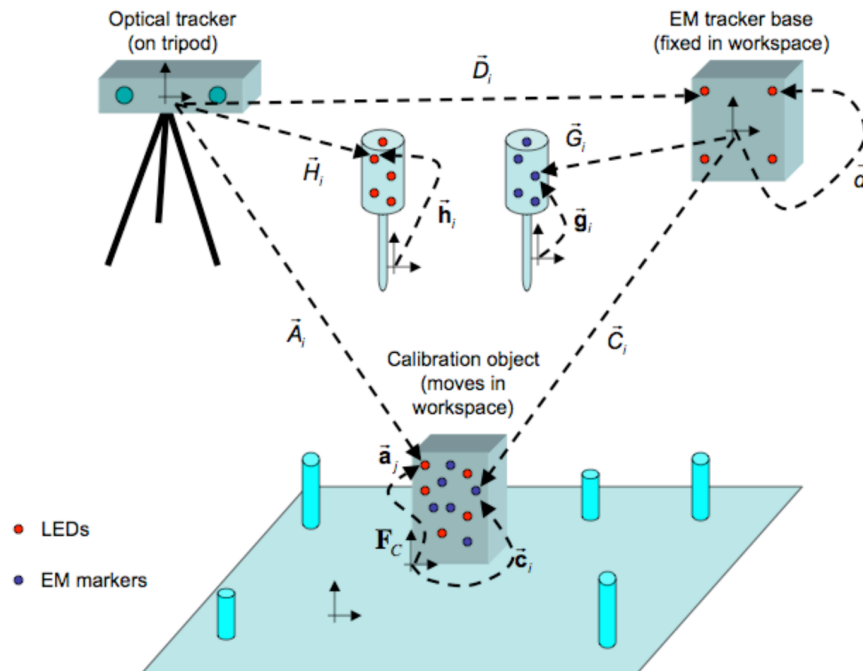
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1 Introduction

1.1 PA1

The purpose of PA1 was to develop an algorithm for 3D point set to 3D point set registration and pivot calibration. The problem involved a stereo tactic navigation system and an electromagnetic positional tracking device. Tracking markers were placed on objects so the optical tracking device and an electromagnetic tracking device could measure the 3D positions of objects in space relative to measuring base units. These objects were then registered so that they could be related in the same coordinate frames. Pivot calibration posts were placed in the system so pivot calibration could be performed and the 3D position of two different probes could be tracked throughout the system. The diagram below from the assignment document gives a visual description of the system.



1.2 PA2

PA2 built upon the same setup as PA1 but with two additional steps. The first step was the development of a distortion calibration algorithm that would be used to model and dewarp the EM tracker frame transformations. We then used this dewarped EM tracker space to repeat our pivot calibration calculations. The second step involved computing the CT to EM tracker registration. The locations of several fiducial pins were determined using the EM tracked probe.

Then point cloud to point cloud registration was performed between these fiducials in EM tracker space and in CT space to compute the registration.

2 Mathematical Approach

2.1 Point Cloud Registration

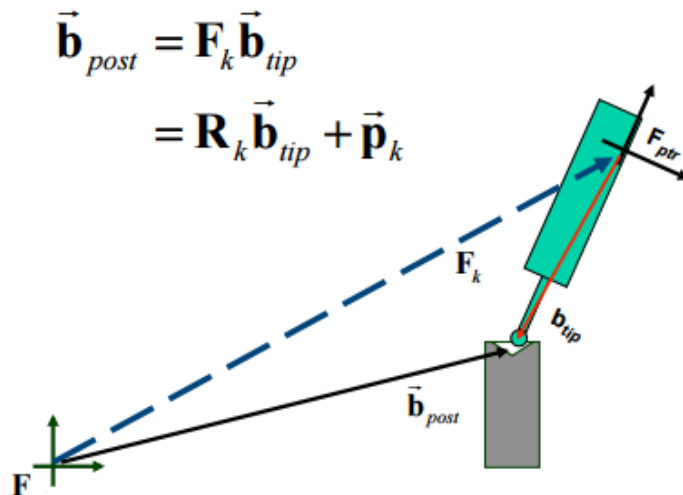
A number of least squares methods could be used to determine a transformation matrix for a 3D point set registration. We chose a solution from 'A Method for Registration of 3-D Shapes', by Besl and McKay, 1992. We seek to solve for R and t , in the equation $B = R \cdot A + t$, where (R, t) are transforms applied to the dataset A to align it with dataset B , as closely as possible. Finding the optimal rigid transformation matrix can be broken down into the following steps:

