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GESTURE RECOGNITION AND MIMICKING IN A HUMANOID ROBOT

By

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Thesis

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Professor Richard A. Peters II

Professor D. Mitchell Wilkes

To my mother and father who have always supported me in everything I have every wanted to do

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My family, of course, has always been truly loyal. While it goes without saying, I would like take this opportunity to thank them for their unending support and say that I love them. My father, Brian, whose footsteps I have followed, has provided me with the greatest of role models. My mother, Margo, has always had my best interests at heart and continues to do anything, and everything, she can to encourage me in my varied endeavors. To the rest of my family I thank you as well. To grandparents, aunts, uncles, cousins, and my brother, you have always supported me and it has shaped who I have become.

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research, but in my life as a whole. I am continually impressed by the effort he puts into helping others and the selfless attitude he takes towards his student's wellbeing, putting them ahead of himself.

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LIST OF ACRONYMS

Acronym	Meaning
.CPP	C++ source (file)
.H	c++ Header (file)
2D	2-Dimensional or 2-Dimensions
3D	3-Dimensional or 3-Dimensions
ADC	Analog to Digital Converter
BGR	Blue Green Red
BMP	BitMaP
BNC	Bayonet Neill-Concelman
CCD	Charge-Coupled Device
CPU	Central Processing Unit
DAC	Digital to Analog Converter
DLL	Dynamic-Link Library
EOF	End Of File
FOV	Field Of View
FPS	Frames Per Second
FT.	FeeT
GB	GigaByte
GUI	Graphical User Interface
HSV	Hue Saturation Value
IN.	INches

IPL	(intel's) Image Processing Library
IPP	(intel's) Integrated Performance Primitives
ISAC	Intelligent SoftArm Control
NN	Neural Network
OpenCV	(intel's) Open Computer Vision (library)
PC	Personal Computer
PCI	Peripheral Component Interconnect
PID	Proportional-Integral-Derivative
PPT	PowerPoinT (presentation)
RAM	Random Access Memory
SVM	Support Vector Machine
WRT	With Respect To
XML	eXtensible Markup Language

CHAPTER I

INTRODUCTION

Humanoid robots generally have manipulators that approximate human extremities [11,36, 46]. Their “arms” often have many degrees of freedom and can approach a task, such as grasping, in a variety of ways. This complexity has made it necessary for researchers to come up with generalized ways to abstract movement, control, and teaching. It is simply too complicated, and time consuming, to attempt to control every joint, muscle, or servo individually all the way up the chain of command [26]. The process of compartmentalizing control signals is very common in programming of all types. The issue of movement, and its associated control, has given rise to many control algorithms such as Neural Networks [22], Fuzzy Logic Controllers [5], and Machine Learning Controllers [16]. All of these controllers have to be tuned and trained in order to be able to accurately translate theoretical coordinates and trajectories into actual, physical, movements. This training generally involves the robot working through a set of movements and creating a mapping relating what control signals were asserted to what movement was observed. These techniques allow the user to know, with varying degrees of accuracy, how the robot will respond to a set of control signals but they do not overcome the problem of efficiently teaching the robot new skills and movements. To address this problem, a robot must first have the capability of

observing and understand human gestures. This particular sub-problem is what this thesis aims to address.

I.1. Problem Statement

At Vanderbilt University resides a humanoid robot named ISAC. ISAC has stereo vision and two manipulators, powered by McKibben artificial pneumatic muscles, which approximate human arms. The goal of this work is the creation of a system by which ISAC will gain the ability to track the gestures made by the moving hands of a human being and then repeat those gestures back to the human operator as best he can given his own limited workspace and movement capabilities. This ability will support experiments in Imitation Learning.

It was important that the system require as little extraneous equipment as possible. A sub-goal was to have this system be able to interact with an untrained operator. Several other projects similar to this one used encoders mounted directly to user's arms to record exact joint angles. This is probably not a practical solution to an everyday gesture recognition system. Therefore this system was designed to require only that the user wear a pair of brightly colored gloves to make identification of their hands easier. This requirement can be eliminated easily should an effective method of locating un-emphasized human hands be developed.

The system, devised for this thesis, can be broken down into two major subsystems: a hand tracking component and an arm control component. The hand tracking component uses ISAC's two Sony XC-999 Cameras for color stereopsis. The

human operator, whose gestures ISAC is to mimic, wears two different brightly colored gloves. As the person moves his or her hands, images are taken periodically by said cameras which represent ISAC's right and left "eyes." A left-right pair of images taken simultaneously is called a conjugal pair. Each image in the pair is analyzed to find the areas occupied by the - gloves. The center point (center of mass) of each glove's area is located in both. A depth from disparity [23] method is used to calculate the relative 3D position of each glove with respect to the camera head. This position is calculated for each conjugal pair over time and the relative 3-D coordinates are recorded. At the end of a gesture, the movement of the gloves becomes small. This is detected and the set of 3D coordinates is partitioned into segments. The partition boundaries correspond to significant changes in direction. Each segment contains a set of points that approximate one continual movement of the human operator's hands. This small set of points that can be translated into via points for ISAC to follow. The via points are used to construct a control policy for arm motion by ISAC so that the robot may mimic the perceived motion with its own articulated arms, The set of points is analyzed for size constraints and then adjusted to ensure that all points fall within ISAC's workspace. If necessary the gesture is scaled up to span as much of ISAC's workspace as possible. Then a trajectory is calculated for ISAC to reach each via point from the last. The trajectory is analyzed by a Neural Network controller that translates the sequence of 3D coordinates to air pressure values for individual air muscles. These air pressure values are coded as voltages which are sent directly to the valves, which control the airflow to ISAC's muscles, via controller cards.

I.2. Background & Motivation

ISAC has existed in a form, similar to his current, for many years. In that time, a wide variety of projects have been undertaken to provide him with many different abilities. Several low level controllers have been created to allow more generalized control of his arms [20, 33]. Vision systems have been implemented to give him the ability to track objects and make sense of the visual world around him [35]. Microphones have been placed in proximity of his head to experiment with data acquisition via sound [25]. Methods have been developed to allow ISAC to keep track of objects in his immediate vicinity whose presence has been detected through a variety of methods [24]. The work described herein enables ISAC to track the movement of human hands then to mimic them much as a small child would [21]. This is useful for several reasons. Pedagogically, it allows people with no special training to interact with ISAC to learn, first hand, about robotic perception and action. Functionally, this type of behavior is the basis for an entire field of study known as Imitation Learning. Giving ISAC the ability to identify, interpret, and then repeat the actions of a human trainer opens the door for research into methods of classifying, retaining, recalling, and combining those actions. Providing ISAC with this function will act as the first step to giving him the ability to behave more like a human being

CHAPTER II

DESCRIPTION OF TOOLS

This project has made use of a wide variety of tools, both hardware and software. This section describes the most important of them.

II.1. ISAC

The robot used for this work is known as ISAC. ISAC stands for Intelligent SoftArm Control and resides in a lab on the third floor of Vanderbilt's Featheringill Hall building. ISAC has been designed as a humanoid robot and has various features that help him to emulate humans in a variety of ways.

Firstly, ISAC has two color cameras that act as his eyes. Secondly, ISAC has two arms actuated by air muscles known, commonly, as McKibben artificial muscles or Rubbertuators. Rotary Encoders at each joint provide data to calculate the location and orientation of the links and the end-effector.

II.1.1. Cameras

ISAC is capable of stereopsis, via two Sony XC-999 color CCD (Charge-Coupled Device) cameras [18] which sit side by side in a quasi-anthropomorphic configuration atop Directed Perception Pan-Tilt bases [6]. The latter give ISAC active vision — the

ability to “look around” by panning and tilting each of the cameras independently. (Figure 1)

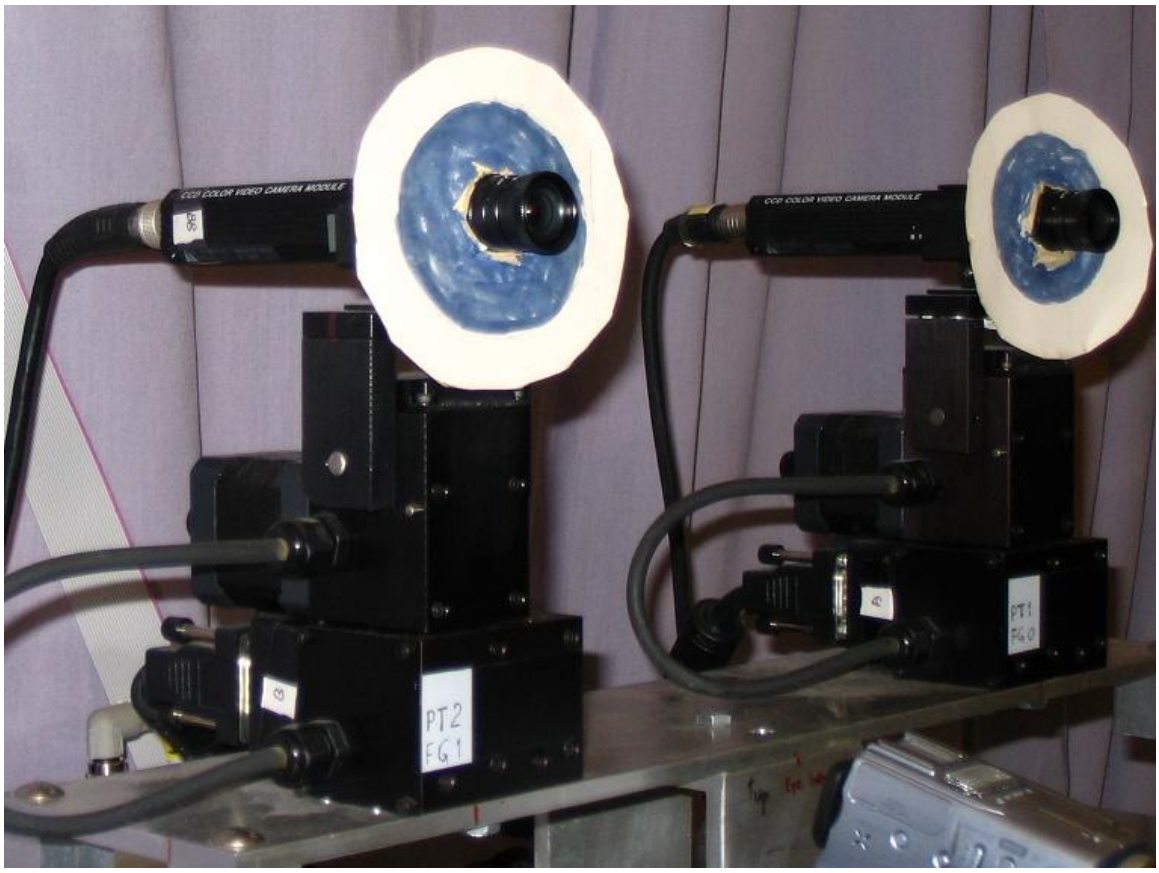


Figure 1: ISAC's Eyes

The cameras have a native resolution of 768×493, however, the ISAC system has them operating at a resolution of 320x240. This is generally suitable for vision problems and drastically reduces the number of pixels (from 378,624 down to 76,800: a reduction of 80%) that must be analyzed in raster-scan style functions. The pan-tilt bases have a

resolution of 0.0514 degrees, although, in this project, the eyes are kept steady and thus, the pan-tilt bases are not utilized. Each camera has a measured horizontal FOV (Field of View) of approximately 55.77° and vertical FOV of 42.78° as shown in Figure 2 (not to scale). The face recognition software used in this project is reliable up to about 5 ft. The cameras are located 11 in. apart from one another. This provides a working area for stereopsis 47 in. high and 51 in. width at a range of 5 ft. in front of ISAC as displayed in Figure 3 (not to scale).

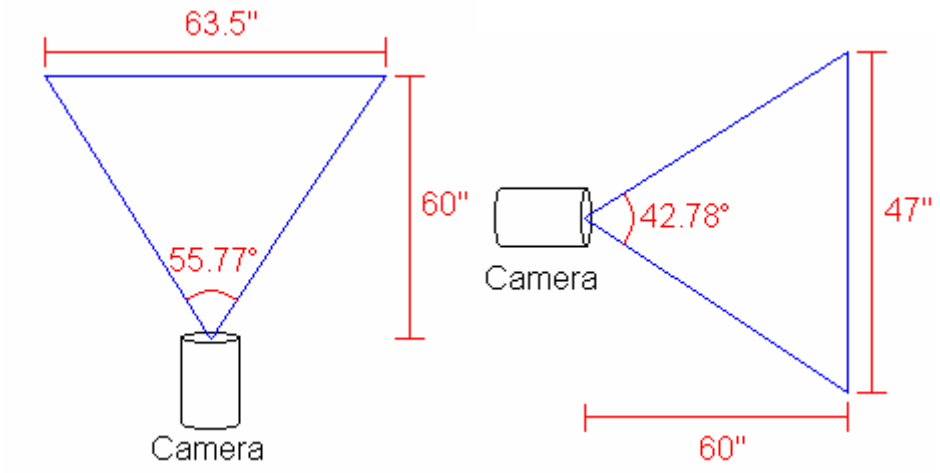


Figure 2: Single Camera FOV

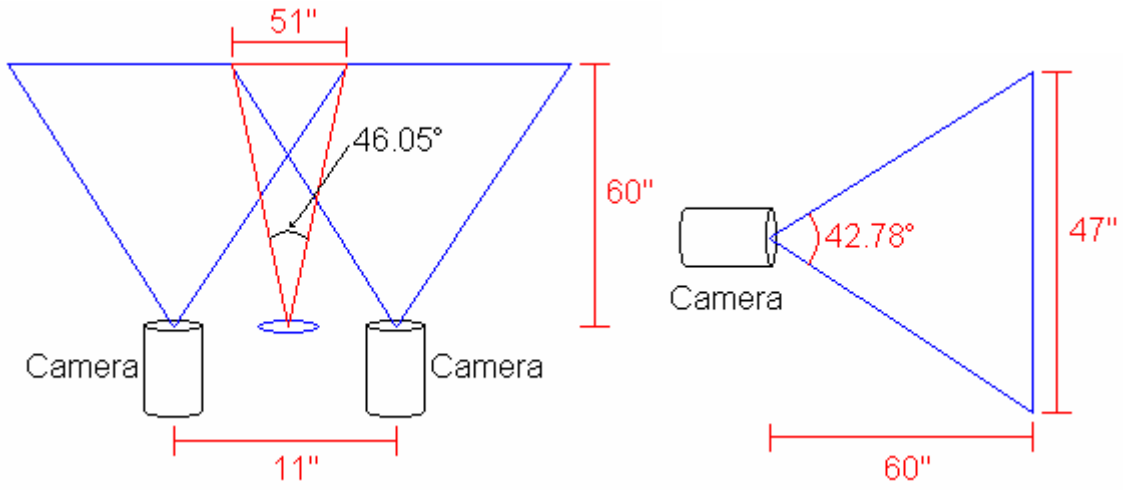


Figure 3: Stereopsis FOV

II.1.2. Arms

ISAC has two arms which are actuated by agonistic pairs of pneumatic air muscles (McKibben Artificial Muscles). They are commonly known as Rubbertuators since that was the commercial name for the McKibben actuators that were manufactured by Bridgestone in the 1980s [44]. (Figure 4)

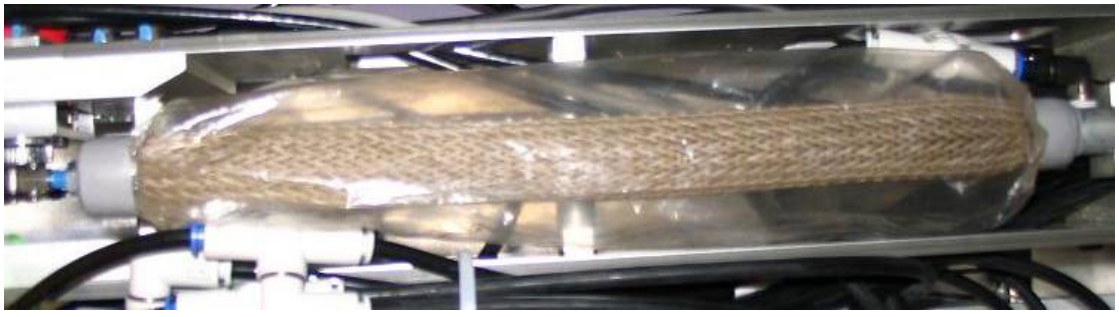


Figure 4: Rubbertuator

The concept behind a Rubbertuator is simple; it is a rubber tube surrounded by a flexible fabric mesh that encloses a constant volume. When the muscle is pressurized it expands. The mesh, holding the volume constant, causes the tube to contract. It thereby converts radial force into a contraction force when filled with pressurized air. Rubbertuators can only exert contractual force; therefore Rubbertuators are generally used in antagonistic pairs to allow for a restoring force to exist.

Rubbertuators have qualities that make them good actuators for a humanoid robot designed to interact with people. They are not rigid, they are compliant. In other words, they give a bit when an opposing force is applied, even at maximum contraction. Mechanical compliance is necessary for a robot that operates in the vicinity of untrained, or lightly trained, human operators. Rubbertuators have the largest strength-to-weight among actuators on the human scale. Once filled with air they can hold the position indefinitely (within the limits of air loss) without the application of continuous power.

One problem with Rubbertuators is that they are inaccurate compared to many electric motor actuators. That is, the uncertainty in expected output given a known input is large by comparison. This characteristic is caused, in part, by changes in the flexibility of the rubber due to changes in temperature and humidity. Interestingly, this characteristic is analogous to the effect of temperature on biological muscles [21] and to the idea that humans can perform approximate motion with no visual feedback and reach an approximate locaiton. Each of ISAC's arms has 12 Rubbertuators paired to work antagonistically on a manipulator chain with 6 degrees of freedom. Figure 5,

below, shows ISAC's left arm. The older, beige Rubbertuators made by Bridgestone [1] and the newer black ones, made by Shadow Robotics [29] are clearly visible.

Figure 5: ISAC's Left Arm

ISAC's joints are typically numbered from 0 to 5 starting at his trunk and working out toward the end effector. Angle 0 corresponds to his entire arm rotating, at the shoulder, about the Z axis. This joint is controlled by a single pair of pneumatic muscles. Angle 1 is the shoulder joint that rotates the arm about an axis parallel to the Y axis. This angle too is controlled by a pair of pneumatic muscles. Angle 2 refers to the elbow joint which lifts the forearm about an axis parallel to the Y axis. Angle 3 rotates the forearm and wrist about an axis parallel to the forearm. Angle 4 controls the pitch of the hand. Angle 5 controls the roll of the hand. The construction of ISAC is a bit complex in that Angles 2 and 3 are controlled by the same set of 4 air muscles. Angles 4 and 5 are also controlled by a single set of 4 air muscles. Each set is arranged in a square. Figure 6 displays this arrangement.

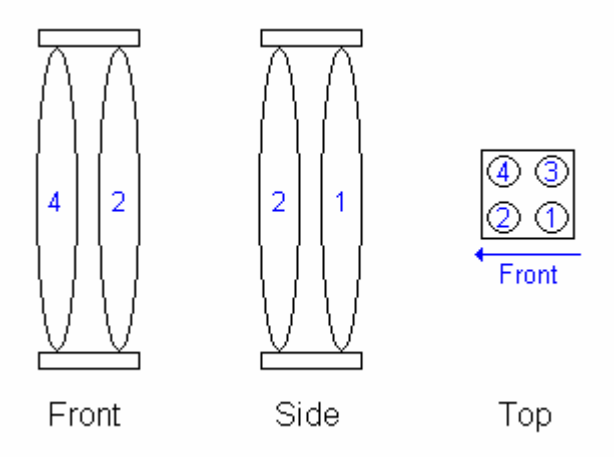


Figure 6: 2 Pair Muscles Configuration

If the elbow joint is taken as an example, ISAC can lift up his forearm but also rotate it. This varied action is accomplished using a universal joint in conjunction with the 4 muscles set. The combination is show, below, in FIGURE X. In reference to Figure 6, the forearm can be lifted by contracting muscles 2 & 4 and relaxing muscles 1 & 3. Clockwise rotation of the forearm can be achieved by contracting muscles 2 & 3 and relaxing muscles 1 & 4.