1. Find the centroids of both datasets
2. Bring both matrices to the origin then find the optimal rotation, R
3. Find the translation t

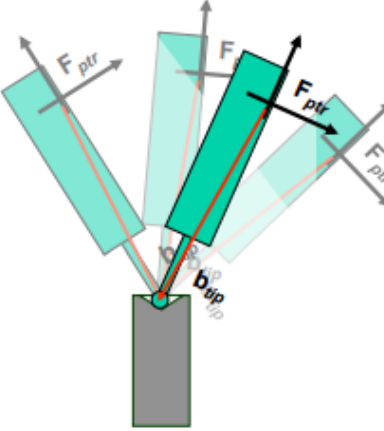
The centroids are simply found by calculating the average (x,y,z) values for each point in datasets A and B . To find the optimal rotation, we make use of singular value decomposition. SVD decomposes the matrix into three other matrices, such that $[U,S,V] = \text{SVD}(E)$, and $E = USV^t$. We first re-center both datasets so that both centroids are at the origin, removing the translation component. We then accumulate matrix H , and solve for $[U,S,V] = \text{SVD}(H)$, and find the rotation matrix $R = VU^t$. The translation is $t = -R \cdot \text{centroid}(A) + \text{centroid}(B)$.

2.2 Pivot Calibration

To perform pivot calibration, we need to simultaneously determine the location of the fiducial post b_{post} and the position of the tip of the tracked tool b_{tip} . We use a least squares method to solve for these values simultaneously. This method requires the transformation, F_k between the tracker and the tool for each of the k frames of data, which we determine using our point cloud registration technique between the tracker and the fiducials placed on the tool.



To determine the local tool frame, we first compute the midpoint of all the fiducial locations, G_i , in the tracker frame. This gives us a reference, g_0 , from which to localize all the other fiducial locations. Once all the g_i are localized we compute the transformation between the g_i and the G_i for each frame k of data to get a set of F_k . We then solve the below least squares problem to solve for b_{post} in the tool frame and b_{tip} in the tracker frame.

$$\begin{bmatrix} \vdots & \vdots & \vdots \\ \mathbf{R}_k & -\mathbf{I} \\ \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} \bar{\mathbf{b}}_{tip} \\ \bar{\mathbf{b}}_{post} \end{bmatrix} \equiv \begin{bmatrix} \vdots \\ -\bar{\mathbf{p}}_k \\ \vdots \end{bmatrix}$$


The diagram illustrates a surgical tool with a central handle and several articulated arms. Each arm is shown in a different frame, represented by a light blue parallelogram. Force vectors are shown acting on these frames: F_{ptr} (purple) and F (black). A red vector $\bar{\mathbf{b}}_{tip}$ originates from the base of the tool, representing the tip position in the tracker frame. The tool is shown in a vertical orientation, with the handle at the bottom and the arms extending upwards.

2.3 Distortion Calibration & Correction

In PA1, we took the naive approach, ignoring possible distortion in our EM tracker frame. In PA2 we address this problem. There are several methods for modelling distortion including Bezier curves, B-Splines, and Bernstein polynomials. We used the Bernstein polynomial approach. n^{th} order Bernstein polynomials are defined as follows:

$$B_{n,\nu}(x) = \binom{n}{\nu} x^\nu (1-x)^{n-\nu}, \quad \nu = 0, \dots, n.$$

Bernstein polynomials have good numerical stability when x is between 0 and 1, which is easy to guarantee by using a “bounding box” to scale the set of points using the maximum and minimum distance values in each direction. Each point x is bounded into a new point u as follows:

$$\vec{\mathbf{u}} = \frac{X - X^{\min}}{X^{\max} - X^{\min}}$$

Before we can correct and dewarp our EM tracker we must first calibrate the Bernstein polynomial coefficient matrix. To do this you need a set of “ground truth” points p_s that are known and a set of distorted points u_s as measured by the EM tracker.

Then we must come up with the following least squares formulation to solve for the c_{ijk} Bernstein polynomial coefficients:

$$\begin{bmatrix} F_{000}(\vec{u}_s) & \cdots & F_{555}(\vec{u}_s) \end{bmatrix} \begin{bmatrix} c_{000}^x & c_{000}^y & c_{000}^z \\ \vdots & \vdots & \vdots \\ c_{555}^x & c_{555}^y & c_{555}^z \end{bmatrix} \cong \begin{bmatrix} p_s^x & p_s^y & p_s^z \end{bmatrix}$$

Where each F_{ijk} is defined as follows:

$$F_{ijk}(u_x, u_y, u_z) = B_{5,i}(u_x)B_{5,j}(u_y)B_{5,k}(u_z)$$

Solving the previous least-squares problems yields coefficient matrix \mathbf{C} that can be used to correct for distortion. Given a new set of distorted points q_s we first scale them to a new set of points u_s using the same “bounding box” as earlier. Then for each u_s we compute its corresponding corrected point p by computing the following:

$$\vec{p} = \sum_{i=0}^5 \sum_{j=0}^5 \sum_{k=0}^5 \vec{c}_{i,j,k} B_{5,i}(u_x)B_{5,j}(u_y)B_{5,k}(u_z)$$

2.4 CT Fiducial Registration

After calibrating the Bernstein polynomial coefficient matrix, we corrected our set of tracker measurements and repeated our pivot calibration following the method described in 2.3. For calculating the location of the other k fiducial pins we had a single frame of data, G_k per pin. We computed the frame transformation F_k between the original pivot calibration data and the new G_k data and then applied this transformation, F_k , to the original pivot location to find the location g_k of the k^{th} fiducial pin. At this point we have the coordinates of the k fiducial pins in the EM tracker frame, g_k , and also the coordinates of the fiducial pins in CT space, b_k . From this we just compute the point cloud to point cloud registration to compute the transformation between CT space and the EM tracker frame, F_{reg} . This F_{reg} is used to compute the location of the EM tracked in CT space for any arbitrary position.

3 Algorithmic Approach

3.1 Parsing

Our program was developed in Python. The Numpy library was used as a Cartesian math package for 3D points, rotations, and frame transformations. The linear algebra package `numpy.linalg` was also used for matrix operations including determinants and inversions. The first step was to develop a parser that could interpret and load the provided data. The parser for each file observes the first line of the file to determine the number of elements and frames for the dataset. It then iterated through the dataset line by line, accumulating arrays where each element represents a 3-dimensional point. These arrays are stored as numpy arrays, allowing for numpy functions and transformations to be applied.

3.2 Point Cloud Transformation

We next developed the algorithm for point cloud to point cloud registration, and determining the rotation and translation components of the transformation between them. As covered above, the function uses singular value decomposition to separate the R and t elements of the transformation. We first load in both point clouds, represented as numpy arrays. The centroids of each array are determined by finding the mean of the $[x,y,z]$ values of each element in the arrays. These mean values are then subtracted from every point in each array to localize the arrays and determine the rotation component. Numpy's `linalg.svd` function is used to decompose H into U , S , V , and R is then calculated as the multiplication of V and U . The translation t is then calculated as $-R * \text{centroid}(A) + \text{centroid}(B)$, using the `numpy.dot` function to calculate matrix dot products. These R and t values are then rounded and returned by the function.

3.3 Pivot Calibration

Both the EM pivot calibration and the Optical pivot calibration are solved using the same function `calibrate_pivot()`. For the optical pivot calibration there is a wrapper around `calibrate_pivot()` called `opt2em_calibrate_pivot()` that translates the optical fiducial locations from the optical tracker frame to the EM tracker frame before performing the pivot calibration. In essence, `calibrate_pivot()` performs the same tasks as mentioned above for pivot calibration. A set of points describing the locations of the fiducial trackers on the tool in the tracker frame are localized by first computing the midpoint of the set of midpoints using `compute_midpoint()`, and then creating a new set of points where each point is the original tracker frame point with the location of the midpoint subtracted from it using `localize()`. Then point cloud to point cloud registration is performed between these two sets of points to get the transformation from tracker to tool for this frame of data.