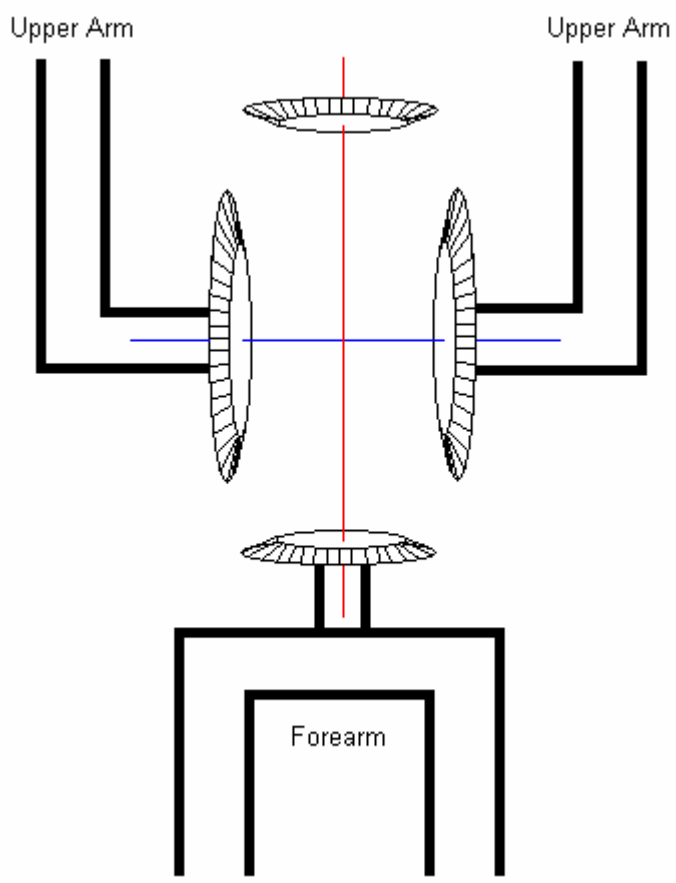


Figure 7: Universal Elbow/Wrist Joint

The Rubbertuator's disadvantages are many. Their performance variability due to temperature and humidity, combined with their compliance, can make them difficult to control accurately in a complex system. Despite their good strength to weight ratio, the fact that they are powered by compressed air and rubber imposes severe limits on the weight they can move. Lastly, Rubbertuators are, for the most part, unsuitable for mobile robots due to their reliance on compressed air. The associated equipment is too large to be attached to a small mobile robot in a practical way.

The compressed air that powers a Rubbertuator is provided by a compressor tank that maintains a constant pressure. The air is fed through a a filter to clean and a cooler to minimize the temperature variance of the muscles. The air is then fed to SMC ITV2050-312CN4 Electro-Pneumatic Regulator valves [30], one per muscle, which regulates how much air will be provided to the actual Rubbertuator. The valves, when supplied with an input voltage from 0 to 5 volts will respond by allowing a proportional amount of air pressure to be passed on to the muscles. When a lower voltage is supplied, than was previously, the current air is exhausted out a port in the back of the regulator until a satisfactory pressure is obtained. An array of these valves is mounted on ISAC's chest and back. His chest, covered in valves, can be seen in Figure 8 below.

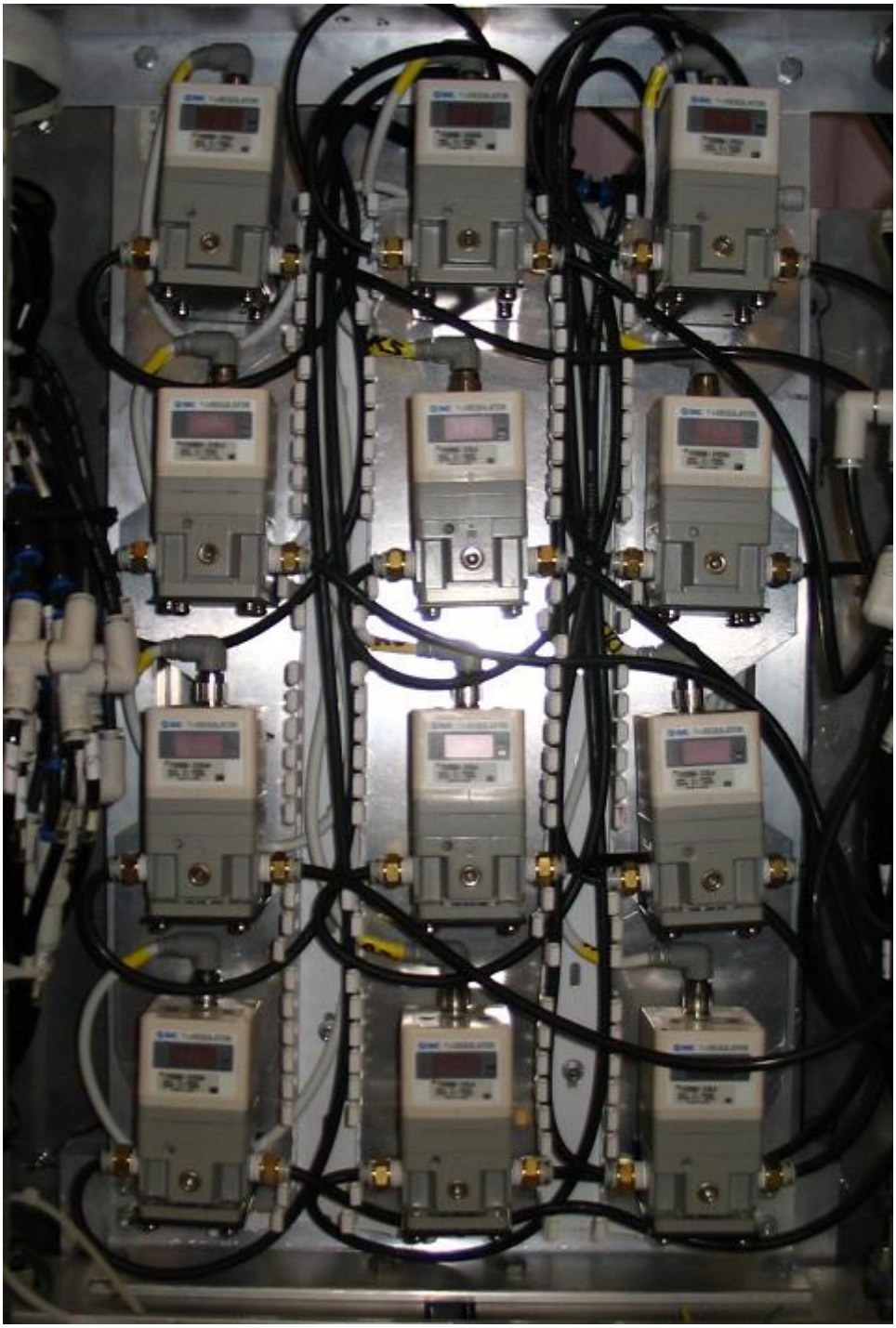


Figure 8: Regulator Valve Array

The valves are controlled by 3 MOTENC-Lite controller cards [40] which sit in a Windows 2000 based PC (Personal Computer). The controller cards allow simple control of the valves and are described below in section II.1.3.

ISAC has encoders at every joint that provide feedback to the system. Joints with a single axis of rotation interface with a single encoder. The universal joints, located at the elbow and wrist, have 2 axes of rotation and, therefore, require 2 encoders. The set of encoders on the universal joints report the angular offset of both the left and right side of the joint which are each controlled by a conjugate pair of Rubbertuators. These angles can then be used to calculate the final angle of rotation on both axes. The encoders on ISAC are either SUMTAK [37] or Epson-Seiko [7] rotary encoders. In Figure 9, a SUMTAK is on the left and an Epson-Seiko is on the right. The encoders rotate with an angular resolution of 0.345 degrees. If they are properly initialized, the instantaneous angle of each joint can be monitored within the resolution listed above.

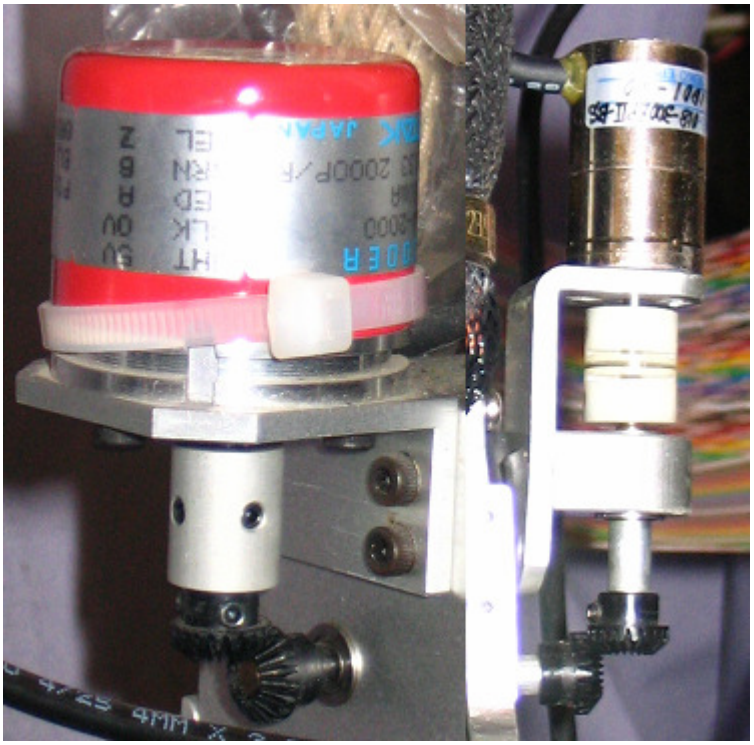


Figure 9: Encoders

Unfortunately, these encoders are obsolete; they are out of production and very little information is available on them. All rotary encoders, however, work in a similar way by generating electrical pulses as a shaft rotates. Two signals, which are out of phase, are constantly sent out while rotation is present. The signals consist of pulses which can be counted to calculate how much rotation has occurred. By looking at which signal is "ahead," due to their difference in phase, one can tell which direction the rotation is in. The encoders are read by the same MOTENC-Lite controller cards as control the valves.

II.1.3. Controllers

ISAC's encoders are read by, and his valves are controlled by, Vital Systems MOTENC-Lite controller cards shown below in Figure 10.

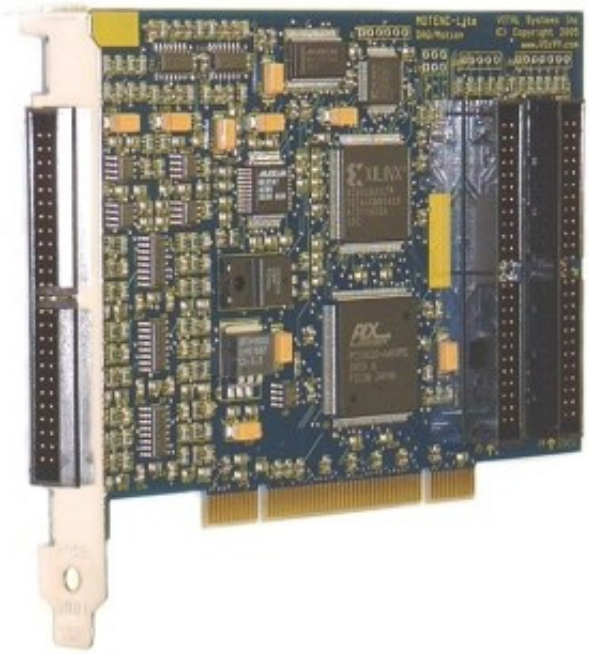


Figure 10: MOTENC-Lite: PCI Board (pn 7541 & 7544)

These cards interface with a PC through the standard PCI (Peripheral Component Interconnect) bus and use drivers written by Vital Systems. They are designed so that several cards can be used in the same system. This is done by assigning each card a unique identifier via jumpers on the board itself. ISAC's control system has three of these cards to control his 24 muscles and read his 12 encoders. Large ribbon cables

extend from each card and run to DAC/ADC/Encoder Termination Boards (pn 7525) shown below in Figure 11 [41].

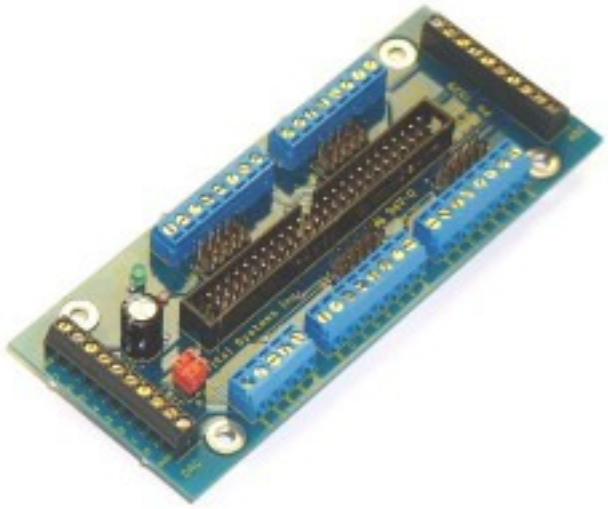


Figure 11: DAC/ADC/Encoder Termination Board for MOTENC-Lite (pn 7525)

The black terminal blocks on the short edges of the Termination Board are ADC (analog to digital converter) and DAC (digital to analog converter) blocks. They connect to the control lines of the valves to read from them and write to them. The larger blue terminal blocks on the long edges are connections specifically designed to read from encoders. As the image shows, four encoders can be read by single card so the three cards support ISAC's twelve encoders. It is a bit harder to see, but each board is capable of supporting eight valves which, again, is in perfect harmony with ISAC's 24 air muscles.

II.2. OpenCV

Much of the computer vision software in the system is built on top of Intel's OpenCV (Open Computer Vision) Library [15, 27, 34]. OpenCV, in its simplest form, is a collection of functions that facilitate computer vision related programming. The efficiency of OpenCV depends on the presence of Intel's IPP (Integrated Performance Primitives) [13] which are a commercial library of functions that perform routines related to multimedia processing and multi-core functionality at the assembly and machine code level. IPP is designed only to work with Intel microprocessors. While the software developed for this thesis does not use IPP due to the associated cost, it could easily be installed to increase the performance of the system's computer vision components.

OpenCV is, in actuality, not just a random collection of functions but is, instead, a well organized set of tools that a programmer can use to quickly implement solutions to computer vision problems. All computer vision functions in OpenCV are designed to operate on the IplImage structure, also defined in OpenCV. The `typedef` for an IplImage is shown in Figure 12.

```
typedef struct _IplImage
{
    int  nSize;         /* sizeof(IplImage) */
    int  ID;            /* version (=0)*/
    int  nChannels;     /* Most of OpenCV functions support 1,2,3 or 4
                           channels */
    int  alphaChannel;  /* ignored by OpenCV */
    int  depth;         /* pixel depth in bits: IPL_DEPTH_8U,
                           IPL_DEPTH_8S, IPL_DEPTH_16U,
                            IPL_DEPTH_16S, IPL_DEPTH_32S, IPL_DEPTH_32F
                            and IPL_DEPTH_64F are supported */
    char colorModel[4]; /* ignored by OpenCV */
    char channelSeq[4]; /* ditto */
    int  dataOrder;     /* 0 - interleaved color channels, 1 - separate
                           color channels.  cvCreateImage can only
                           create interleaved images */
    int  origin;        /* 0 - top-left origin,
                           1 - bottom-left origin (Windows bitmaps
                           style) */
    int  align;         /* Alignment of image rows (4 or 8).  OpenCV
                           ignores it and uses widthStep instead */
    int  width;         /* image width in pixels */
    int  height;        /* image height in pixels */
    struct _IplROI *roi;/* image ROI. when it is not NULL, this
                            specifies image region to process */
struct  _IplImage *maskROI;    /* must be NULL in OpenCV */
void    *imageId;              /* ditto */
struct  _IplTileInfo *tileInfo;/* ditto */
int     imageSize;             /* image data size in bytes
                               (=image->height*image->widthStep
                               in case of interleaved data)*/
char    *imageData;            /* pointer to aligned image data */
int     widthStep;             /* size of aligned image row in bytes */
int     BorderMode[4];         /* border completion mode, …*/
int     BorderConst[4];        /* … ignored by OpenCV */
char    *imageDataOrigin;      /* pointer to a very origin of image data
                               (not necessarily aligned) -
                               it is needed for correct image
                               deallocation */
}
IplImage;
```

Figure 12: IplImage Structure (condensed) [31]

The IplImage structure was designed by Intel for their Intel Image Processing Library (IPL). The Intel IPL is no longer a supported product [14] and has since been integrated into the Intel Performance Primitives product. OpenCV allows for many complex image

operations to be done via a single, one line, functions. In addition to premade functions OpenCV also comes bundled with HighGUI [32] which allows a programmer to setup a simple GUI (Graphical User Interface), for testing, extremely quickly. Details on the specific, usage of the OpenCV library are discussed further in the Vision System section III.1.

II.3. CalTech Image Calibration Toolbox for Matlab

Computer Vision is used in a wide variety of applications and can be built upon anything from a $10 web-cam with an old laptop to setups that costs many thousands of dollars with state-of-the-art equipment. The precision of any computer vision system depends on accurate knowledge of the projective transformations imposed by the cameras. Those transformations depend on the camera's focal length, sensor size and density, sensor noise characteristics, optical distortion including the point-spread function and radial position deviation, etc. Some of these parameters are published by the camera manufacturer, particularly for higher end equipment. However, information on some of the more subtle camera parameters can be hidden even for the expensive components. For an amateur, with a web-cam that was pulled out of an old box of electronics, it is very possible that none of this information is readily available. That is where the CalTech Image Calibration Toolbox [3] comes in handy.

Dr. Jean-Yves Bouguet [4] of the Computer Vision Research Group at CalTech saw this problem and designed a tool to help overcome it. The Calibration Toolbox works in the following way. It takes, as input, a set of images with a test sheet in different orientations. This test sheet is a checkerboard pattern with identical squares of

known sizes. The software uses its *a priori* knowledge of the checkerboard pattern to analyze the set of images distorted by the camera. The analysis returns estimates of the parameters which are used to estimate the projective transformations. This allows the user to then design computer vision software optimized for the camera's unique parameters. For this research, the camera parameters were estimated with the CalTech software.

II.4. Previously Developed Code

To expedite creation of the system, code that had been previously developed by other students was used. For the most part, that code included low level drivers and interfaces for components like the cameras and arm control. Each instance of borrowed code is described below.

II.4.1. PXC Drivers

ISAC's cameras provide data to a PC in the form of a stream of video frames that are delivered via Phase 1 Technology PS-99SU Frame Grabbers. Software drivers are necessary to interface with these frame grabbers. Code, called PCX, that makes the frames accessible to C++ programs was preexisting in the lab although it is unclear who wrote it.

Modifications were made by Katherine Achim in February of 2005 and by this author, for this project, in January 2008[1]. The PXC code works as follows: Create a camera object, initialize it, and then get an image. In order for this image to be used by OpenCV it must be reopened as an IplImage. The example code in Figure 13, below, shows how this can be done.

```
CPXCk_FG camera; //initialize a PXC camera object
char *image = (char*)"C:/Temp/image.bmp"; //specify a temp location
IplImage *frame; //initialize an IplImage

camera.Initialize(0);  //initialize the camera (PXC function)
camera.GetImage(image); //grab a frame & save it to temp (PXC function)
frame=cvLoadImage(temp); //load the image into the IplImage structure
```

Figure 13: PXC Code Example

Once the image is read from the Frame Grabber into in a BMP (bitmap), and then opened as an IplImage, it is in a suitable form to be sent to almost any OpenCV function.

[1] The actual drivers appear to be in DLLs located at I:\etc\pxc2\ and include pxc_95.dll, frame_32.dll, pxc_nt.dll, pxc_31.dll and frame_16.dll. It appears that pxc_95.dll, pxc_nt.dll, and pxc_31.dll are drivers that correspond to Windows 95, Windows NT, and Windows 3.1 and that frame_16.dll and frame_32.dll correspond to either 16 and 32 bit architectures or 16 and 32 bit images. It seems more likely that they correspond to 16 and 32 bit architectures since a 24 bit version should be included if they corresponded to images. The software that makes the drivers accessible in C++ is contained in PXCk_FG.h and PXCk_FG.cpp. All of the PXC code is located at I:\etc\pxc2\.