Once the frame transformation has been calculated for each frame of data, the frames are formatted into a matrix according to the following graphic by the `pivot_calibration()` function:

$$\begin{bmatrix} \vdots & \vdots \\ \mathbf{R}_k & -\mathbf{I} \\ \vdots & \vdots \end{bmatrix} \begin{bmatrix} \vec{\mathbf{b}}_{tip} \\ \vec{\mathbf{b}}_{post} \end{bmatrix} \cong \begin{bmatrix} \vdots \\ -\vec{\mathbf{p}}_k \\ \vdots \end{bmatrix}$$

Once the R and p matrices are assembled, we call Numpy's lstsq() function to solve the least squares problem. It returns a vector b that contains the $\vec{\mathbf{b}}_{tip}$ and $\vec{\mathbf{b}}_{post}$ solutions.

3.4 Distortion Calibration & Correction

Distortion calibration is done using the `calibrate_distortion()` function. It takes in a set of ground truth points p, a set of distorted points q, and the order of the Bernstein polynomial to use which has a default value of 5. First q is bounded between 0 and 1 with a call to `ScaleToBox()` which takes as an argument q, as well as q_{min} and q_{max} and returns a bounded set u. Then we iterate through each point u_s in u and compute the F_{ijk} as described in 2.3. For each point u_s we compute an array of $n^3 F_{ijk}$, where n is the order of the Bernstein polynomial. Each array of F_{ijk} is concatenated vertically to create a $s \times n^3$ matrix called **F**. Then we solve the least squares problem $\mathbf{FC} = \mathbf{p}$ for **C** which is our Bernstein polynomial coefficient matrix.

Now that we have **C** we can correct the distortion in other sets of data using `correct_distortion()` which takes as arguments a set of distorted points q, the previously calculated matrix C, and the q_{min} and q_{max} bounds that we originally calculated **C** with. First we create a bounded set u from q just like we did for the calibration. Then we iterate through each point u_s in u calculating the corrected point p according this equation as mentioned in 2.3:

$$\vec{\mathbf{p}} = \sum_{i=0}^5 \sum_{j=0}^5 \sum_{k=0}^5 \vec{\mathbf{c}}_{i,j,k} B_{5,i}(u_x) B_{5,j}(u_y) B_{5,k}(u_z)$$

This set of points p will be the set of distortion-corrected points.

3.5 CT Fiducial Registration

The first step in CT registration is to repeat the pivot calibration using our distortion corrected data, which we do by calling `em_pivot_calibration()`. Then we iterate through the k data frames to determine the locations g_k of the fiducial pins in EM tracker space. For each data frame G_k we compute the frame transformation F_k between G_k and the set of data G used for the pivot calibration using `get_transform(G, G_k)`. Then we apply this transform F_k to the location of the fiducial pin used for pivot calibration to get the location of the new fiducial pin in EM tracker space. This is done using `transform_3D()`.

Then we simply call `get_transform()` to compute F_{reg} between the set of fiducials in EM tracker space g_k and the set of fiducials in CT space b_k . This transformation F_{reg} is then used to compute the CT coordinates of the EM tracked tool tip for a set of orientations. This transformation calculation is handled by the function `get_tip_coordinates()` which first transforms the new orientation of EM tracked tool into the frame used for pivot calibration, and then transforms that into CT coordinates.

4 Structure of Program

The functions making up the assignment 1+2 implementation are as follows, with the newly implemented functions in **bold**:

p1_driver	The main function for program 1. Loads in each of the datasets, performs pivot calibration and point cloud transformations. Creates and populates output files for evaluation.
p2_driver	The main function for program assignment 2. Loads each of the datasets, performs pivot calibration and point cloud transformations, as well as computing and applying distortion correction. Creates output files in the format of assignments 1 and 2.
read_cal_readings	Reads the cal_readings file into a numpy array dataset.
read_cal_body	Reads the cal_body file into a numpy array dataset.
read_em_pivot	Reads the em_pivot file in a numpy array dataset.
read_opt_pivot	Reads the opt_pivot file into a numpy array dataset.
get_transform	Takes in two matrices A and B. Determines the rotation matrix R and translation component t such that $B = R \cdot A + t$, and returns R and t.
calibrate_pivot	Takes in the em_pivot dataset G, the set of points where the tool is in contact with a fiducial pin. Returns p_tip, the vector from the tool frame to the end of the tool, and p_post, the vector from the EM base frame to the top of the fiducial post.
compute_midpoint	Called by calibrate_pivot, returning the mean points [x, y, z] of the input array.
localize	Called by calibrate_pivot, returning a numpy array with the mean points [x,y,z] subtracted from each point element.
opt2em_calibrate_pivot	Calculates the transform between the EM and Optical tracker for each frame of data.
p1_tests	Runs unit tests on the dataset loading, transformation, and pivot calibration functions to ensure they're working properly outside of the final output.
p2_tests	Runs unit tests on the new dataset loading, transformation and pivot calibration, as well as the distortion correction functions.
calibrate_distortion	Creates a coefficient matrix for n^{th} -order Bernstein polynomial

	distortion correction. Requires a ground truth data set and a corresponding distorted data set.
correct_distortion	Given a previously calculated Bernstein polynomial coefficient matrix, corrects for the error in a set p of EM tracked points.
get_tip_coordinates	Computes the location of the tool tip in CT coordinates after both pivot calibration and registration has been performed.

These functions have been organized into the following files:

p1_driver.py	The driver for PA1, producing output files.
p1_tests.py	Contains the unit tests for all core functions of PA1.
read_datasets.py	Contains all dataset parsing functions.
transformation.py	Contains all point cloud transformation functions.
calibrate_pivot.py	Contains all pivot calibration functions.
p2_driver.py	The main driver for PA2, producing output files.
p2_tests.py	Contains the unit tests for all core functions of PA2.
correct_distortion.py	Contains all functions for distortion calibration and correction

Assignment 2 Run Instructions

Additionally, data and output folders contain all input datasets, and all output produced for each of these datasets, respectively. To run the program on all datasets at once, navigate to the source folder, and enter:

```
python p2_driver.py
```

Then, refer to the output folder to find all generated output files. Each output-1 file contains the em and opt pivot calibration position estimates as the second and third lines. The remaining lines cover the expected values C for each point and frame in the respective dataset. Additionally, each output-difference file lists the difference between the expected and true C values for each of the datasets.

The assignment 2 driver also produces output-2 files for each of the datasets. These display the positions of the probe tip in CT coordinates, corresponding to the frames of data in the em-nav files for each dataset. These have been compared against the provided output-2 files for evaluating the program.

Extensive comments have been provided in each of the source files to outline the structure and flow of the program. The driver iterates through each of the 10 provided datasets in assignment 2, each time setting the names of each of the dataset components and loading them into the system as a numpy array. The EM and Optical pivot calibration functions are then called, with their values stored to be printed in the output file. The C values are then iterated through frame by frame, with the expected Cs calculate through get_transform and appended to the final expected C list. Finally, output files are generated and saved in the output folder.

Then, moving on to the requirements of assignment 2, the distortion correction function is built using the calibrate_distortion as described in the analytical breakdown above. We then use this corrected distortion to repeat pivot calibration for the EM probe, by running correct_distortion followed by calibrate_pivot. Next, we compute the registration frame Freg by determining the transform between the CT image and the EM tracker. Finally, we compute the EM tracked tool's coordinates in the CT image by iterating through the frames of EM_Nav. The new output-2 files contain the calculated positions of the probe in CT coordinates, and are filled following the completion of the driver algorithm for each dataset.

To run the program's unit tests, navigate to the source folder and enter:

```
python p2_tests.py
```

All unit tests have been found to pass properly, as outlined in the next section.

External Libraries

As stated above, the NumPy library was used as our Cartesian math package. The specific submodules of NumPy used were np.linalg, np.matrix, and np.testing.

5 Results and Discussion

5.1 Programming Assignment 1

Validation

We used several approaches to ensure the validation and accuracy of our program. Methods were developed incrementally, first verifying that dataset input and matrix generation was working as intended, before moving on to point cloud transformations and ultimately pivot calibration. To assess the accuracy of our final output, we generate not only an output1.txt file for each dataset, but also an output-difference.txt for each file to determine the accuracy of our C expectations. Pivot calibration output was also compared against the auxiliary files for each of the debug datasets. In addition to assessing final output, unit tests were written to ensure the accuracy of the program's subroutines. These include the dataset input, determining the rotation and translation matrices during point cloud registration, producing expected values from given transformations, and validating the pivot calibration output.