II.4.2. Connected Components Extraction

In Computer Vision it is often necessary that objects be found in a scene and then isolated (segmented). This system uses color to segment and track objects. Segmentation is performed via hue filtering. To do this an image mask is used.[2] Any pixels that are, say, green, are marked as *foreground* in the mask all others are marked *background*. This mask has is black wherever there is background and white wherever there is foreground. Figure 14, below, shows an example of a frame, on the left, and its associated mask, on the right, when a green hue is the target. This particular image also displays the results of a morphological erode and dilate. Usage of such a function is described further in section III.1.1.

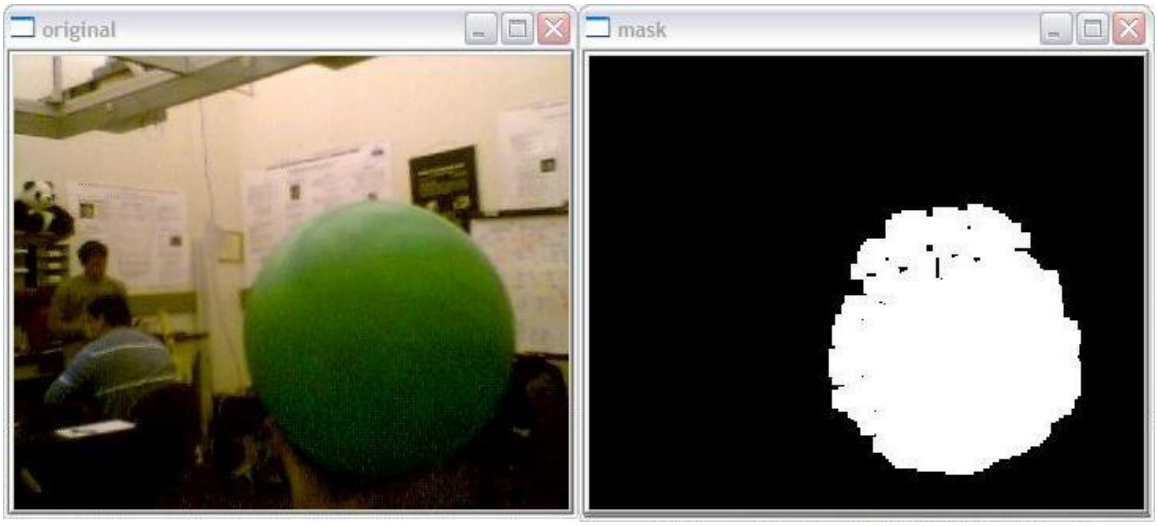


Figure 14: Green Hue Mask Example

[2] An image mask is a binary image with the same dimensions as the image that is being masked. The polarity of a pixel in the mask typically indicates that the corresponding pixel in the image is of interest or not. For example a one might indicate that the pixel has a specific feature, zero indicates that it does not.

Multiple objects are distinguished using Connected Component labeling. A Connected Component is simply a set of foreground pixels that are all touching one another. If there is a break between foreground pixels, by background, then those pixels are deemed to be part of separate connected components. A previously written program for connected component labeling, written by Tom Billings and Jack Noble, was used to accomplish this task. This author made minor modifications to it removing some hard coded values for image height and width and replacing them with values gleaned from the image structure itself. From the list of connected components, returned by the program, the largest was selected as the object of interest.

II.4.3. New Neural Network / PID Controller

The first part of this project involved the tracking of an object in 3D and second revolves around filtering out its generalized motion. The third, and final, objective is to cause ISAC's arms to move so as to mimic the motion of the object. Several controllers have been created that cause ISAC to move an arm to a specific 3D location in its workspace. One of these is a combination Neural Network [42] and PID controller. That controller was modified by this investigator for this project. The Neural Network portion of the controller works by training ISAC to associate muscle pressures and 3D locations of the end-effector (hand). The PID portion of the controller moves the arm to minimize the distance between the desired location and the actual location as computed from the outputs of the joint position encoders. The controller is fast relative to the speed of arm motion so the resultant motion is fairly smooth. The composite controller initiates the neural network which moves the arm to a rough approximation of the target

location within a time interval that can be set by the designer. A common interval might be on the order of 500ms. Then it initiates the PID controller to make final, precision, adjustments. In this system, only the Neural Network is considered, the PID controller has been disabled. This is primarily for safety. The system is designed to interact with human being. Since the Neural Network is entirely open-loop if it encounters an obstacle, such as a person, it will not continue to try to work through it [38]. A PID controller, on the other hand, is closed-loop and thus it will notice that it is not at its desired location and will continue to instruct the manipulator to go there possibly causing injury to the human obstacle. Furthermore, the Neural Network based controller more closely mirrors the muscle memory operations of a human. If an actual human were to repeat an observed gesture, such as a wave, the attempt would be primarily from muscle memory with little, if any, visual feedback being utilized place.

The Neural Network used in this controller is not extraordinary in any way and follows from the standard model. It is known, more specifically, as a Back-Propagation Neural Network with a Generalized Delta Rule. This is an excellent choice for the system due to the non-linearity of the McKibben muscles caused by hysterysis which derives from the friction of the woven membrane on the outside of the muscles. Because of this hysterysis two separate Neural Networks have been created. One applies only to forward motion, the other only to backward motion.

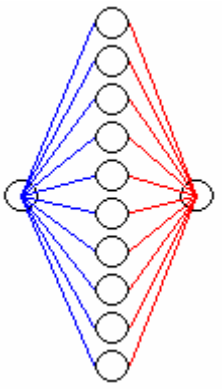


Figure 15: Neural Network

As is shown in Figure 15, the input and output layers of the Neural Network each consist of a single neuron. The middle layer consists of ten neurons. The system was trained with a 10,000 epochs, between 150 and 250 data points, a learning rate of 0.001, and 1,000,000 iterations. This gave rise to errors of only a few degrees which was deemed suitable for this system [8].

CHAPTER III

THE COMPLETE SYSTEM

The goal of this project was to create a system by which ISAC would be able to see a person making an arm gesture and then repeat it (given the limitations imposed by ISAC's workspace). Figure 16 is a list of the tasks that must be accomplished for ISAC to achieve the goal.

1. Initialize ISAC's cameras
2. Retrieve a frame from ISAC's left and right cameras
3. Detect the object of interest in both the left and right frame
4. Calculate the 3D location of the objects of interest
5. Save the 3D location along with its relative timestamp
6. Repeat steps 2 – 5 until the gesture is complete. A list of 3D coordinates is now saved
7. Filter the list of 3D points to eliminate artifacts and noise
8. Compress the list of 3D points down to as few points as are necessary to capture the general motion of the object of interest
9. Scale the list to fit within ISAC's workspace
10. Calculate Joint Angles via Inverse Kinematics
11. Upload the list of joint angles to ISAC's arm control system (located on a separate PC from the vision control system)
12. Iterate through the list of joint angles and have ISAC move his arm to the associated location

Figure 16: Solution Outline

The rest of this section provides details of the implementation (e.g., the routines and parameters used) and a description how it works.

III.1. Vision Subsystem

ISAC's vision system operates from the PC in the Cognitive Robotics Lab named Sally, which runs Windows XP. Two Sony XC-999 Cameras, each mounted on its own Directed Perception pan-tilt unit, connect to twin Phase 1 Technology PS-99SU Frame Grabbers which in turn plug into PCI capture cards in the computer. Frames are retrieved using the PXC software, described in section II.4.1, and are made available to the rest of the program which is described, in detail, below.[3]

III.1.1. Object Detection

Object detection is performed on a per-frame per-object basis. That is to say, in order for the system to track two objects using two cameras, the object detection routine is run four times. The function is show below in Figure 17.

```
void detectObject(IplImage* img, CvTarget *tar, int low, int high)
{
      //Temporary Images
      IplImage* hsv = cvCreateImage(cvGetSize(img), 8, 3);
      IplImage* hue = cvCreateImage(cvGetSize(img), 8, 1);
      IplImage* sat = cvCreateImage(cvGetSize(img), 8, 1);
      IplImage* val = cvCreateImage(cvGetSize(img), 8, 1);
      IplImage* maskH = cvCreateImage(cvGetSize(img), 8, 1);

      //kernel for use with erode/dilate
      IplConvKernel * selem =
      cvCreateStructuringElementEx(3,3,1,1,CV_SHAPE_RECT);

      //Extract Hue/Sat/Val from BGR Image
```

[3] The code examples have been cleaned up, condensed, and formatted so that they fit cleanly in this document. However, none of the functionality has been changed. Comments have simply been rearranged or taken out. When necessary, lengthy code has been replaced with more concise pseudo-code.

```
	cvCvtColor(img, hsv, CV_BGR2HSV); //convert from BGR to HSV
	cvSplit (hsv, hue, sat, val, 0); //extract hue/sat/val channels

	//Filter by Hue
	cvInRangeS(hue, cvScalar(low), cvScalar(high), maskH);

	//Erode/Dilate maskH to eliminate noise
	cvErode(maskH,maskH,selem,3);
	cvDilate(maskH, maskH, selem, 3);

	//Find the largest positive object
	getConnectedComps(maskH,Comps);

	if (comptot != 0)
	{
		//find largest component
		maxcomp = 0;
		maxarea = Comps[0]->area;
		for (int j = 0; j < comptot; j++)
		{
			if (Comps[j]->area > maxarea)
			{
				maxarea = Comps[j]->area;
				maxcomp = j;
			}
		}

		//get center
		tar->x = Comps[maxcomp]->rect.x + Comps[maxcomp]->
		rect.width/2;
		tar->y = Comps[maxcomp]->rect.y + Comps[maxcomp]->
		rect.height/2;

		//get radius
		if (Comps[maxcomp]->rect.width > Comps[maxcomp]-
		>rect.height) tar->r = Comps[maxcomp]->rect.width/2;
		else tar->r = Comps[maxcomp]->rect.height/2;
	}

	//Release Images
	cvReleaseImage(&hsv);
	cvReleaseImage(&hue);
	cvReleaseImage(&sat);
	cvReleaseImage(&val);
	cvReleaseImage(&maskH);
}
```

Figure 17: detectObject code (condensed)

The function is called `detectObject`. It takes a pointer to an IplImage (`img`), a lower hue bound (`low`) and an upper hue bound (`high`) as inputs. A pointer to a `CvTarget` object (`tar`) is used as an output. The process begins by converting the image from the 32-bit per pixel, BGR (Blue Green Red) representation provided by the frame grabber into a 32-bit HSV (Hue Saturation Value) representation. The HSV image, which is a single three-band image, is then split into three, 8-bit, one-band images: hue, saturation, and value. The saturation and value bands are not used. The hue image is then segmented for a specific range of hues that have been computed from earlier images of the target object. A black and white mask is created by a raster scan thresholding of the hue image. If the hue value of a pixel is between the low bound and the high bound (the extrema of the specified hue range) then the corresponding pixel in the mask image is colored white. Otherwise it is colored black. The mask image is then eroded and dilated with a 3×3 square structuring element [9, 10]. The erosion gets rid of noise by eliminating any small instances of foreground (white) in the mask. The dilation then returns the foreground areas that survived the erosion back to their original sizes.[4] The mask is then analyzed by the `getConnectedComps` function (cf. section II.4.2) which returns a list connected foreground components. This list is searched for the largest component. Its radius and center point are then found and stored in the `tar` variable. The `tar` variable is returned with the location and size of the largest object of a particular color. Lastly the image variables are released to free up that memory.

[4] Erosion followed by dilation with the same structuring element is called *opening*.

III.1.2. Haar Face Detection

To effectively find the location of the user's face, a detection algorithm that takes advantage of Haar-like features was used [12, 39]. These Haar-like features allow for classification, of an object of interest, to be described by its light and dark regions and their proximity to one another. Figure 18 displays the current, extended, set of Haar-like features.

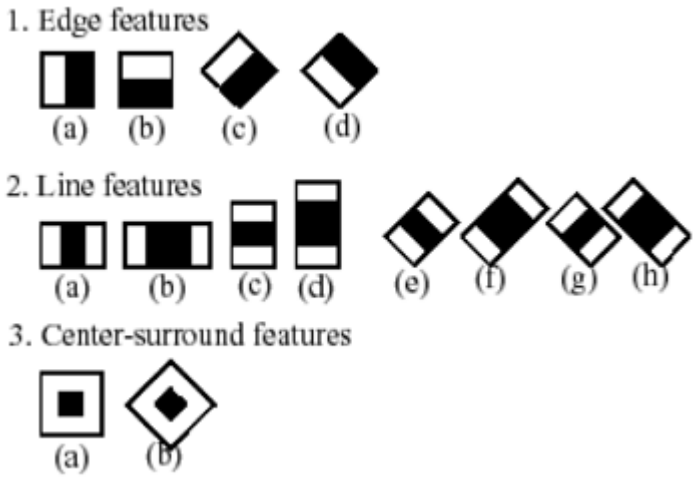


Figure 18: Extended Set of Haar-like Features [17]

Each one of the features listed above can be applied to an object of interest. Take a human face, for example. *Edge feature (b)* would be applied to the forehead/eye socket region because the eye sockets cause that area of the face to be darker then the forehead which reflects light well. *Line feature (a)* would be inverted and then applied to the eyes and nose because, again, the eye sockets cause the left and right regions of

the middle face to be darker then the center which contains the bridge of the nose. It is not required that a developer calculates and inputs all of these features by hand. OpenCV comes bundled with software designed to analyze a set of test images that contain both positive and negative samples. These test images, for a successful outcome, should number in the thousands. If this many, unique, images cannot be acquired, functionality also exists to distort a smaller set of images to artificially create more positives. Once this analysis is complete an XML file, known as a *cascade file*, is created that contains all of the necessary feature information. This cascade file can then be applied to any project. This entire procedure is detailed in *Naotoshi Seo's haartraining Guide* [19]. Particularly in the case of face detection, this functionally takes place behind the scenes and a predefined cascade prepared for faces already exists within OpenCV. This author has selected the cascade file `haarcascade_frontalface_alt2.xml`. When using the OpenCV implementation for face detection, it is not necessary that a developer be familiar with these workings. The function that this author has used is derived largely from the `facedetect.cpp` example provided with the OpenCV package. The, modified, function, along with several required global variables, is shown in Figure 19.

```
const char* cascade_name = "haarcascade_frontalface_alt2.xml";
static CvHaarClassifierCascade* cascade =
      (CvHaarClassifierCascade*)cvLoad( cascade_name, 0, 0, 0 );
static CvMemStorage* storage = cvCreateMemStorage(0);

void haarFaceDetect(IplImage* img, CvTarget *tar)
{
      //initialize variables
      int radius;
      int i;
      double scale = 1.3;
      IplImage* gray = cvCreateImage( cvSize(img->width,img-
            >height), 8, 1 );
      IplImage* small_img = cvCreateImage( cvSize( cvRound
            (img->width/scale), cvRound (img->height/scale)), 8, 1 );

      //convert image to a small grayscale version
      cvCvtColor( img, gray, CV_BGR2GRAY );
      cvResize( gray, small_img, CV_INTER_LINEAR );
      cvEqualizeHist( small_img, small_img );
      cvClearMemStorage( storage );

      //if a cascade has been setup, find the faces
      if( cascade )
      {
            CvSeq* faces = cvHaarDetectObjects( small_img, cascade,
                  storage, 1.1, 2, 0/*CV_HAAR_DO_CANNY_PRUNING*/,
                  cvSize(30, 30) );

            tar->r = 0; //initialize the target radius to 0
            //cycle through detected faces to find the largest
            for( i = 0; i < (faces ? faces->total : 0); i++ )
            {
                  CvRect* r = (CvRect*)cvGetSeqElem( faces, i );
                  radius = cvRound((r->width + r->height)*0.25*scale);

                  //if new r (face) > old r (face), save loc to tar
                  if (radius > tar->r)
                  {
                        tar->r = radius;
                        tar->x = cvRound((r->x + r->width*0.5)*scale);
                        tar->y = cvRound((r->y + r->height*0.5)*scale);
                  }
            }
      }

      //release images
      cvReleaseImage( &gray );
      cvReleaseImage( &small_img );
}
```

Figure 19: haarFaceDetect code

The global declarations, shown above the `haarFaceDetect` function point to a predefined Haar cascade file, initialize the cascade based on the cascade file, and setup memory storage for use in the function, respectively. Within the `haarFaceDetect` function several variables including holders for a gray version of the input image and a small version of grayscale image are declared. Then the image is converted to grayscale and scaled down. Now is where the real Haar detection begins. If a cascade has been initialized then a `CvSeq` (or sequence) is created to hold face matches. The sequence is then iterated through and the largest face object is found and recorded into the `tar` variable which represents the size and location of the largest face in the image. This variable also acts as the function's output since it was passed in by reference. Lastly the newly created images are release to avoid congestion in memory.

III.1.3. Object Tracking

Section III.1.1 described how a single object was located in a single frame. This section attempts to describe how the `detectObject` function is used to keep track of the location of the object over a period of time. A condensed version of the main loop in the program is show below in Figure 20.

```
for(;;)           //loop forever
{
      start = GetTime();

      //proceed if a frame is successfully retrieved
      if(cameraL.GetImage(tempL) && cameraR.GetImage(tempR))
      {
            frameL=cvLoadImage(tempL);    //load the left frame
            frameR=cvLoadImage(tempR);    //load the right frame
      }
      else
      {
            //error if we can't get a frame from the camera
            fprintf(stderr, "ERROR: Could not retrieve frames from
            Cameras\n");
            break;
      }

      //haar detect/draw face
      haarFaceDetect(frameL, &lf);
      haarFaceDetect(frameR, &rf);

      //detect object 1 (light blue bean bag)
      detectObject(frameL, &l1, HUE_LIGHT_BLUE_BAG[0],
      HUE_LIGHT_BLUE_BAG[1]); //detect object 1 in our Left Image
      detectObject(frameR, &r1, HUE_LIGHT_BLUE_BAG[0],
      HUE_LIGHT_BLUE_BAG[1]); //detect object 1 in our Right Image


      //detect object 2 (green lego lid)
      detectObject(frameL, &l2, HUE_BIG_GREEN_BALL[0],
      HUE_BIG_GREEN_BALL[1]); // detect object 2 in our Left Image
      detectObject(frameR, &r2, HUE_BIG_GREEN_BALL[0],
      HUE_BIG_GREEN_BALL[1]); //detect object 2 in our Right Image

      //draw object 1 targets onto the original image
      drawTarget(frameL, l1, 0);
      drawTarget(frameR, r1, 0);

      //draw object 2 targets onto the original image
      drawTarget(frameL, l2, 7);
      drawTarget(frameR, r2, 7);

      //calculate relative XYZ depth
      calculateXYZ(&obj1loc, l1, r1);
      calculateXYZ(&obj2loc, l2, r2);

      //print the coordinates to a text file
      fprintf(coordsfile,"%d,,%d,%d,%d,%d,%f,%f,%f,,%d,%d,%d,%d,%f,%f,%
      f\n",counter,l1.x,l1.y,r1.x,r1.y,obj1loc.x,obj1loc.y,obj1loc.z,l2
      .x,l2.y,r2.x,r2.y,obj2loc.x,obj2loc.y,obj2loc.z);

      //display images to the user
      cvShowImage("Tracker Left", frameL);      //show the left frame
```

```
        cvShowImage("Tracker Right", frameR);     //show the right frame

        //give the user a chance to break the loop by hitting any key
        if(cvWaitKey( 10 ) >= 0) break;

        counter++;          //increment the time counter

        //ensure loop is 400ms each time
        stop = GetTime();
        total = stop - start;
        if (total < 400) Sleep(400-total);

}
```

Figure 20: Main Vision Loop code (condensed)

The loop begins by retrieving a frame from both the left and right cameras. If the frames cannot be retrieved, then the program errors out. Each frame must then be loaded into an IplImage structure so that it is in a form suitable for the OpenCV code to operate on. The `haarFaceDetect` function searches for human faces based on Haar-like identifiers. This function is described in greater detail in section III.1.2. The `detectObject` function, described in section III.1.1, is then run 4 times to cover objects 1 & 2 in both the left and right cameras. As mentioned in section III.1.1, the location and radius of the object is returned in a `cvTarget` variable. `l1`, `l2`, `r1`, `r2`, `lf`, & `rf` are all `cvTarget` variables designed to store the location and size of each object in both the left and right frames[5]. The targets are then drawn onto the original frames via the `drawTarget` function described in section III.1.4. Next, the 3D location

[5] It is important to note that in the current implementation with the current code: *object 1* refers to the *teal bean bag* and is intended to be held in the user's *left* hand. *Object 2* refers to the *green Lego lid* and is intended to be held in the user's *right* hand.

object 1, object 2, and the face are calculated in the `calculateXYZ` function described in section III.1.4. Then, both the 2D and 3D location information is saved into a comma delimited text file for processing later in the program. Both frames, with the targets drawn on, are then displayed to the user via the `cvShowImage` function. The user is then given an opportunity to break out of this loop by pressing a key when the gesture recording is complete. Lastly, a time counter is updated so that the relative time at which a point has been recorded can be preserved.

III.1.4. Calculating 3D Locations

Using a method known as Depth from Disparity a 3D (xyz) location can be calculated from two 2D (xy) points so long as the two 2D points meet certain requirements. For the method used here, the 2D points must come from cameras that are coplanar. Certain information about the cameras focal points and their distance from one another must be known as well. Depth from Disparity works using the principle of similar triangles. Figure 21, below, illustrates this principle.

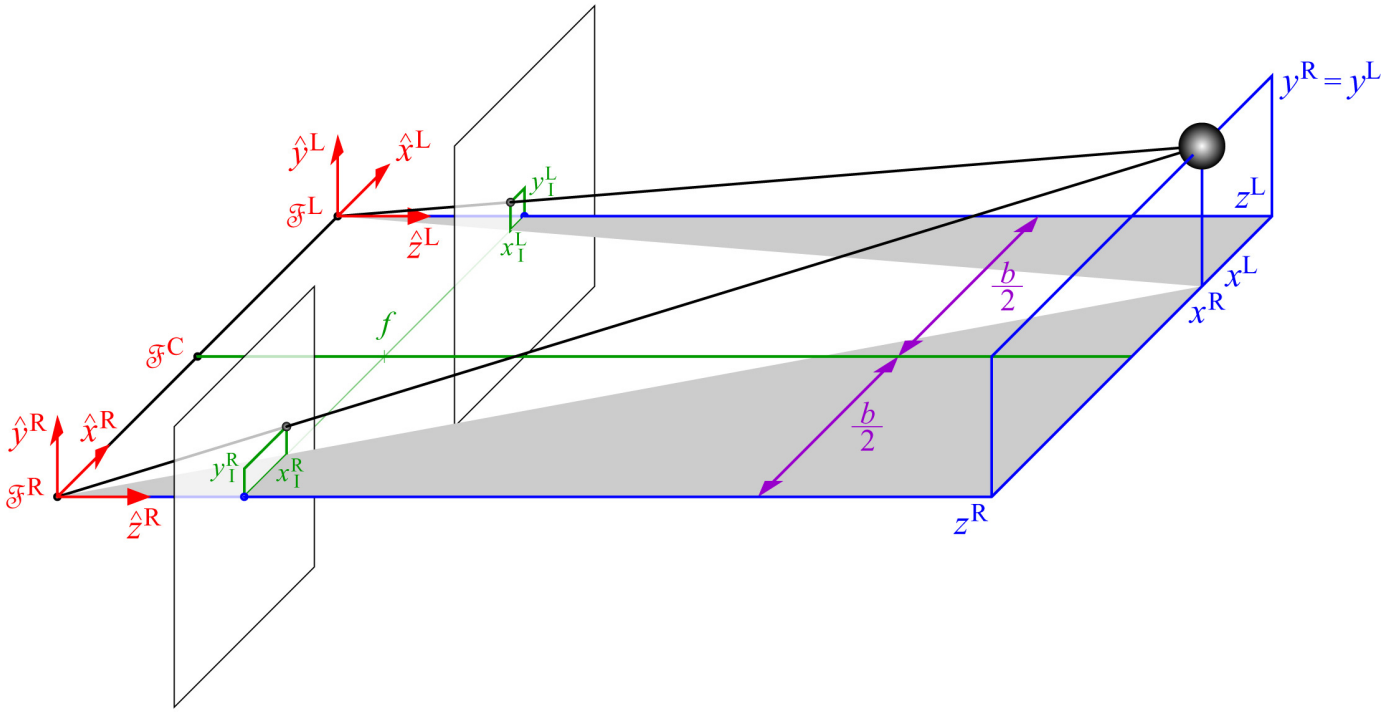


Figure 21: Depth from Disparity [23]

Using the principle of similar triangles one can construct several equations that relate the focal length of the cameras, the 2D coordinates of the object in the image, and the z distance of the object in space. Figure 22 shows these equations and how they can be manipulated to provide a concise equation for the depth of an object.

$$\frac{x_I^R}{f} = \frac{x^R}{z^R} \Rightarrow x_I^R = f\frac{x^R}{z^R} \qquad \frac{x_I^L}{f} = \frac{x^L}{z^L} \Rightarrow x_I^L = f\frac{x^L}{z^L} \quad (1)$$

$$x_I^R = f\frac{x^R}{z^R}, \quad x_I^L = f\frac{x^R - b}{z^R} \Rightarrow x_I^L = x_I^R - f\frac{b}{z^R} \Rightarrow z^R = \frac{fb}{x_I^R - x_I^L} \quad (2)$$

$$z^L = z^R = \frac{fb}{x_I^R - x_I^L} \quad (3)$$

$$\frac{y_I^R}{f} = \frac{y^R}{z^R} \Rightarrow y_I^R = f\frac{y^R}{z^R} \qquad \frac{y_I^L}{f} = \frac{y^L}{z^L} \Rightarrow y_I^L = f\frac{y^L}{z^L} \quad (4)$$

$$y^R = \frac{y_I^R * z^R}{f} \qquad y^L = \frac{y_I^L * z^L}{f} \quad (5)$$

$$y_I^L = y_I^R \quad \& \quad y^L = y^R \quad (6)$$

$$x^L = \frac{x_I^L * z^L}{f} \qquad x^R = \frac{x_I^R * z^R}{f} \quad (7)$$

Figure 22: Depth from Disparity equations [23]

Equation 3 demonstrates that z in both the left and right frames are equal, as it should be and show how this can be calculated from the x location of the object in the left and right frames along with the focal length and baseline (distance between the cameras). The focal length, f, and baseline, b, will be in some real units such as millimeters. The x values, by default will be in pixels. In order for the equation to yield a z that is also in millimeters the x values must be converted from pixels into millimeters which can be done based on the parameters of the camera itself. The camera will have a CCD of a certain size and will produce images of a certain resolution. These two values can be

used to calculate how many pixels per millimeter the camera produces. Equations 5 & 7 show how the real y and x coordinates can be calculated based on the z coordinate that was calculated along with the focal length and original y (or x) coordinate on the image plane.

The above equations were used to create the `calculateXYZ` function which is show below in Figure 23.

```
void calculateXYZ(CvPoint3D32f *objloc, CvPoint left, CvPoint right)
{
	double f = 15262.5;	//focal length: 305.25 millimeters (50
				//px/mm) = 15262.5 px
	double b = 14000;  //base: millimeters (50 px/mm) = 14000 px
	double sigma = 50; //pixels per mm

	//get pixel coords
	xri = (double)right.x; xli = (double)left.x;
	yri = (double)right.y; yli = (double)left.y;

	//find z in weird units
	z=f*b/((double)xli-(double)xri);

	//calculate real y and x values in weird units
	yr=yri*z/f; yl=yli*z/f;
	xr=xri*z/f; xl=xli*z/f;

	//average x & y
	x=(xr+xl)/2; y=(yl+yr)/2;

	//write the values into the objloc to be returned
	objloc->x=x; objloc->y=y; objloc->z=z;
}
```

Figure 23: calcuateXYZ code (condensed)

The function starts by defining the focal length, `f`, and baseline, `b`, will which have been found via the CalTech Image Calibration Toolbox for Matlab. This Toolbox is described

in further detail in section II.3. Next the pixel coordinates are extracted from the CvPoint objects and then used, along with f and b to find the z. As mentioned before, the X & Y images coordinates must be translated into real units in order to get real units out. However, the relative motion of the objects, not their absolute positions, is the primary concern. Some math was thereby avoided in doing this conversion. The 3D points end up in "unknown" units. This, however, is not a problem as any units would have to be rescaled to fit within ISAC's workspace. The next step is to calculate the associated X and Y locations in these unknown units. Since an X and Y location are found for both the left and right images. They are averaged to come up with a single X and a single Y value. The values are then saved to the output variable `objloc`. This procedure is done for every single set of 2D image coordinates that are gathered by ISAC's vision system. As described in the vision section, the 2D coordinates along with a timestamp and the newly calculated 3D coordinates are saved to a text file that can be filtered and processed.

III.1.5. drawTargets Function

The `drawTargets` function is very simple and allows a circle with a dot in the center to be drawn onto a frame taken, in this case, from ISAC's cameras. The, short, function is show below in.

```
void drawTarget(IplImage *img, CvTarget obj, int clr)
{
	if (obj.x <= img->width && obj.y <= img->height && clr <
	NUM_COLORS)
	{
		//draw a circle on the screen
		cvCircle( img, obj, obj.r, COLORS[clr], 3, 8, 0 );
		cvCircle( img, obj, 1, COLORS[clr], 3, 8, 0 );
	}
}
```

Figure 24: drawTarget code (condensed)

The if statement in the function checks to make sure that the center point defined by the `cvTarget` is in the image, and that `clr`, a numeric reference to a color defined by the array `COLORS` is within its range. If both of these conditions are met, then 2 circles are drawn on the screen. Both circles are at the location specified. However only the first has the radius specified by the `cvTarget`. The second has a radius of 1 and performs the function of drawing a dot in the center of the first.

III.2. Processing Subsystem

The next large subsystem is Processing. It engages after the Vision System has completed. That is to say, once a set of 2D points from both the left and right images has been collected, they must be processed to convert them to a single set of 3D locations (per object). This set of 3D locations must then be further filtered and processed in order for it to be usable by ISAC's control systems. The processing is done in the same program as the Vision System operates and happens after the Vision

System has collected the necessary data points. As such, it is also contained on the Windows XP machine known as Sally. Figure 25, below, displays the code for the main Processing routine.

```
//PROCESSING SUBSYSTEM

//calculate the average face location and rewrite to file
avgFaceLoc(coords, facedcoords);

//flip the Y coordinate about it's average value to account for
//upsidedown calculation
flipY(facedcoords,flippedcoords);

//Difference and Recursivly filter the set of XYZ coordinates stored in
//C:/Temp/facedcoords.txt
//and save the results in C:/Temp/filteredcoords.txt
filterCoords(flippedcoords, tempcoords, filteredcoords);

//Filter for large changes in direction to compress the number of
//points on the graph to as few as possible for simpler movement
compressCoords(filteredcoords, compressedcoords1, compressedcoords2);

//scale coords and rearrange axes for ISAC
fitCoordsToISAC2(compressedcoords1, fittedcoords1, RIGHT_ARM);
fitCoordsToISAC2(compressedcoords2, fittedcoords2, LEFT_ARM);

//calculate Joint Angles from Coordinates using Inverse Kinematics
calcJointAngles(fittedcoords1, angles1, RIGHT_ARM, END_EFF_NO,
      SIMPLE_INV_KIN);
calcJointAngles(fittedcoords2, angles2, LEFT_ARM, END_EFF_NO,
      SIMPLE_INV_KIN);

//interpolate angles between existing angles
interpolateAngles(angles1, interpolated1);
interpolateAngles(angles2, interpolated2);

//Open the joint angles file and upload the points to the shared I //drive to
be read by the Neural Network Controller (located on another //computer:
Octavia)
//angles2 goes to uploadL (left hand)
//angles1 goes to uploadR (right hand)
uploadToNNbatch(uploadL, uploadR, interpolated2, interpolated1);

//Upload Start.Now file to indicate that the joint angles are ready and
//that the controller should begin execution
uploadGoFlag(goflag);
```

Figure 25: Processing routine

Processing begins by averaging the face's location. The assumption is made that the user will not move their body around as their gestures are being recorded. This is a valid assumption since the user is asked to keep his, or her, head still during the recording. Averaging of the face location allows for anomalies and frames in which no face was detected to be discarded without adversely affecting the system. `avgFaceLoc` is described in greater detail in section III.2.1. The `flipY` function, described in section III.2.2, is then run to account for a disconnect between the program's logic and ISAC's world frame. The coordinates are then filtered to eliminate artifacts in the signals using the `filterCoords` function described in section III.2.1. `compressCoords` is then run to reduce the number of points that describe the motion to as few as possible. `compressCoords` is described in detail, in section III.2.4. Once the coordinates have been compressed they must be fit to ISAC's workspace. This is done using the `fitCoordsToISAC2` function described in section III.2.5. The fitted coordinates represent locations that ISAC must reach to. In order for these locations to be realized, the appropriate joint angles must be calculated. `calcJointAngles` is responsible for this conversion and is described in section III.2.6. Once the angles have been calculated, `interpolateAngles` (section III.2.7) is run to fill in points between each change of position. These points are calculated in such a way as to smooth the motion by creating intermediate angles. Finally, after all of the angles have been prepared, the points are uploaded to the Controller so that it may execute the motions have ISAC's response can be realized. `uploadToNNbatch` is described in detail in section III.2.7.

III.2.1. avgFaceLoc Function

While the Haar face detect function (section III.1.2) is fairly reliable it can never be counted on to return a face location every frame and it cannot be depended on to be without error. To overcome this problem the `avgFaceLoc` function has been developed. This function, shown in Figure 26, simply analyzes all of the face locations and, ignoring any blank entries, calculates the average location. It then rewrites that average location to each entry.

```
void avgFaceLoc(char coords[], char out[])
{
      coordsfile = fopen(coords);

      for(;;)     //loop forever
      {
            linearray = fgets(coordsfile) //get a line

            //update totals
            XLtotal+=linearray[15]; //2D left X
            YLtotal+=linearray[16]; //2D left Y
            XRtotal+=linearray[17]; //2D right X
            YRtotal+=linearray[18]; //2D right Y
            count++;                //total read

            if (linearray == NULL) break; //break at EOF
      }

      //calculate averages
      left.x = XLtotal/count;
      left.y = YLtotal/count;
      right.x = XRtotal/count;
      right.y = YRtotal/count;

      //calculate XYZ location
      calculateXYZ(&faceloc, left, right);


      //rewrite the coords file
      coordsfile = fopen(coords);
      outputfile = fopen(out);

      for(;;)     //loop forever
      {
            linearray = fgets(coordsfile); //get a line

            //print line to output with the adjusted face values
            fprintf(outputfile, linearray[0-14],left.x,left.y,right.x,
                  right.y,faceloc.x,faceloc.y,faceloc.z);

            if (linearray == NULL) break; //break at EOF
      }
}
```

Figure 26: avgFaceLoc pseudo-code

The function first opens up the coordinates file. It then iterates through the file adding the left frame's and right frame's X & Y coordinates to a running total as well as

incrementing a count variable which keeps a total of all lines read[6]. These values are then used to compute averages. The 3D location of the average is then found. The file is close and reopened and the lines are then written to the output file with the new average face location in place of the original face locations.

III.2.2. flipY Function

Due to a difference in the way ISAC's world is perceived and the way the program was originally written to run there is a discrepancy in the representation of the Y axis. Rather then rewrite many parts of the program it was decided that a simpler solution would be to write an intermediate function designed to simply flip the Y motion about its average. The function finds the average for $Y1$, $Y2$, $Y\text{-}face$, and then rewrites these variables flipped across that average. The code is displayed in Figure 27.

[6] Note that, due to the way the coordinate values are stored, it is not necessary to formally search for or remove frames in which no face was found. In these cases the face location is, essentially, stored at 0,0.

```
void flipY(char coords[], char flippedYcoords[])
{
      //GET Y AVERAGES

      coordsfile = fopen(coords);   //open input

      while(1)    //loop forever
      {
            linearray = fgets(coordsfile); //get a line

            if (linearray == NULL) break; //break if EOF

            Y1tot=Y1tot+linearray[6];     //Y1 total
            Y2tot=Y2tot+linearray[13];    //Y2 total
            Yftot=Yftot+linearray[20];    //Y-face total
            count++;
      }

      fclose(coordsfile);

      //calculate average Y value
      Y1avg=Y1tot/count;
      Y2avg=Y2tot/count;
      Yfavg=Yftot/count;


      //FLIP AND REWRITE THE Y's
      //start back at the beginning
      coordsfile = fopen(coords);   //open input
      flippedfile = fopen(flippedYcoords); //open output

      while(1)    //loop forever
      {
            linearray = fgets(coordsfile);  //get line

            if (linearray == NULL) break; //break if EOF


            //print to new file
            fprintf(flippedfile,linearray[0-12],
                  2*Y2avg-linearray[13],
                  linearray[14-19],
                  2*Yfavg-linearray[20],linearray[21]);
      }
}
```

Figure 27: flipY pseudo-code

The `flipY` function, begins by calculating the average values of $Y1$, $Y2$, and $Y\text{-}face$. This gives a center point for the signal to be flipped over. Once the average has been calculated the input file is reopened and rewritten 1 line at a time. Everything is written exactly as it was read except $Y1$ & $Y2$. These values are subtracted from 2 times the average value. This has the effect of flipping the entire signal about the average value.

III.2.3. Filtering the Coordinates

Filtering of the location data is necessary for several reasons. The biggest need of filtering comes from the fact that movement in the X direction causes artifacts to appear in both the Y and Z directions. Movement in the Z direction causes artifacts to appear in both the X and Y directions. This behavior is illustrated below in Figure 29. This author's best estimate as what causes these anomalies relates to disparity error caused by the discrete nature of the pixels on the CCD. Motion in the real world is analog and continuous. The CCD has a finite resolution and, thus, each pixel associates with a square of visual data that gets larger and larger as the region of interest moves farther away from the camera. (Figure 28) This anomaly appears to come from only the X & Z directions because the X direction is used to calculate the Z value and the X direction is the one in which the natural, desired, disparity occurs. The Y value in both the left and right are virtually identical and are not their disparity is not even analyzed.