Point Cloud Registration

We have been able to ensure that point cloud registration is working properly by finding the transformation of one point cloud to another and then the opposite. Multiplying these two transformation matrices together resulted in an identity matrix, as was expected. We also tested the input data set, ensuring that our final output was within a reasonable tolerance range.

Pivot Calibration

The position of the tip of the probe when calibrated by RM gave results very similar to those listed in the auxiliary files for each dataset, well within our tolerance range. For further information on testing, please refer to the p1_tests.py file in the source folder. To view our output for each dataset, refer to the output folder.

Unknown Data Summary

The following table covers the em and opt pivot estimations, and average difference between the expected and listed C points, for each of the unknown datasets:

Dataset	EM Pivot	Optical Pivot	C Difference
unknown-h	[188.238, 231.994, 215.170]	[398.694, 393.650, 203.851]	20.525
unknown-i	[190.662, 204.362, 210.669]	[396.570, 398.576, 204.645]	17.336

unknown-j	[192.482, 194.217, 200.665]	[390.077, 397.445, 195.166]	16.636
unknown-k	[201.905, 187.854, 197.049]	[398.649, 412.293, 197.833]	16.509

For the debugging datasets where an auxiliary file was provided we were able to compare our EM and Optical pivot outputs against the provided coordinates. It was found that our output coordinates were very accurate, as shown below:

Dataset	EM Pivot	Optical Pivot
debug-a-out	[191.74, 200.48, 198.22]	[401.57, 392.03, 191.57]
debug-a-aux	[191.72, 200.48, 198.22]	[401.60, 392.03, 191.59]

Results were found to be similarly accurate for each of the output datasets. For further information, please refer to the driver's output in the output/ folder.

5.2 Programming Assignment 2

Distortion Correction

In addition to the previous unit tests from assignment 1, new unit tests have been added to verify that the `calibrate_distortion` and `correct_distortion` are working correctly. A distortion function may be applied to a dataset, followed by calling the distortion functions, and checking that the output is within a threshold of the initial pre-deformation dataset. Additionally, the `test_correct_distortion` function checks that the final probe tip positions in CT coordinates are within an error threshold of the output values provided. Here, our metric for error is the relative difference between our calculations and the debug output files. It was found that each individual point coordinate has a less than 20% difference from the debug output, with the vast majority of points having well below a 5% difference error.

For the assignment 2 datasets, error sources and propagation can come from a variety of sources, including EM distortion, EM Noise, and OT jiggle, as covered in the assignment outline. While we were able to account for the EM distortion through our distortion correction functions, it is expected that some amount of EM Noise, distortion, and jiggle will be propagated throughout the system that we are unable to account for. For instance, if both the optical and EM tracker are off with a common distortion component, this could cause the Bernstein curve to misestimate the actual curve, and consequently cause the registration between the CT scan and the other sensors to have a higher error.

Unknown Data Summary

The following tables list the estimated probe tip positions in CT coordinates returned by our p2_driver for each of the unknown datasets.

Dataset	Nav Point 1	Nav Point 2	Nav Point 3	Nav Point 4
g	119.01, 31.06,65.27	98.11, 171.4, 59.15	87.41, 131.41, 91.54	79.61, 96.98, 116.09
h	159.03, 119.39, 66.38	127.7, 103.74, 60.28	141.38, 152.01, 76.38	162.08, 162.18, 151.88
i	82.75, 38.98, 78.32	86.64, 29.3, 49.23	115.25, 109.68, 21.02	129.62, 171.1, 164.75
j	40.68, 66.52, 106.67	34.01, 109.05, 157.35	102.52, 157.02, 32.65	160.69, 28.51, 137.32

Each of these nav point coordinates was compared against the output file for each debugging dataset, and were also tested to be within a threshold of the output in the test_correct_distortion function, leading us to conclude the program was functioning properly. Assignment 1 and 2 outputs for each of the assignment 2 datasets may be found in the output/ folder.

6 Additional Information

This program was developed collaboratively by Josh Shubert and Nathan Smith, with the vast majority of the program written together. Nathan covered most of the file input and output, while Josh covered most of the pivot calibration functions, however all files were developed with input from both members. For programming assignment 2, all coding was completed together.