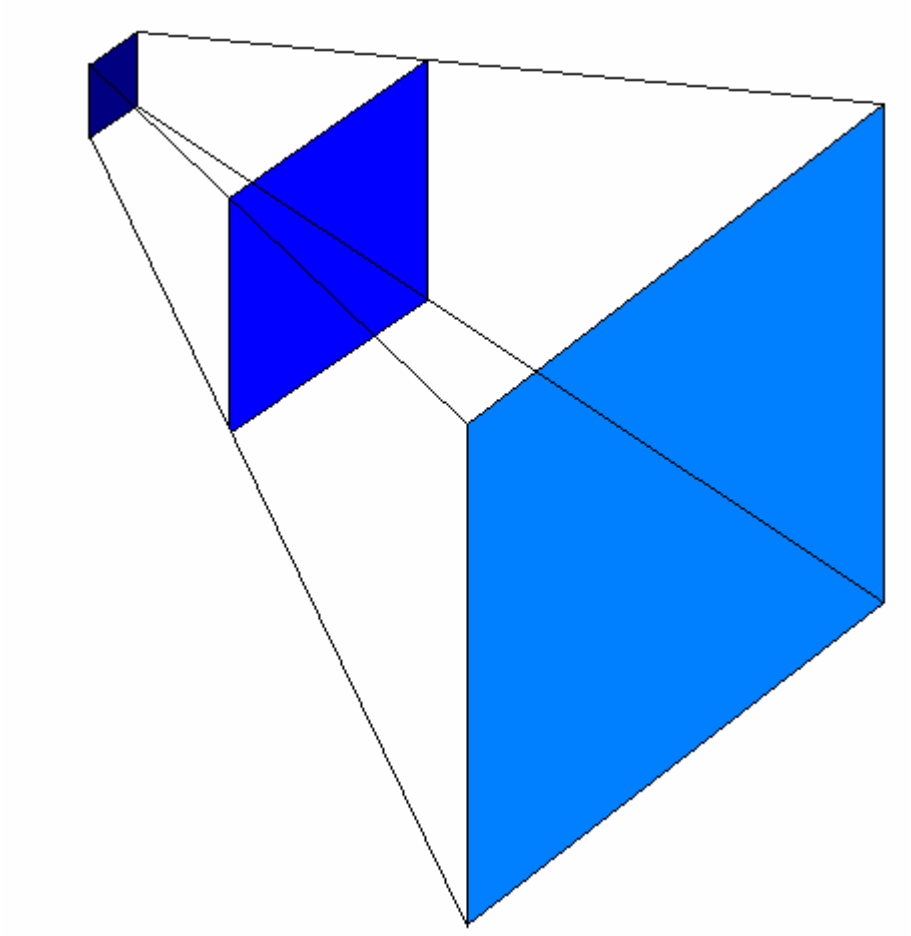


Figure 28: Pixel Area WRT to Distance

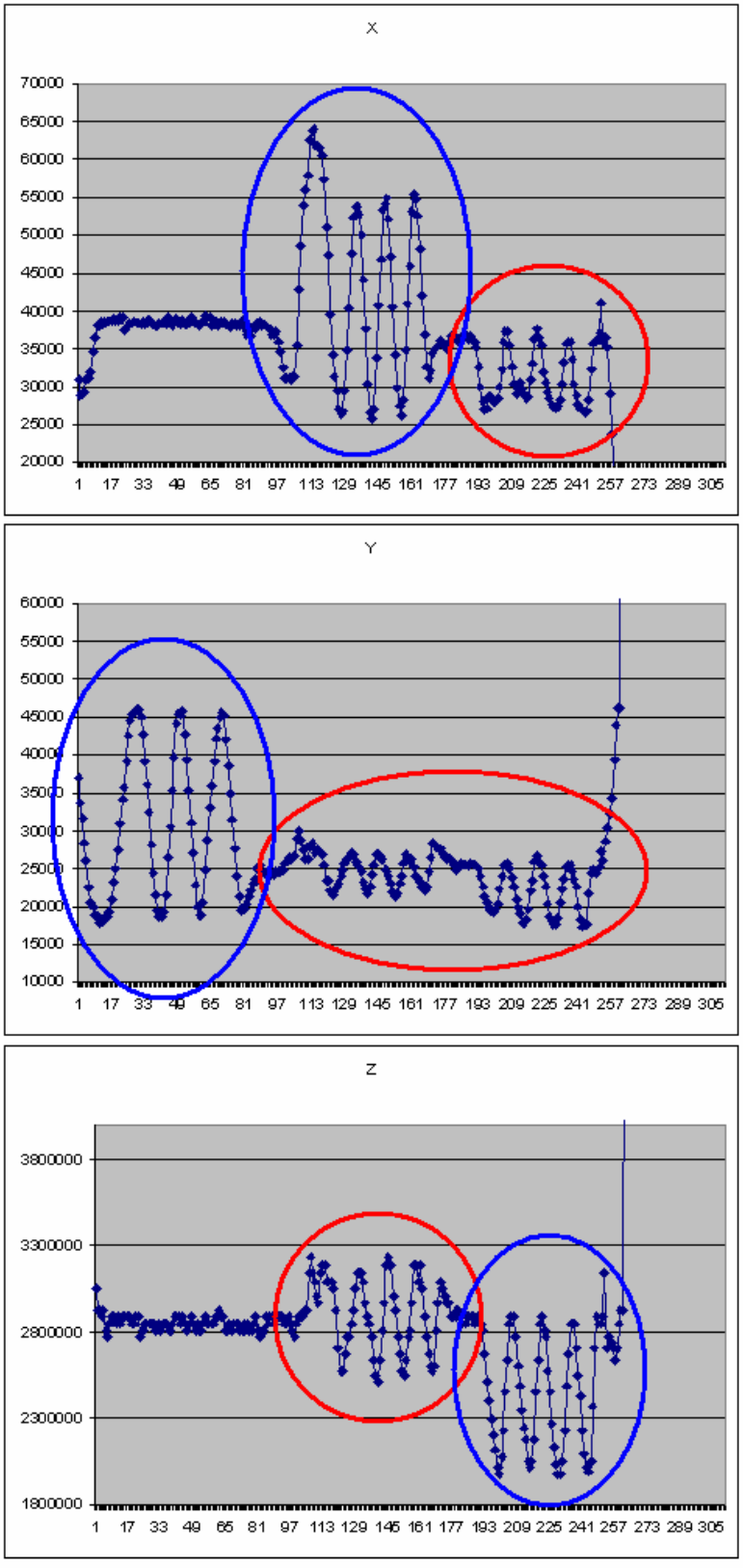


Figure 29: Motion Artifact Illustration

Each graph is titled either X, Y, or Z. These graphs correspond to what recorded motion has taken place in the X, Y, and Z directions. The motion that formed these graphs involved moving an object of interest 1 meter first in the Y, then the X, then the Z direction. That is, first up and down, then left and right, then out and in. The blue circles identify portions of the motion that correspond to actual movement. The red circles identify apparent motion that did not actually happen. These sections are caused by artifact motion from either the X or Z motion.

To get rid of the artifacts a filter was developed which has been called the Difference Filter. This filter was devised by this author after analysis of graphs, similar to those in Figure 29, in Microsoft Excel. It was found that the anomalies corresponded to the motion in other directions exactly, from both a temporal and relative magnitude standpoint. Experimentation was then done to develop the appropriate equations. The filter simply subtracts a scaled version of the offending cardinal direction from the affected direction. The Difference Filter works according to the equations shown in Figure 30. The values of 0.008 and 0.025 were found experimentally. An example of difference filtering on the Y axis of the same motion example can be seen below in Figure 31. It is the opinion of this author that no better, and if so only marginally better, results could be achieved using a more complex and computationally intensive higher-order filter.

Difference Filter Equations

$$X[i] = X[i] - Z[i] * 0.008 \quad (8)$$

$$Y[i] = Y[i] - Z[i] * 0.008 \quad (9)$$

$$Z[i] = Z[i] * 0.025 - X[i] \quad (10)$$

Figure 30: Difference Filter Equations

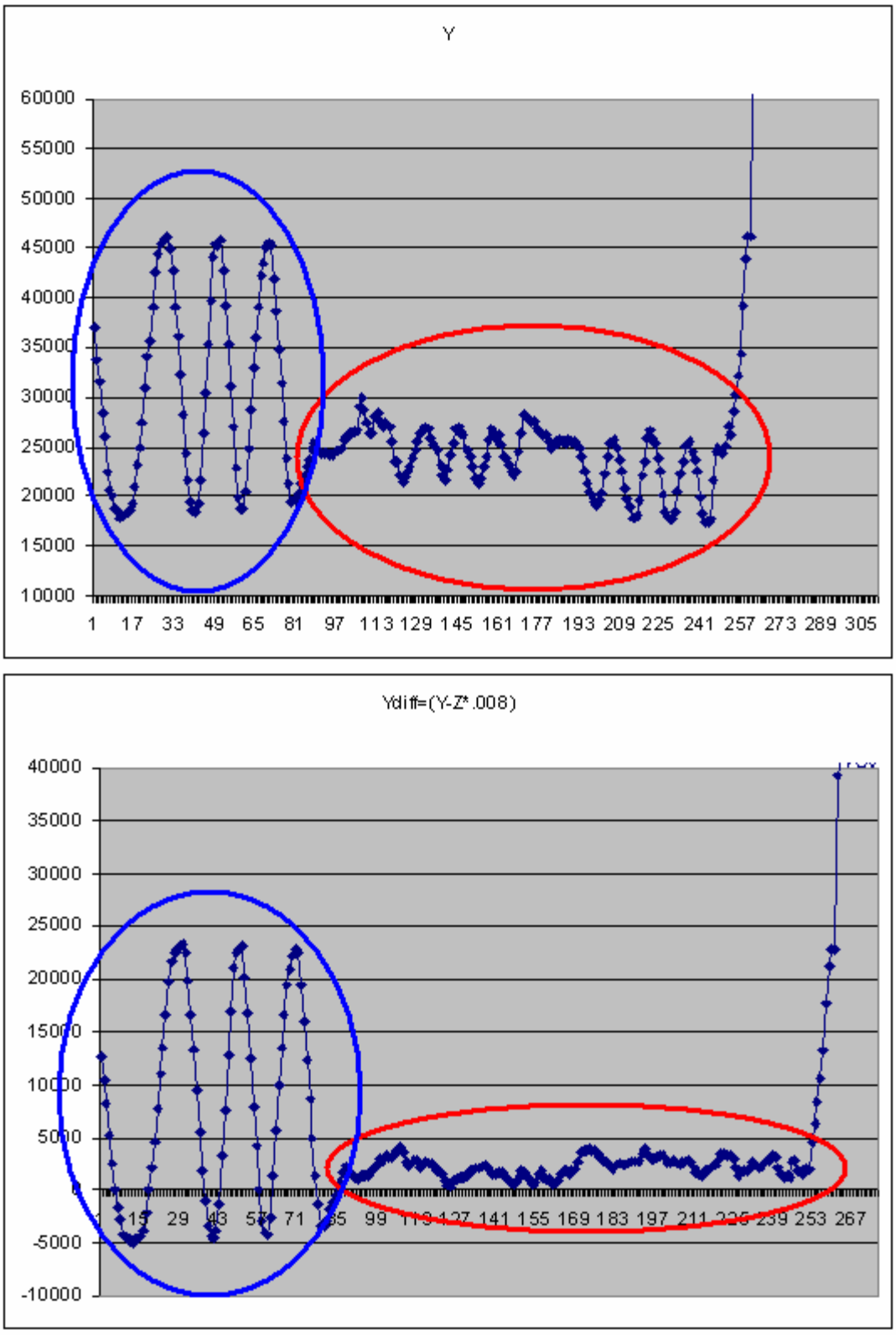


Figure 31: Difference Filter on Y

The first graph is of the unfiltered Y signal. The second graph shows the same signal after undergoing a difference filter where the Z signal (which is effected by X artifacts as well) scaled by 0.008 and then subtracted from the original Y signal. Again, the red circle indicates where the artifact motion was. The blue circle identifies the actual, desired, Y motion. Its shape and relative magnitude are left unchanged.

Most of the experimentation with the difference filter was done using Microsoft Excel. In order for the difference filter to be included into the system it had to be implemented in C++ which turned out to be fairly involved. Since the code is quite long Figure 32 shows pseudo-code to help you understand how it was implemented. The full code can be found at the end of this document in the code listing under the `filterCoords` function.

```
void filterCoords(char coords[], char tempcoords[], char filteredcoords[])
{
      //FILTER PASS 1 (DIFFERENCE OF X & Y)
      coordsfile = fopen(coords, "r");    //open coordinates
      tempfile = fopen(tempcoords, "w");  //open file to write too

      fclose(coordsfile);

      //start at the beginning of the file
      coordsfile = fopen(coords, "r");    //open coordinates
      while(fgets(coordsfile) != NULL)    //loop through coordsfile
      {
            line = fgets(coordsfile); //get a line from coordsfile

            //difference filter X & Y
            dfiltered[X]=line[X]-line[Z]*.008;
            dfiltered[Y]=line[Y]-line[Z]*.008;

            //save line to tempcoords file
            fprintf(tempfile, dfiltered[X], dfilterd[Y], dfiltered[Z]);
      }

      //close files
      fclose(coordsfile)

      //FILTER PASS 2 (DIFFERENCE FILTER Z)
      coordsfile = fopen(tempcoords, "r"); //open temp coordinates
      filteredfile = fopen(filteredcoords, "w"); //open write file

      while(fgets(coordsfile) != NULL)    //loop through coordsfile
      {
            //get next line
            line=fgets(coordsfile);

            //difference filter Z
            dfiltered[Z]=line[Z]/40-line[X];

            //print line to file
            fprintf(filteredfile, dfiltered[X], dfilterd[Y],
            dfiltered[Z]);

      }
}
```

Figure 32: filterCoords pseudo-code

As the comments in the pseudo-code suggest, the filtering is split into 2 passes. This is because the filtered X signal must used for the difference filtering of the Z signal,

otherwise the Z signal's presence in the X signal would entirely cancel it out. The code begins by opening up the appropriate text files. A while loop then beings which cycles through every entry in the coordinates file. Each entry is then Difference filtered. The filtered point is then written to a new, temporary, file. Once the first pass is completed, the second pass is begun which applies the Difference filter to the Z signal. This pass has the same basic structure as the first pass. This second pass uses the output of the first pass as its input and writes to the final filtered coordinates file.

III.2.4. Compressing the Coordinates

Once the filtering of the coordinates has been completed there are still many more data points than is necessary to describe the generalize motion of the target objects. It is important to reiterate that, in the project, the goal has been to replicate the gestures of a human user. Where possible the system has been modeled in such a way as to approximate human behavior both in method and result. If a human were to replicate another human's gestures an exact measure of their movements would not be taken. Instead a general sense of the motion would be gathered by focusing on the major changes in velocity and direction. Compression takes place here in a similar fashion with similar motivations and results.

Generally speaking, the system looks for changes in direction of the motion on a specific axis. When that change in direction is found the system checks to see if there is sufficient is a change magnitude when compared to the previous change in direction.

This acts as a final filter to eliminate insignificant motion or noise in the system. Figure 33 displays the pseudo-code for the point compression.

```
void compressCoords(char coords[], char compressedcoords[])
{
      coordsfile = fopen(coords, "r"); //open uncompressed coords
      compressedfile = fopen(compressedcoords1 "w"); //open file to
                                                     //hold compressed
                                                     //coords

      //get 1st uncompressed XYZ point, print, & save as lastpoint
      lastpoint=fgets(coordsfile);
      fprintf(compressedfile, lastpoint); //print 1st line to output

      lastsavedpoint = lastpoint;   //fill in last saved point buffer

      currpoint=fgets(coordsfile);  //get 2nd uncompressed XYZ point
                                    //and save as currpoint

      //set the direction of each axis
      for(i=1;i<4;i++)
      {
            pointdiff[i] = currpoint[i] - lastpoint[i];
            if (pointdiff[i] > 0) direction[i]=1;
            else if (pointdiff[i] < 0) direction[i]=-1;
            else direction[i]=0;
      }

      while(1)    //loop through the rest of the uncompressed points
      {
            lastpoint=currpoint;    //update last point

            currpoint=fgets(coordsfile);  //get the next point

            //if we reach the end of the file, break out of the loop
            if(currpoint = NULL) break;

            //get temporary directions
            for(i=1;i<4;i++)
            {
                  pointdiff[i] = currpoint[i] - lastpoint[i];
                  if (pointdiff[i] > 0) temppdir[i]=1;
                  else if (pointdiff[i] < 0) temppdir[i]=-1;
                  else temppdir[i]=0;
            }

            //check for changes in direction, if a change is found
            //check that the magnitude of the change is large enough
            for(i=1;i<4;i++)
            {
```

```
                    if (tempdir[i] != direction[i])
                    {
                          if(abs(currpoint[i]-lastsavedpoint[i]) > 1000)
                          changeflag = 1;
                    }
              }

              //if a change has occurred, print & save the point
              if (changeflag)
              {
                    fprintf(compressedfile, lastpoint);
                    lastsavedpoint = lastpoint;
              }

              changeflag=0;     //reset changeflag

              //update directions
              direction=tempdir;
        }
}
```

Figure 33: compressCoords pseudo-code

The code begins by opening the uncompressed coordinates file and creating a file to hold the compressed results. The first point is then read in and saved as the `lastpoint` and `lastsavedpoint`. The `lastpoint` is the most recently opened by before the current point and is used to check for a change in direction. The `lastsavedpoint` is that most recent point that has been identified as a suitable change of direction point and has been saved to the compressed output file. Next the second point is retrieved and saved as the `currpoint` (current point). The `currpoint` and `lastpoint` are used to calculate the initial direction, that is, does the signal in the X, Y, & Z directions have a positive or negative slope. This is done by subtracting the last point from the current point. If the number is positive, that means that the `currentpoint` has a greater magnitude then the last point and the slope is

positive. If it is negative then the slope is negative. If the answer is 0 they have the same magnitude. Now the main loop can begin and the rest of the points can be analyzed. The loop first updates the `lastpoint` and then gets the next point in the file. If that attempt returns `NULL` it means that the end of the file has been reached and it is necessary to break out of the loop. Temporary directions are then found for the current point versus the last point in the same manner as the original directions were found. The temporary directions (`tempdir`) are then checked against the previous directions (`directions`), if an inconsistency is found in either X, Y, or Z, that means that a change in direction has occurred. The change is then checked for magnitude by subtraction of the current and last points. If the change is less then 1000, it is ignored. If it is greater, it is considered significant enough to be recognized and the `changeflag` is set from 0 to 1 to indicate that a valid change in direction has occurred. If a change has occurred then the point is saved to the compressed points output and the `lastsavedpoint` buffer is updated. Regardless of the state of `changeflag` it is then reset to 0 and the directions are updated. This process continues until the entire set of points has been analyzed. Figure 34, below, shows a graphical representation of this technique in action.

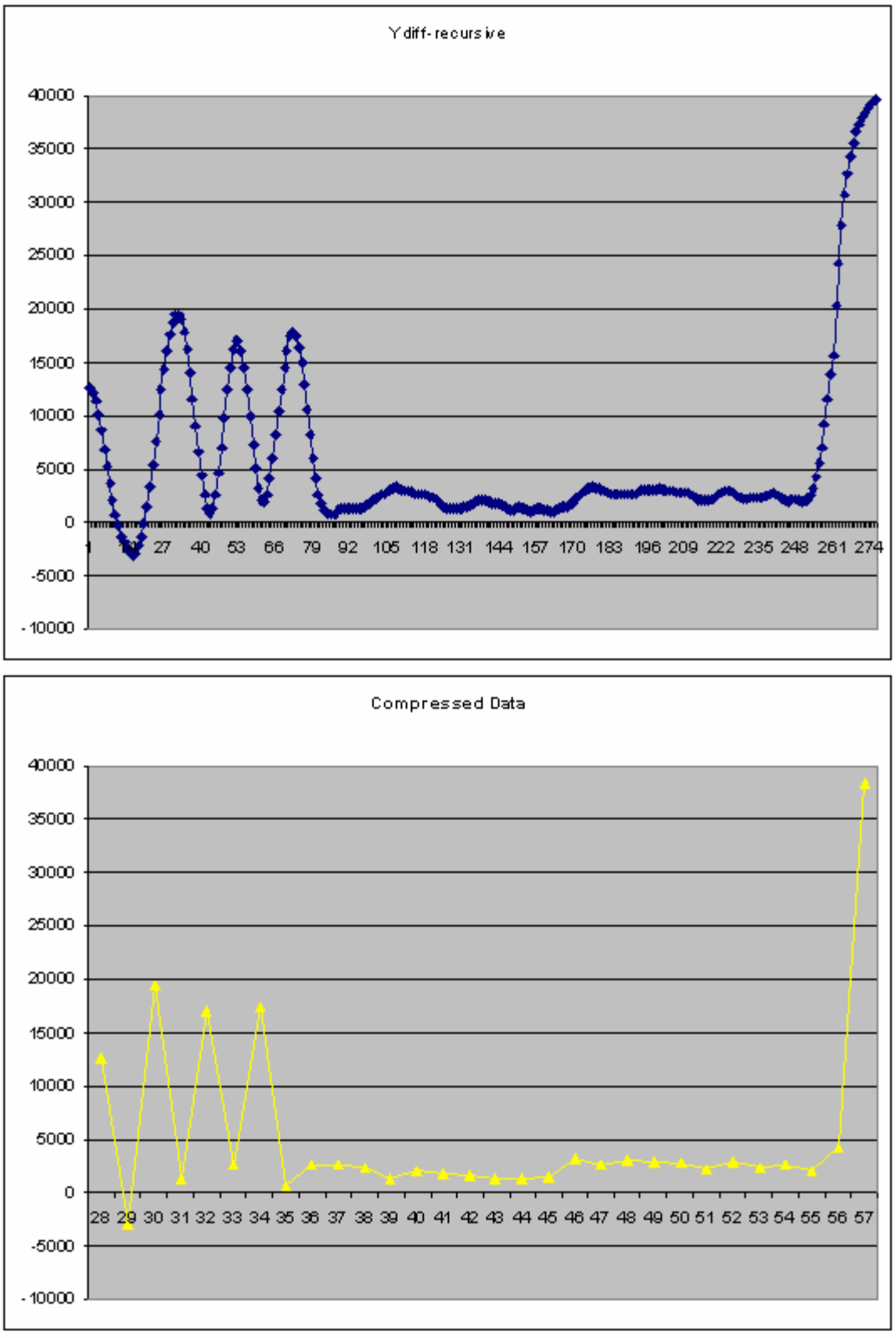


Figure 34: Compression on Y

The compression algorithm is designed to save points that represent a major change in direction of the X, Y or Z signals. The beginning of the graph from 28 to 35 shows an excellent example of where the Y signal was the driving factor for points being saved. The rest of the graph, from points 36 to 56, contains points that were saved due to changes in either the X or Z directions. The last point at 57 is due to the removal the object of interest from ISAC's field of view at the end of the test. As the graph demonstrates, a significant amount of compression takes place while the general shape of the signal is still maintained. In this particular case the number of points was reduced from 276 points to 29 points. In this case, the signal is adequately represented by 90% fewer points. The number of necessary points in this example would be significantly less if the only sizable motion in the test was in the Y direction because almost all of the points on the graph between 35 and 57 would be eliminated bringing the total point count down to about 10.

III.2.5. Fitting the Coordinates to ISAC's Workspace

Once filtering and compression have been completed the coordinates are still in relative units. These units are not compatible with ISAC's workspace. In addition, ISAC represents the world as a rotation of the original representation of the world. Where originally, the Y is vertical, X horizontal, and Z away from ISAC, ISAC sees the world with Z being vertical, Y horizontal, and X away from himself. To make the coordinates compatible a conversion was necessary. This conversion, essentially, switches the axes appropriately and further alters the coordinate signals to fit within ISAC's

workspace. This involves both a scaling and a shift. ISAC's workspace is an irregular manifold. To simplify calculations, a cubic subset of ISAC's workspace was used. To calculate these scaling and shift factors a sample workspace for ISAC was analyzed a method for finding the appropriate factors automatically was devised. The method works by first finding the minimum and maximum values of X, Y, & Z. Then calculating their difference to find the range of a given direction. The range is divided by ISAC's range to come up with a scale factor in X, Y & Z. Then a shift factor is computed by dividing a known point in the original space by the scale factor and subtracting the associated known point in ISAC's space. Figure 35, below, shows the pseudo-code that carries out this operation.

```
void fitCoordsToISAC2(char coords[], char fittedcoords[], int rl)
{
	coordsfile = fopen(coords);   //open our coords for reading
	fittedfile = fopen(fittedcoords);   //open a new file for output

	//initialize maxs and mins
	for(i=1;i<4;i++)
	{
		maxs[i]=-999999999999;
		mins[i]=999999999999;
	}

	//find the maxs and mins for X, Y, & Z
	for(;;)
	{

		//get the next point in the file
		currpoint=fgets(coordsfile);

		//if we have reached the end of the file, break the loop
		if (currpoint == NULL) break;

		//find current maxs/mins
		for(i=1;i<4;i++)
		{
			//maxs
			if(currpoint[i]>maxs[i]) maxs[i] = currpoint[i];
			//mins
			if(currpoint[[i]<mins[i]) mins[i] = currpoint[i];
		}
	}
	fclose(coordsfile);

	//CALCULATE DIFFERENCES
	for(i=1;i<4;i++)
	{
		diffs[i]=maxs[i]-mins[i]; //get the range of each axes
	}

	//FIND BIGGEST RANGE & DIVIDE DIFFERENCE BY ISAC'S RANGE
	if(diffs[1] > diffs[2])
	{
		//ensure movement is greater then a minimum
		if (diffs[1] > MIN_MOVEMENT)
			div = diffs[1]/(ISAC_Y_MAX-ISAC_Y_MIN);
		else
			no_move = 1;
	}
	else
	{
		//ensure movement is greater then a minimum
		if (diffs[2] > MIN_MOVEMENT)
			div = diffs[2]/(ISAC_Z_MAX-ISAC_Z_MIN);
		else
			no_move = 1;
	}
```

```
	//CALCULATE SHIFT FACTOR based on Face Location
	shift[1]=(mins[1][1]/div-FACE_Y)*-1;
	shift[2]=(maxs[1][2]/div-FACE_Z)*-1;

	//IF RIGHT ARM :: GET LARGEST LEFT/RIGHT (X->Y) VALUE
	armshift = maxs[1][1]/div+shift[1];

	coordsfile = fopen(coords);   //open our coords for reading

	//REWRITE FILE LINE BY LINE APPLYING SCALE & SHIFT & REARRANGE
	for(;;)
	{
		currpoint = fgets(coordsfile); //get the next point
		if(currpoint == NULL) break;  //if we reach EOF, break loop

		modpoint[0]=currpoint[0] //new TIME = old TIME

		//scale & shift the point
		for(i=1;i<4;i++)
			modpoint[i]=currpoint[i]/div+shift[i];

		if (rl == RIGHT_ARM) //shift if right arm
				modpoint[1]=modpoint[1]-armshift;

		//SAFTEY SHIFT
		//shift the points further from the center to ensure ISAC
		wont hit his own hands together
		if (rl == RIGHT_ARM)
			modpoint[1]=modpoint[1]-SAFETY_SHIFT;
		else
			modpoint[1]=modpoint[1]+SAFETY_SHIFT;

		//write to the new file in ISAC's order
		if (no_move)
			fprintf(fittedcoordsfile,"%f,%f,%f,%f\n",modpoint[0],
			FOREARM+HAND_L,CENTER_TO_ANGLE_0+SHOULDER_OFFSET,-
			UPPERARM);
		else
			fprintf(fittedcoordsfile,"%f,%f,%f,%f\n",modpoint[0],
			CONST_X,modpoint[1],modpoint[2]);
	}
	//close our file handles
	fclose(coordsfile);
	fclose(fittedfile);
}
```

Figure 35: fitCoordsToISAC pseudo-code

The function, like most, begins by opening the existing coordinates file for reading and a second, empty file, for writing the output to. The `maxs` and `mins` are then initialized to very large and very small values, respectively. The actual `maxs` and `mins` of each axis are then found by looping through the points, and recording the largest and smallest values replacing them when necessary. Once the `maxs` and `mins` are found the computation of the scale and shift factors begins. First the differences of each max and min set (X, Y, Z) are found. These differences represent the range of each signal. Then the X & Y ranges are compared to find the larger of the two. We then take whichever is larger and use that to compute our scaling factor. If the larger of the two is still below a certain `MIN_MOVEMENT` threshold then the movement is ignored entirely and that arm is instructed to remain in the home position. Assuming that there is suitable movement detected, the larger difference is divided by ISAC's range in that direction and that value is used as our scaling factor. This scaling factor allows for the recorded points to be put into ISAC's range. Next the shift factor is calculated according to the location of the gesture movements relative to the face. A second shift factor that applies only to ISAC's Y motion is then calculated to be applied to the right arm points only. This is done because all of the left and right calculations are virtually identical, and much of the code can be reused if the concession is made to shift the right arm points over at the end. The point is then scaled and shifted according to the previously calculated values. A final "safety shift" is then applied to further move ISAC's arms apart from one another. Finally the scaled and shifted point is written to the `fittedcoords` output file. The axes are written in a modified order to apply the

rotation to ISAC's workspace and the X value is written as a constant `CONST_X`. This is done because ISAC's range in the X direction is very limited and looks proper.

III.2.6. Calculating Joint Angles

The systems calls for approximate mimicking of arm sized gestures. A discrete Inverse Kinematics routine exists. However, for it interface smoothly with the rest of the Processing Subsystem a function must exist to call the Inverse Kinematics routine for each point. This function is called `calcJointAngles` and its pseudo-code is shown below in Figure 36.

```
void calcJointAngles(char coords[], char angles[], int rightleft, int EndEff,
int simple)

      if(!simple)
            pdAngles = new double[6];

      coordsfile = fopen(coords);   //open our input file
      anglesfile = fopen(angles);   //open out output file

      for(;;)
      {
            //get the next point in the file
            currpoint=fgets(coordsfile);

            //breakout of the loop if we reach EOF
            if (currpoint=NULL) break;

            //convert points to appropriate container
            if(simple)
            {
                  point.x = currpoint[1];
                  point.y = currpoint[2];
                  point.z = currpoint[3];
            }
            else
            {
                  for(j=0;j<3;j++)
                        pdPos[j]=currpoint[j+1];
            }
            //INVERSE KINEMATICS
            if(simple)
                  pdAngles = simpleInverseKinematics(point, rightleft);
            else
                  inverseKinematics(pdPos, pdAngles, (short)rightleft,
                        (short)EndEff);

            //write time + joint angles to the new joint angles file
            fprintf(anglesfile,
                  "%f,%f,%f,%f,%f,%f,%f\n",currpoint[0],pdAngles[0],pdA
                  ngles[1],pdAngles[2],pdAngles[3],pdAngles[4],
                  pdAngles[5]);
      }
}
```

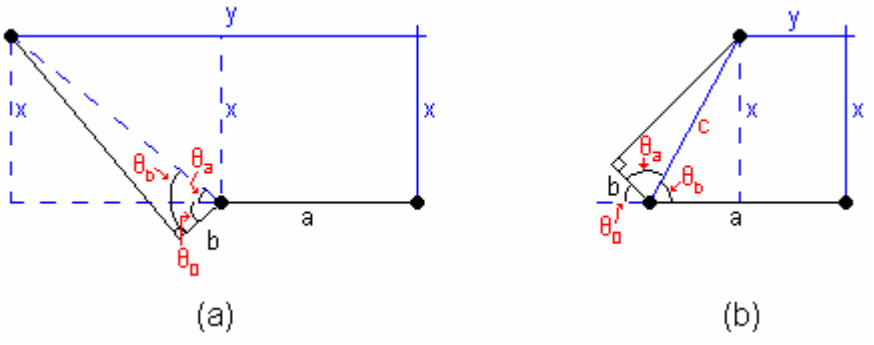
Figure 36: calcJointAngles pseudo-code

This function is essentially a wrapper for the actual Inverse Kinematics. This function allows the user to pass it an entire set of points to be converted and also gives a choice

between a simple and a complex Inverse Kinematics model. The primary difference being whether all joints should be considered or the roll joints (3 and 5) should be ignored. The function begins by opening out the input and output files. Then the input file is looped through and as points are read out of it, the input parameters are checked. If a simple model has been requested, then the point is formatted in a `CvPoint3D32f` and passed along to the `simpleInverseKinematics`. If a complex model has been requested, then the point is formatted in the appropriate array and passed along to it. The request for a right or left arm consideration is passed along as well. The end effector variable is only used for the complex model and is supposed to ignore then end effector when set to 0. In practical testing, however, it does not perform up to expectations. Since the simple Inverse Kinematics model is the model of choice, the complex model will be left at that. The simple model is described in greater detail now.

It is not required that the gripper approach the desired point from a certain direction or with a specific orientation. Therefore the Inverse Kinematics, which allow joint angles to be calculated from a desired 3D point, can be greatly simplified by ignoring the gripper and its complex axes of rotation. When the gripper is not considered, the Inverse Kinematics becomes that of a 3 link manipulator. Angles 0 relates to the rotation of the shoulder about an axis parallel to ISAC's Z axis. Angles 1 & 2 relate to the extension of ISAC's arm at the shoulder and elbow. This configuration allows the Inverse Kinematics to be split into two sub-problems. Angle 0 can be calculated by considering the X & Y coordinates done in such a way as to cause the arm to "point" toward its intended target. Then angles 1 & 2 can be calculated using only the X & Z coordinates to cause the arm to reach out the appropriate distance.

Geometry was used to determine the appropriate angles of joints 0, 1 & 2. Figure 37 displays a graphical representation of the two different cases for angle 0 along with the associated equations.



$$\theta_a = \arctan\left(\frac{x}{y-a}\right) \quad (11)$$

$$\theta_b = \arccos\left(\frac{b\sin\theta_a}{x}\right) \quad (12)$$

$$\theta_0 = \theta_b - \theta_a \quad (13)$$

$$\theta_b = \arctan\left(\frac{x}{a-y}\right) \quad (14)$$

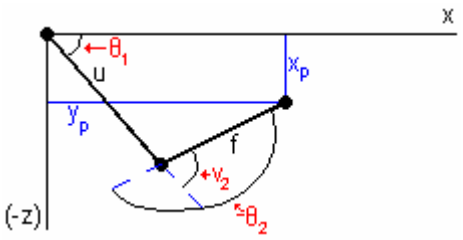
$$c = \frac{x}{\sin(\theta_b)} \quad (15)$$

$$\theta_a = \arccos\left(\frac{b}{c}\right) \quad (16)$$

$$\theta_0 = \pi - \theta_a - \theta_b \quad (17)$$

Figure 37: Angle 0 graphs and equations

Figure 38 displays a graphical representation of the angles 1 & 2 and associated equations. The equations used to calculate angles 1 & 2 were taken directly from the geometric discussion of a 2 link manipulator in *Modelling and Control of Robot Manipulators pgs. 68-69* [28].



$$c_2 = \frac{x_p^2 + y_p^2 - u^2 - f^2}{2uf} \qquad (18)$$

$$v_2 = \arccos(c_2) \qquad (19)$$

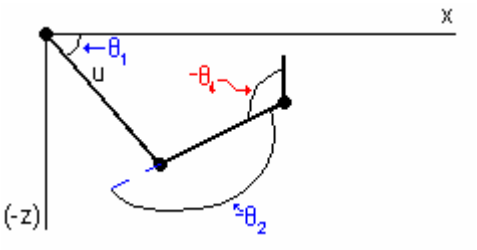
$$\alpha = \arctan\left(\frac{y_p}{x_p}\right) \qquad (20)$$

$$\beta = \arccos\left(\frac{x_p^2 + y_p^2 + u^2 + f^2}{2u\sqrt{x_p^2 + y_p^2}}\right) \qquad (21)$$

$$\theta_2 = -v_2 - \frac{\pi}{2} \qquad \theta_1 = \alpha + \beta \qquad (22), (23)$$

Figure 38: Angles 1 & 2 graph and equations

Lastly, although it is not considered in the calculation of joint angles relative to the target 3D location angle 4 is calculated as well. Instead of attempting to aim the tip of the gripper at the target point the gripper instead points directly up. This is to help give the illusion that ISAC is waving and gesturing back in a realistic manner. Angling the gripper upward exposes ISAC "palm" to the user. FIGURE Z shows a graphical representation of this situation and the corresponding equation used to calculate angle 4.



$$\theta_4 = -(\pi + \theta_1 + \theta_2) \qquad (24)$$

Figure 39: Angle 4 graph & equation

All of these equations were then, of course, translated into C++ code for which the pseudo-code can be seen below in Figure 40.

```
double* simpleInverseKinematics(CvPoint3D32f point)
{
	//set constant holders
	a = CENTER_TO_ANGLE_0;
	b = SHOULDER_OFFSET;
	u = UPPERARM;
	f = FOREARM;
	h = HAND_L;

	//adjust x, y, z for math
	x = point.x;
	y = point.y;
	z = -point.z;

	//Calculate Theta 0 (shoulder X Y)
	if (y >= a)
	{
		Ta = atan(x/(y - a));
		Tb = acos(b*sin(Ta)/x);
		T0 = Tb - Ta;
	}
	else
	{
		n  = a - y;
		Tb = atan(x/n);
		o  = x/sin(Tb);
		Ta = acos(b/o);
		T0 = -(PI - Ta - Tb);
	}

	//Calculate Theta 1 (elbow) & Theta 2 (shoulder X Z)
	alpha = atan2(z,x);
	beta = acos((x*x+z*z+u*u-(f+h)*(f+h))/(2*u*sqrt(x*x+z*z)));
	c2 = (x*x + z*z - u*u - (f+h))/(2*u*(f+h));
	v1 = alpha + beta;
	v2 = acos(c2);

	//conversion to ISAC's frame
	T1 = v1;
	T2 = -v2 - PI/2;

	//Calculate Theta 4 (wrist up/down)
	T4 = -(PI + T1 + T2);

	//populate return array in degrees
	ret[0]=T0; ret[1]=T1; ret[2]=T2; ret[3]=0; ret[4]=T4; ret[5]=0;

	return ret;
}
```

Figure 40: simpleInverseKinematics pseudo-code

The function follows the equations laid out in FIGURES X & Y exactly. The output of the function is a 6 element array that corresponds to ISAC's 6 joints. As evident in the code, the return array is populated by the calculated theta values except angles 3 and 5 which are purposefully set to 0 as they correspond to the roll of the forearm and wrist, respectively.

III.2.7. interpolateAngles Function

Having ISAC move from one point to another that is physically distant cause visually violent motion. In addition to this being visually displeasing it also increases the likelihood that ISAC damages himself through the aggressive motion. This damage could manifest itself as a simple misaligned chain or it could be more destructive such as a blow muscle. To avoid this situation an `interpolateAngles` function was devise. This function's purpose is to create a set of intermediate points between two original points. This does not conflict with the `compressCoords` function (section III.2.4) as they serve different purposes. `compressCoords` eliminates the notion of variable acceleration in the movement. The `interpolateAngles` function aims to maintain this constant acceleration while smoothing out ISAC's movement. Figure 41 displays the `interpolateAngles` pseudo-code.

```
void interpolateAngles(char anglesIn[], char anglesOut[])
{
      anglesInFile = fopen(anglesIn);           //open input
      anglesOutFile = fopen(anglesOut);         //open output

      //get 1st line from anglesIn
      lastangle = fgets(anglesIn);

      while(1)    //loop forever
      {
            //get a line from anglesIn
            currangles = fgets(anglesIn);

            if (currangles == NULL) break; //if we reach EOF, break

            //get the time between 2 sets of angles
            span = currangles[0] - lastangles[0];

            //calculate increments for interpolation
            for(i=1;i<7;i++)
            {
                  increments[i]=(currangles[i] - lastangles[i])/span;
            }

            //write original point + new interpolated points
            for(i=0;i<span;i++)
            {
                        fprintf(anglesOutFile,"%f,%f,%f,%f,%f,%f,%f\n",
                        lastangles[0]+i,
                        lastangles[1]+i*increments[1],
                        lastangles[2]+i*increments[2],
                        lastangles[3]+i*increments[3],
                        lastangles[4]+i*increments[4],
                        lastangles[5]+i*increments[5],
                        lastangles[6]+i*increments[6]);
            }

            //update lastpoint
            for(i=0;i<7;i++)
                  lastangles[i]=currangles[i];
      }

      //print out the last point
      fprintf(anglesOutFile,"%f,%f,%f,%f,%f,%f,%f\n",lastangles[0],
            lastangles[1],lastangles[2],lastangles[3],
            lastangles[4],lastangles[5],lastangles[6]);


      //close files
      fclose(anglesInFile);
      fclose(anglesOutFile);
}
```

Figure 41: interpolateAngles pseudo-code

The `interpolateAngles` function begins by recording the 1st set of angles in the `lastangles` variable. Then the rest of the file is iterated through. During each iteration the new point is read into `currangles`. The `span` variable is calculated to be the range between the `currangles` time variable and the `lastangles` time variable. This tells the function how many points to create in-between. By using a variable number of interim points, the timing is kept consistent. The function then calculates the increments necessary to go from the `lastangles` value to the `currangles` value in number of time steps represented by `span`. The `lastangles` along with the new interpolated angles are then written to the output file. This continues until the last point is reached at which time the loop breaks out and the last point is written

III.2.8. Uploading The Coordinates To ISAC's Control Systems

The final step that is executed on the machine *Sally* is to upload the coordinates to a location that can be accessed by the Arm Control System which is located on a, physically, separate machine known as *Octavia*. This is done by simply reading the final filtered, compressed, and fitted coordinates file and writing it onto a shared location at `I:/Temp/uploadL.txt` and `I:/Temp/uploadR.txt` corresponding to the points that the left and right arms should follow. The, condensed, code is show below in Figure 42.

```
void uploadCoordsToNNbatch(char uploadL[], char uploadR[], char coordsL[],
char coordsR[])
{
	char line [512];	//holder for a single line of a coordsfile as
				//it is parsed
	FILE *uploadfileL; //file handle for temp upload file to send
				//info to the NN L
	FILE *uploadfileR; //file handle for temp upload file to send
				//info to the NN R
	FILE *coordsfileL; //file handle for coords to be uploaded L
	FILE *coordsfileR; //file handle for coords to be uploaded R

	//open coords files
	coordsfileL = fopen(coordsL, "r");  //coordinates to be uploaded
	coordsfileR = fopen(coordsR, "r");  //coordinates to be uploaded

	uploadfileL = fopen(uploadL, "w");
	uploadfileR = fopen(uploadR, "w");

	//copy to a text file on the shared I drive for use by the Neural
	//Network Controller
	for(;;)
	{
		if(fgets(line, 512, coordsfileL) != NULL)
		{
			fprintf(uploadfileL, line);
		}
		else break; //if we reach EOF, break out of the loop
	}

	for(;;)
	{
		if(fgets(line, 512, coordsfileR) != NULL)
		{
			fprintf(uploadfileR, line);
		}
		else break; //if we reach EOF, break out of the loop
	}

	fclose(uploadfileL);
	fclose(uploadfileR);
	fclose(coordsfileL);
	fclose(coordsfileR);
}
```

Figure 42: uploadCoordsToNNbatch (condensed)

After the declaration of variables, the function starts by opening up 2 local coordinates files that correspond to the left and right arms' paths. Then 2 files are opened up for

uploading purposes that are on a shared network drive. The next step is repeated twice, once for each set. A loop is setup and a line is simply read from the local drive and written to the network drive until the upload is completed.

III.3. Control/Arm System

While Vision and Processing are bundled together on the Windows XP machine *Sally*, the Control System is separate on located on a Windows 2000 Machine named *Octavia*. The system is built on the locally written Neural Network / PID Controller by Erdemir and Ulatas. Their contribution is discussed in more detail in section II.4.3. The rest of this section will describe the controller as it relates to the project.

III.3.1. The Controller

The actual controller is a combination Neural Network / PID controller. At its most basic level it works like this. The controller takes in a set of joint angles, which is fed to a lookup table whose values have been populated using a Neural Network training method. This lookup table associates joint angles to specific air pressures that should be in each muscle represented by voltages than need to be applied to the valves. A certain amount of time is given for this portion of the controller to bring the arm as close to the objective point as possible. Then the PID portion kicks in. This portion reads in actual joint angles, computes the location that the arm is reaching to, and compares it to the objective point. If the points do not match, then adjustments are made. This is continued for set amount of time to give the arm a chance to reach its

destination. Either one of these sections can be disabled making the controller purely Neural Network or purely PID based.

III.3.2. The Modifications

The original design of the controller had the desired point hard coded in and allowed for only a single point to be reached to per run of the software. The devised system requires that a set of points be achieved in series. The bulk of the modifications to the controller revolved around making this happen. The modifications started with the replacement of the hard coded goal point with code that opened up a text file and read the desired point in. This text file corresponds to the file uploaded by the Vision and Processing System. The entire `main` function was then wrapped in a loop that would allow for multiple points to be read in and moved to in succession. Several minor modifications were necessary to make this all happen but they were mostly minutiae related to coding, not to the essence of the software.

III.3.3. Integration with the Vision & Processing Systems

The integration of the Control System with the Vision & Processing Systems is fairly straight forward. Wrapping both systems in TCP/IP code and having the system communicate live over the network was considered. Upon further scrutiny, however, it was decided that approach was unnecessary and added complexity but did not enhance the capabilities of the system itself. Instead a simpler approach was taken. The Control System is started up first. The Vision & Processing System is started up

second. The Vision & Processing Systems works through, as described in sections III.1 and III.2, and finish their execution by first uploading the coordinates files to `I:/Temp` and then uploading an indicator file. Meanwhile, the Control System is sitting in a loop searching for this indicator file. When it finds it, it begins execution by downloading the coordinates files. When the Control System has completed, it deletes the indicator file resetting for another run.

CHAPTER IV

EXPERIMENT

IV.1. Goals

Due to the nature of the project, the results are necessarily subjective. The goal of the project was to create a system by which ISAC could see and mimicking arm gestures. Thus, the final output of the system is the movement of ISAC's arms and the main standard by which the quality is measured lies with the observer. This makes traditional experimentation difficult. A truly in-depth experiment regarding the quality of the yield of this project would require something akin to a double blind study where by the individual observing the output would have no knowledge of the input and associates would be need to be made. This type of experiment is outside the scope of this project and besides that, the logic fails in a minor way. The system has been designed to allow ISAC to repeat a gesture back to a user. Therefore, given the current design of the system and the original project goals, the individual observing the system's output will always be either the user supplying the input or another individual within close proximity who has had the opportunity to see both the input and the output. Therefore, the specific goal of this experiment will be a subjective one whereby the user supplying the input will have to judge whether the output is sufficiently similar.

IV.2. Procedure

An experiment will be conducted by which a user will move their hand slowly and steadily in the specified directions. ISAC's response will be monitored and the observations will be distilled down into either a recognizable or unrecognizable gesture. The user will perform the following gestures. If only 1 hand is listed as moving, the other should remain still.

1. Left hand, Y axis, ½ meter, 3 repetitions
2. Right hand, Y axis, ½ meter, 3 repetitions
3. Left hand, X axis, ½ meter, 3 repetitions
4. Right hand, X axis, ½ meter, 3 repetitions
5. Both hands, Y axis, ½ meter, 3 repetitions
6. Both hands, X axis, ½ meter, 3 repetitions
7. Left hand, diagonal upper left to lower right, 3 repetitions
8. Right hand, diagonal upper left to lower right, 3 repetitions

Figure 43: Experiment Tests

After a test is performed ISAC will, by design, repeat the gesture. The output behavior will be noted, the gesture will be classified as recognizable or unrecognizable, and any

abnormalities will be noted. Additional an approximation of the range of ISAC's repeated motion will be given.

IV.3. Results

Trial #	Recognizable?	≈Distance Moved	Notes
1	Yes	24"	A bit of extra Z motion ≈12"
2	Yes	24"	A bit too low
3	Yes	20"	Forearm flops at apex
4	Yes	20"	-
5	Yes	20"	Movement is a bit out of sync
6	Yes	20"	Forearm flops at apex
7	Yes	18"	-
8	Yes	18"	-

Figure 44: Experiment Results

IV.4. Discussion

Overall the results of the experiment were deemed acceptable. There are areas where the motion could be improved. Most of this work will go into the controller and devising ways of providing for smooth movement. As was noted in Figure 44, in some cases there was extraneous movement. This implies that, while the human operators movement was primarily in, say, the Y direction, there was some output movement in another direction. While this occurred it was of a lesser magnitude then the intended movement and did not hinder the gesture as being recognizable.

Trial 1 involved moving the left hand back and forth along the Y axis a distance if ½ meter. The results were good although there was a bit of movement in the Z axis that was not desired. This is partially due to error inherent to the disparity calculations and partially due to error in the Neural Network. The arm moved over approximately a 24" range.

Trial 2 was a copy of trial 1 using the right hand instead of the left hand. Again the movement was good, there was a slight bit of extraneous Z axis motion and the entire motion occurred over a range of approximately 24".

Trials 3 and 4 were very good. They had the user moving their left and right hands, independently, up and down a distance of ½ meter. ISAC repeated these actions very well although the left forearm has a tendency to fall back onto the left upperarm when it passes vertical. This is because, in the current architecture of ISAC, the rear upper-arm muscles have been disabled. This provides no tension to avoid this problem displayed here. The movement ranged over approximately 20" in both trials.

Trials 5 performed well, very similar to trials 1 and 2 although a new, minor issue, was introduced. There is a bit of a temporal shift in one arm compared to the other. What this means is that, although the user moved their arms in sync, ISAC moved his arms out of sync.

Trial 6 was very good and very similar to trials 3 and 4. The left arm suffered from the same problem as in trial 3. This problem is not as apparent in ISAC's right arm because ISAC's right gripper is lighter then his left. This puts less torque on the right elbow. The motion in this trial was approximately 20" for both arms.

Trials 7 and 8 were very good as well. The motion was quite recognizable and the only issue to speak of was in smoothness of motion. An upgrade to the controller would help to work out this problem. It is necessary that the controller operate at a fast enough pace to keep the arms in motion. Jerkiness appears when the arm is asked to start and stop at each via point along its path. The motion in both trials 7 and 8 occurred over a path of approximately 18".

As a basis for Imitation Learning the entire project is considered a success. It is this author's hope that future work goes into the project to improve it in every way possible. Many areas for improvement are been discussed in section V.2.1.

CHAPTER VI

WRAP-UP

V.1. Conclusion

Throughout many months of work, this project has gone from experiments with a cheap webcam to a fully functional system that employs most all of ISAC's available hardware to complete its goal. The system successfully bestows the ability to track simple arm gestures, performed by a human user, and repeat said arm gestures back in a recognizable way. Throughout the development many surprises were overcome. Additionally many subsystems were created that were not originally anticipated. Improvements to the Neural Network based controller and a complete, from scratch, creation of an Inverse Kinematics solution were not expected but proved beneficial to the system. The entire concept of filtering the signals was not projected. However, it was, like all other obstacles overcome. The system effectively combines elements of computer vision, signal processing, kinematics, and control systems to achieve the goals set forth at the start of the project and is considered a success.

V.2. Recommendations for Future Work

While the system that has been developed is quite robust and flexible there is, of course, room for improvement. In addition the creation of the system has led to the

development of several ideas for tangent projects that could be beneficial. This section will describe the possible improvements and potential projects that have arisen out of the months of work that have gone into the system.

V.2.1. Improvements to the Current System

V.2.1.1. Save/Load of frames as BMPs

There are several instances where a shortcut was taken and those areas should be revisited. The instances in question never hurt the functionality of the software but sometimes would result in lower performance. The first instance is in the retrieving of frames from the cameras and loading of said frames into IplImage structures. In the current version of the software, the retrieved frames are saved as a BMP file on the local hard drive of the machine and then reopened and loaded into an IplImage structure. This, of course, is functional but it is the opinion of this author that higher performance could be achieved during the recording of the gestures if this step of saving as and open up a BMP file could be eliminated. Ideally the frame, retrieved from the cameras would be loaded directly into an IplImage structure.

V.2.1.2. Colored Gloves

The current setup requires that the user wear brightly colored gloves or hold brightly colored objects to assist in the detection of the hands. The initial exploration of the project found that Haar-detection of hands was not feasible given the types of sample image that were able to be generated in the lab. In addition detecting hands

using color segmentation proved difficult as most of the lab environment is of a hue similar to human skin. The walls are beige, the doors and shelves are tan. Both of these colors share the same basic hue as human skin. It would be ideal if the colored gloves requirement could be lifted. This could come about by revisiting Haar detection, exploring Kalman filters, or investigating some other technology. Perhaps a combination of existing technologies would prove effective. Regardless, the colored gloves requirement is the only requirement related to the user wearing equipment and it would be practical to eliminate it.

V.2.1.3. Keyboard Start/Stop of Gesture Recording

At the present time, the recording of a user's gesture is started and stopped via a keystroke on the keyboard of the *Sally* PC. This makes it difficult for a single user interact with ISAC using the system and it also acts as a deterrent for repeated gestures mimicking, although it does not prohibit it. Modification to the start/stop mechanism to eliminate this reliance on the keyboard would be useful. One possibility is to integrate voice recognition and allow the user to start and stop gesture recording with a voice command. Perhaps a specific gesture, such as the shake of the both hands, could initiate gesture recording. A discontinuation in hand movement could signal the completion of a gesture and stop gesture recording. No matter what solution is chosen, removing this restriction would add usability and flexibility to the system.

V.2.1.4. Objects Leaving ISAC's Field of View

Currently, when ISAC is recording a gesture, he simply looks for the location of the hand (colored object) in both images and calculates the 3D location using that information. This, essentially, fails when the object leaves the FOV of one of ISAC's eyes but not the other. When this happens the points no longer correspond and a false value is recorded for the 3D location. It would be advantageous for this problem to be addressed. It could be as simple as pausing recording when an object leaves the FOV of one of ISAC's cameras. A more complex, but also more complete, solution might be to have ISAC track the object via his pan-tilt units. Were such a subsystem created, it could integrate seamlessly with the rest of the Processing and Control code in the system.

V.2.2. Tangent Projects Built on the Current System

V.2.2.5. Improvement to the Communications Methods

At present, the Vision & Processing Subsystems communicate with the Control System through the upload of files to a shared location along with the upload of a flag file that the Controller searches for to initiate mimicking. A more robust solution would be to incorporate a TCP/IP based protocol. At a higher level, this could be designed as a client/server architecture [43] or perhaps as a publish/subscribe [45] architecture. A move to a system of this type would not only be more resilient against accidentally file deletion, it would also be more flexible allowing many systems to integrate with the current system via standardized protocol.

V.2.2.6. Real-time Gesture Mimicking

Currently the system is designed to go through a gesture recording phase and then move into a gesture replication phase. A tangent project might be to modify the existing system to work in real time. This is a very possible upgrade to the existing system and it may be advantageous to include some sort of software switch that would allow both real-time and record/playback behavior to coexist. To modify the system in such a way as to have real-time mimicking the Vision Subsystem and Processing Subsystem would have to be closely intertwined. Instead of the current scheme where the Processing Subsystem works on a set of points, it would have to be modified to work on each point in turn. This project would benefit from the communications upgrades outlined in section V.2.2.5. In addition to real-time behavior a switch could be put in to allow for mirrored mimicking or non-mirrored mimicking. Presently, the mimicking is not mirrored. When the user moves their left hand, ISAC responds by moving his left hand. In a mirrored configuration, ISAC would move his right hand in response to the user moving his or her left.

V.2.2.7. System Performance Improvements

The frame rate of the current system is about 2.5 FPS (frames per second). In some cases, such as for fast gestures, this may not be sufficient. There are several simple steps that could, reasonably, be taken to improve the performance of the system. The changes outlined in section V.2.1.1 may help. In addition, OpenCV is designed to take advantage of IPP (Intel's Performance Primitives) if they are found on the host machine. IPP is designed to take advantage of machine code level routines

that are specially designed for high performance execution of image and signal processing. By purchasing and installing IPP a performance boost could be seen immediately. Also, the system could be rewritten as a multithreaded application allowing several image processing functions to take place at once. An obvious choice here would be to have both hands and the face detected in both faces simultaneously. The computer that this system is running on is a 3Ghz Pentium 4 with 1 GB of RAM. The multithreading could be further enhance if a newer, multicore CPU based computer were used as the host machine.

V.2.2.8. Improved Neural Network Controller

The current Artificial Neural Network based controller has a single input node, a single output node, and 10 hidden nodes. This comes from the fact that only a single joint is considered during training. This would be fine if the other joints had no bearing on the performance of a given joint, but this is not the case. The position of other joints changes the center of gravity and the range of motion of a given joint. Therefore, a more effective controller scheme might be to have a more complex Neural Network in which all 6 joints were represented as inputs and outputs instead of 1 at a time. Training the system on a Neural Network of this type would allow for interactions between the various joints to be taken into account. Another possible controller scheme would involve Support Vector Machines [2]. An SVM could be used to find correlations and patterns within the high dimensionality data acquired from ISAC. Either of these methods could provide more accurate control of ISAC's arms while still maintaining the open-loop nature of the system.

REFERENCES

[1] Bridgestone Corporation. http://www.bridgestone.com/

[2] Cristianini, N. and J. Shawe-Taylor, *An Introduction To Support Vector Machines (and other kernel-based learning methods)*, Cambridge University Press, 2000. http://www.support-vector.net/

[3] Computational Vision at CalTech, "Camera Calibration Toolbox for Matlab." http://www.vision.caltech.edu/bouguetj/calib_doc/

[4] Computational Vision at CalTech, "Jean-Yves Bouguet's WWW Homepage." http://www.vision.caltech.edu/bouguetj/index.html

[5] Dadone, P., "Design Optimization of Fuzzy Logic Systems", PhD thesis, Virginia Polytechnic Institute and State University, 2001

[6] Directed Perception, "Model PTU-46-17.5." http://www.dperception.com/pdf/specs-ptu-d46.pdf

[7] Epson Seiko. http://www.epson.co.jp/e/ & http://en.wikipedia.org/wiki/Epson

[8] Erdemir, E., "Design and Optimization of a Fuzzy-Neural Hybrid Controller Structure for a Rubbertuator Robot Using Genetic Algorithms" MS thesis, Boğaziçi University, 2006

[9] Gardner, R. J. (2002). "The Brunn-Minkowski inequality". Bulletin of the American Mathematical Society (N.S.) 39 (3): 355–405 (electronic)

[10] Gonzalez, R. C. and R. E. Woods, *Digital image processing*, 2nd ed. Upper Saddle River, N.J.: Prentice Hall, 2002

[11] Honda. "ASIMO: The Honda Humanoid Robot ASIMO." http://world.honda.com/ASIMO/

[12] Hong, K., J. Min, W. Lee, J. Kim, Real Time Face Detection and Recognition System Using Haar-Like Feature/HMM in Ubiquitous Network Environments, Springer Berlin / Heidelberg, 2005

[13] Intel®, "Intel® Integrated Performance Primitives 5.3." http://intel.com/software/products/ipp

[14] Intel®, "Intel Software Products." http://www.intel.com/software/products/perflib/ijl/

[15] Intel®, “Open Source Computer Vision Library.”
http://www.intel.com/technology/computing/opencv/

[16] Kearns, M. J., The Computational Complexity of Machine Learning, The MIT Press, 1990.

[17] “Learning-Based Computer vision with Intel’s Open Source Computer Vision Library.” *Compute-Intensive, Highly Parallel Applications and Uses* 09-01 (May 19, 2005)
http://www.intel.com/technology/itj/2005/volume09issue02/art03_learning_vision/p04_face_detection.htm

[18] Leutron Vision, “Leutron Vision: XC-999/999P.”
http://www.leutron.com/english/cameras/xc999_f.htm

[19] Naotoshi Seo., “Tutorial: OpenCV haartraining (Rapid Object Detection With A Cascade of Boosted Classifiers Based on Haar-like Features).”
http://note.sonots.com/SciSoftware/haartraining.html

[20] Northrup, S., “A PC-Based Controller for the Soft Arm Robot”, PhD diss., Vanderbilt University, 2001

[21] Nosaka, K., K. Sakamoto, M. Newton, P. Sacco, “Influence of Pre-Exercise Muscle Temperature on Responses to Eccentric Exercise,” Journal of Athletic Training 39 (Apr. – June 2004): 132-137. (electronic)
http://www.pubmedcentral.nih.gov/picrender.fcgi?artid=419505&blobtype=pdf

[21] Oztop, E., M. Kawato, M. Arbib, Mirror neurons and imitation: a computationally guided review, Neural Networks, v.19 n.3, p.254-271, April 2006

[22] Pérez-Uribe, Andrés, “Structure-Adaptable Digital Neural Network.” PhD thesis, Swiss Federal Institute of Technology-Lausanne, 1999

[23] Peters II, R. A, EECE 254 Computer Vision Lecture Notes: Stereopsis (Coplanar), Department of Electrical Engineering and Computer Science, Vanderbilt University (PowerPoint Presentation)

[24] Peters II, R.A., K. E. Hambuchen, K. Kawamura, and Wilkes, D. M., The Sensory EgoSphere as a Short-Term Memory Humanoids, *Proceedings of the IEEE-RAS International Conference on Humanoid Robots*, pp 451-459, Waseda University, Tokyo, Japan, 22-24 November 2001.

[25] Rojas, J. L., “Sensory Integration with Articulated Motion on a Humanoid Robot”, MS thesis, Vanderbilt University, 2004

[26] Schaal, S. (1999). Is imitation learning the route to humanoid robots?, *Trends in Cognitive Sciences*, **3**, **6**, pp.233-242. http://courses.media.mit.edu/2003spring/mas963/schaal-TICS1999.pdf

[27] Schröder, J., "Position Control of a Humanoid Robot Arm actuated by Artificial Muscles", MS thesis, University of Karlsruhe, 2003

[28] Sciavicco, L., and B. Siciliano, *Modelling and Control of Robot Manipulators*, 2d ed. Springer, 2000, pp. 68-69.

[29] Shadow Robotics Company. http://www.shadowrobot.com/

[30] SMC Pneumatics, "ITV2050-312CN4." http://www.coastpneumatics.com/floaters/I3-J/ITV2050-312CN4.html

[31] SourceForge.net, "CxCore – OpenCV Library Wiki," http://opencvlibrary.sourceforge.net/CxCore

[32] SourceForge.net, "HighGUI – OpenCV Library Wiki." http://opencvlibrary.sourceforge.net/HighGui

[33] SourceForge.net, "SourceForge.net: Open Computer Vision Library." http://sourceforge.net/projects/opencvlibrary/

[34] SourceForge.net, "Welcome – OpenCV Library Wiki." http://opencvlibrary.sourceforge.net/

[35] Srikaew, Atit, "A Biologically Inspired Active Vision Gaze Controller", PhD diss., Vanderbilt University, 2000

[36] Staff Writer, "Humanoid performing robot debuts," *Taipei Times*, pg. 12, Oct. 10, 2007. http://www.taipeitimes.com/News/biz/archives/2007/10/10/2003382566

[37] SUMTAK. http://www.sumtak.co.jp/english/top.html

[38] Ulutas, B., E. Erdemir, and K. Kawamura, A Hybrid Neural Network-Based and PID Controller with Non-contact Impedance and Grey Prediction, 2008

[39] Viola, P. and M. Jones. *Rapid object detection using a boosted cascade of simple features*. In IEEE Conference on Computer Vision and Pattern Recognition, 2001

[40] Vital Systems, "Motion Control PCI Card." http://www.vitalsystem.com/web/motion/motionLite.php

[41] Vital Systems, "Motion Control Breakout Boards." http://www.vitalsystem.com/web/common/breakout.php

[42] Wikipedia, “Artificial neural network.” http://en.wikipedia.org/wiki/Artificial_neural_network

[43] Wikipedia, “Client-server.” http://en.wikipedia.org/wiki/Client-server

[44] Wikipedia, “Pneumatic artificial muscles.” http://en.wikipedia.org/wiki/Pneumatic_artificial_muscles

[45] Wikipedia, “Publish/subscribe.” http://en.wikipedia.org/wiki/Publish/subscribe

[46] Williamson, M., Postural primitives: Interactive behavior for a humanoid robot arm. In Pattie Maes, Maja Matari'c, Jean-Arcady Meyer, Jordan Pollack, and Stewart Wilson, editors, Fourth International Conference on Simulation of Adaptive Behavior, pages 124--131, Cape Cod, MA, 1996. MIT Press. http://citeseer.ist.psu.edu/williamson96postural.html

APPENDIX

A. Vision & Processing Code Listing

A.1. TrackColor.cpp (main Vision & Processing Code)

```
//Sean Begley
//Imitation Learning
//Hand Following
//1/23/2008

//INCLUDES
#include "TrackColor.h"
#include "Kinematics.h"

int main( int argc, char** argv )
{
	//INITALIZE VARIABLES

	//TEMPORARY STORAGE
	char * tempL = (char*)"C:/Temp/tempL.bmp";
		//left frame
	char * tempR = (char*)"C:/Temp/tempR.bmp";
		//right frame
	char coords[] = "C:/Temp/coords.txt";
		//initial coordinates
	char filteredcoords[] = "C:/Temp/filteredcoords.txt";
	//filtered coordinates
	char tempcoords[] = "C:/Temp/tempcoords.txt";
	//tempory storage during filtering
	char compressedcoords1[] = "C:/Temp/compressedcoords1.txt";
	//compressed coordinates for object 1
	char compressedcoords2[] = "C:/Temp/compressedcoords2.txt";
	//compressed coordinates for object 2
	char fittedcoords1[] = "C:/Temp/fittedcoords1.txt";
	//coordinates fitted to ISAC's workspace for object 1
	char fittedcoords2[] = "C:/Temp/fittedcoords2.txt";
	//coordinates fitted to ISAC's workspace for object 1
	char uploadL[] = "I:/Temp/uploadL.txt";
		//upload location to share with Neural Network (left arm)
	char uploadR[] = "I:/Temp/uploadR.txt";
		//upload location to share with Neural Network (right arm)
	char angles1[] = "C:/Temp/angles1.txt";
		//joint angles for object 1
	char angles2[] = "C:/Temp/angles2.txt";
		//joint angles for object 2
	char goflag[] = "I:/Temp/Start.Now";
		//flag file to tell the controller to start
```

```
      char facedcoords[] = "C:/Temp/facedcoords.txt";
      //coords file with the averaged face location
      char flippedcoords[] = "C:/Temp/flippedcoords.txt";
      //coords after all Y's have been flipped
      char interpolated1[] = "C:/Temp/interpolated1.txt";
      //angles1 with interpolation applied
      char interpolated2[] = "C:/Temp/interpolated2.txt";
      //angles2 with interpolation applied
      int counter = 0;
                  //time counter used to keep track of relative time of saved
points
      LARGE_INTEGER ticksPerSecond, start_ticks, end_ticks, cputime,
tick;//variables for timing vision loop


      //TEST VARIABLES: set these to enable and disable different portions of
the system

      int usevision = 1;                  //test variable to enable (1) and
disable (0) Vision Subsystem usage
                                                //if set to 0, the vision &
gesture tracking will have no effect
                                                //and filtering / processing
will take place on whatever coords.txt
                                                //exists in C:/Temp
      int usearms = 1;              //test variable to enable (1) and disable
(0) Controller Subsystem
                                                //usage.  if set to 0, the
UploadL, UploadR, & Start.Now files will NOT
                                                //be written to the shared I
drive and, thus, the Controller will NOT
                                                //be signalled to start

      //left & right frame buffers, camera objects, temporary image storage
    IplImage *frameL, *frameR;
      CPXCk_FG cameraL, cameraR;

      //left & right camera coords/radius for object 1 (BLUE BEAN BAG)
      CvTarget l1 (160, 120, 0);
      CvTarget r1 (160, 120, 0);

      //left & right camera coords/radius for object 2 (GREEN LEGO LID)
      CvTarget l2 (160, 120, 0);
      CvTarget r2 (160, 120, 0);

      //left & right face location for Haar facedetect
      CvTarget lf (160, 120, 0);
      CvTarget rf (160, 120, 0);

      //relative coords of tracked objects
      CvPoint3D32f obj1loc;
      CvPoint3D32f obj2loc;
      CvPoint3D32f faceloc;
      faceloc.x=0;faceloc.y=0;faceloc.z=0;

      //coordinate storage
```

```
      FILE * coordsfile;                        //file handle to store
unparsed coordinates



      //BEGIN PROGRAM

      //create output windows
    cvNamedWindow("Tracker Left", 1);
      cvNamedWindow("Tracker Right", 1);
      //cvNamedWindow("Val Mask", 1);
      //cvNamedWindow("Hue Mask", 1);


      //haar initialization
      cascade_name =
"I:/Etc/OpenCV/data/haarcascades/haarcascade_frontalface_alt2.xml";
      cascade = (CvHaarClassifierCascade*)cvLoad( cascade_name, 0, 0, 0 );
      storage = cvCreateMemStorage(0);

      //timer initializiation
      if (!QueryPerformanceFrequency(&ticksPerSecond))
            if (!QueryPerformanceCounter(&tick))
                  printf("visual system counter doesnt work\n");

      cameraR.put_FrameGrabberID(1);                  //set the Right camera
as ID 1 (Left is ID 0)

      if(cameraL.Initialize(0) && cameraR.Initialize(0) && hd.Initialize())
      //proceed if everything successfully initialize
      {
            printf("****All Initializations Complete Successfully\n");
      }
      else
      {
            //error if we can't initialize the Cameras
            fprintf(stderr, "ERROR: Could not Initialize Cameras\n");
            cvDestroyWindow("Tracker Left");
            cvDestroyWindow("Tracker Right");
            return 0;

      }
      //continually get a frame and run the detection function
      printf("\n TRY TO KEEP YOUR FACE STILL AS YOU MOVE YOUR ARMS DURING
GESTURE RECORDING \n");
      printf("\n*******************************************\n");
      printf("* PRESS ANY KEY TO BEGIN GESTURE RECORDING *\n");
      printf("*******************************************\n");
      while(1)
      {
            if(cameraL.GetImage(tempL) && cameraR.GetImage(tempR))
      //proceed if a frame is successfully retrieved
            {
            frameL=cvLoadImage(tempL);    //load the retrieved frame into an
IplImage structure
```

```
                  frameR=cvLoadImage(tempR);    //load the retrieved frame
into an IplImage structure
            }

            //display images to the user
            cvShowImage("Tracker Left", frameL);      //show the left frame
            cvShowImage("Tracker Right", frameR);     //show the right frame

            if(cvWaitKey( 10 ) >= 0) break;     //do not start tracking until
a user hits a key
      }

      hd.Home();        //ensure the pan/tilts are at the home position

      if(usevision)
      {
            coordsfile = fopen(coords, "w");
            if (coordsfile == NULL) return 0;               //break out of
the if statement and end the program if the coordsfile cannot be opened

      fprintf(coordsfile,"TIME,PX1L,PY1L,PX1R,PY1R,X1,Y1,Z1,PX2L,PY2L,PX2R,PY
2R,X2,Y2,Z2,FACE_PXL,FACE_PYL,FACE_PXR,FACE_PYR,FACE_X,FACE_Y,FACE_Z\n");
      }

      printf("\n*****************************************\n");
      printf("* PRESS ANY KEY TO STOP GESTURE RECORDING  *\n");
      printf("*****************************************\n");

      //VISION SUBSYSTEM LOOP
    for(;;)       //loop forever
    {
            QueryPerformanceCounter(&start_ticks);    //get start time

        if(cameraL.GetImage(tempL) && cameraR.GetImage(tempR))
      //proceed if a frame is successfully retrieved
            {
            frameL=cvLoadImage(tempL);    //load the retrieved frame into an
IplImage structure
                  frameR=cvLoadImage(tempR);    //load the retrieved frame
into an IplImage structure
            }
            else
            {
                  //error if we can't get a frame from the camera
                  fprintf(stderr, "ERROR: Could not retrieve frames from
Cameras\n");
                  break;
            }

            //haar detect/draw face(s)
            haarFaceDetect(frameL, &lf);
            haarFaceDetect(frameR, &rf);

            //detect object 1 (light blue bean bag)
            detectObject(frameL, &l1, HUE_LIGHT_BLUE_BAG[0],
HUE_LIGHT_BLUE_BAG[1]);       //detect object 1 in our Left Image
```

```
            detectObject(frameR, &r1, HUE_LIGHT_BLUE_BAG[0],
HUE_LIGHT_BLUE_BAG[1]);       //detect object 1 in our Right Image


            //detect object 2 (green lego lid)
            detectObject(frameL, &l2, HUE_BIG_GREEN_BALL[0],
HUE_BIG_GREEN_BALL[1]);       //detect object 2 in our Left Image
            detectObject(frameR, &r2, HUE_BIG_GREEN_BALL[0],
HUE_BIG_GREEN_BALL[1]);       //detect object 2 in our Right Image

            //draw Haar face on original image
            drawTarget(frameL, lf, 2);
            drawTarget(frameR, rf, 2);

            //draw object 1 targets onto the original image
            drawTarget(frameL, l1, 0);
            drawTarget(frameR, r1, 0);

            //draw object 2 targets onto the original image
            drawTarget(frameL, l2, 7);
            drawTarget(frameR, r2, 7);

            //calculate relative XYZ depth
            calculateXYZ(&obj1loc, l1, r1);
            calculateXYZ(&obj2loc, l2, r2);

            //print the coordinates to a text file
            if (usevision)
fprintf(coordsfile,"%d,%d,%d,%d,%d,%f,%f,%f,%d,%d,%d,%d,%f,%f,%f,%d,%d,%d,%d,
%f,%f,%f\n",counter,l1.x,l1.y,r1.x,r1.y,obj1loc.x,obj1loc.y,obj1loc.z,l2.x,l2
.y,r2.x,r2.y,obj2loc.x,obj2loc.y,obj2loc.z,lf.x,lf.y,rf.x,rf.y,faceloc.x,face
loc.y,faceloc.z);


            //display images to the user
            cvShowImage("Tracker Left", frameL);      //show the left frame
            cvShowImage("Tracker Right", frameR);     //show the right frame

        if(cvWaitKey( 10 ) >= 0) break;         //give the user a chance to
stop the tracking and continue with processing

            counter++;                                              //increment
the time counter
            QueryPerformanceCounter(&end_ticks);      //get stop time

            //wait for a bit to ensure that each cycle takes a consistent 400
ms
            while(((float)(end_ticks.QuadPart-
start_ticks.QuadPart)/ticksPerSecond.QuadPart*1000) < (float) VISION_TIME)
                  QueryPerformanceCounter(&end_ticks);
            cputime.QuadPart = end_ticks.QuadPart - start_ticks.QuadPart;
      //calculate the total time (should always be around VISION_TIME)
            printf("detection time: %f\n",
(float)cputime.QuadPart/(float)ticksPerSecond.QuadPart*1000);     //print out
how long it takes for detection cycle

    }
```

```
      //close the object coords file
      if (usevision) fclose(coordsfile);


      //PROCESSING SUBSYSTEM

      //calculate the average face location and rewrite to file
      avgFaceLoc(coords, facedcoords);

      //flip the Y coordinate about it's average value to account for
upsidedown calculation
      flipY(facedcoords,flippedcoords);

      //Difference and Recursivly filter the set of XYZ coordinates stored in
C:/Temp/facedcoords.txt
      //and save the results in C:/Temp/filteredcoords.txt
      filterCoords(flippedcoords, tempcoords, filteredcoords);

      //Filter for large changes in direction to compress the number of
points on the graph to as few
      //as possible for simpler movement
      compressCoords(filteredcoords, compressedcoords1, compressedcoords2);

      //scale coords and rearrange axes for ISAC
      fitCoordsToISAC2(compressedcoords1, fittedcoords1, RIGHT_ARM);
      fitCoordsToISAC2(compressedcoords2, fittedcoords2, LEFT_ARM);

      //calculate Joint Angles from Coordinates using Inverse Kinematics
      calcJointAngles(fittedcoords1, angles1, RIGHT_ARM, END_EFF_NO,
SIMPLE_INV_KIN);
      calcJointAngles(fittedcoords2, angles2, LEFT_ARM, END_EFF_NO,
SIMPLE_INV_KIN);

      //interpolate angles between existing angles
      interpolateAngles(angles1, interpolated1);
      interpolateAngles(angles2, interpolated2);

      //Open the joint angles file and upload the points to the shared I
drive
      //to be read by the Neural Network Controller (located on another
computer: Octavia)
      //angles2 goes to uploadL (left hand)
      //angles1 goes to uploadR (right hand)
      if (usearms) uploadToNNbatch(uploadL, uploadR, interpolated2,
interpolated1);

      //Upload Start.Now file to indicate that the joint angles are ready and
      //that the controller should begin execution
      if (usearms) uploadGoFlag(goflag);

      //create test points to be fed through the inverse kinematics based on
an expected workspace
      //testSetForInverseKinematics(testfile, 400, 475, 50, 150, -90, 200,
5);

      //create test set for forward kinematics to help find workspace
```

```
      //testSetForForwardKinematics(testfile, 2*PI, 1);

      //release our resources
    //cvReleaseImage(&frameL);
      //cvReleaseImage(&frameR);

      //kill the results window
    cvDestroyWindow("Tracker Left");
      cvDestroyWindow("Tracker Right");
      //cvDestroyWindow("Val Mask");
      //cvDestroyWindow("Hue Mask");

    return 0;
}

void detectObject(IplImage* img, CvTarget *tar, int low, int high)
{
      //Temporary Images
      IplImage* hsv = cvCreateImage(cvGetSize(img), 8, 3);
      IplImage* hue = cvCreateImage(cvGetSize(img), 8, 1);
      IplImage* sat = cvCreateImage(cvGetSize(img), 8, 1);
      IplImage* val = cvCreateImage(cvGetSize(img), 8, 1);
      IplImage* maskH = cvCreateImage(cvGetSize(img), 8, 1);
      //IplImage* maskV = cvCreateImage(cvGetSize(img), 8, 1);
      //IplImage* maskHV = cvCreateImage(cvGetSize(img), 8, 1);
      //IplImage* blur = cvCreateImage(cvGetSize(img), 8, 3);
      //IplImage* blur2 = cvCreateImage(cvGetSize(img), 8, 3);

      IplConvKernel * selem =
cvCreateStructuringElementEx(3,3,1,1,CV_SHAPE_RECT);  //kernel for use with
erode/dilate


      //Send the image through a bilateral blur 3 times
      //Bilateral tends to preserve edges
      //cvSmooth(img, blur, CV_BILATERAL, 50, 3);
      //cvSmooth(blur, blur2, CV_BILATERAL, 50, 3);
      //cvSmooth(blur2, blur, CV_BILATERAL, 50, 3);

      //Extract Hue/Sat/Val from BGR Image
      cvCvtColor(img, hsv, CV_BGR2HSV);
      //convert from BGR to HSV
      cvSplit(hsv, hue, sat, val, 0);
      //extract hue/sat/val channels

      //Filter by Hue
      cvInRangeS(hue, cvScalar(low), cvScalar(high), maskH);      //filter by
Hue
      cvErode(maskH,maskH,selem,3);
      //Erode/Dilate maskH to eliminate noise
      cvDilate(maskH, maskH, selem, 3);

      //Filter by Value
      //cvInRangeS(val, cvScalar(0), cvScalar(255), maskV); //filter by Value
      //cvErode(maskV,maskV,selem,3);
      //Erode maskV to elimniate noise
```

```
	//create a combined Hue/Val mask
	//cvZero(maskHV);
	//cvCopy(maskH, maskHV, maskV);
	//cvShowImage("Hue Mask", maskH);
	//cvShowImage("Val Mask", maskV);

	//Find the largest positive object
	getConnectedComps(maskH /*maskHV*/,Comps);
	//retrieve a list of all connected components in filtered image
	if (comptot != 0)
	{
		//find largest component
		maxcomp = 0;
		maxarea = Comps[0]->area;
		for (int j = 0; j < comptot; j++)
		{
			if (Comps[j]->area > maxarea)
			{
				maxarea = Comps[j]->area;
				maxcomp = j;
			}
		}

		//get center
		tar->x = Comps[maxcomp]->rect.x + Comps[maxcomp]->rect.width/2;
		tar->y = Comps[maxcomp]->rect.y + Comps[maxcomp]->rect.height/2;

		//get radius
		if (Comps[maxcomp]->rect.width > Comps[maxcomp]->rect.height)
tar->r = Comps[maxcomp]->rect.width/2;
		else tar->r = Comps[maxcomp]->rect.height/2;


	}

	//Clean Up
	cvReleaseStructuringElement(&selem);
	cvReleaseImage(&hsv);
	cvReleaseImage(&hue);
	cvReleaseImage(&sat);
	cvReleaseImage(&val);
	cvReleaseImage(&maskH);
	//cvReleaseImage(&maskV);
	//cvReleaseImage(&maskHV);
	//cvReleaseImage(&blur);
	//cvReleaseImage(&blur2);
}

void drawTarget(IplImage *img, CvTarget obj, int clr)
{
	if (obj.x <= img->width && obj.y <= img->height && clr < NUM_COLORS)
	{
		//draw a circle on the screen at the largest blobs center
location
		cvCircle( img, obj, obj.r, COLORS[clr], 3, 8, 0 );
		cvCircle( img, obj, 1,     COLORS[clr], 3, 8, 0 );
	}
```

```
}

//*********************************************************************
//Authors: Jack Noble & Tom Billings
//Description: getConnectedComponents is used to distinguish between
foreground
//          and background elements within the image.  It does so by
rasterscanning the image
//          for foreground pixels (pixel == 255) and numbers the areas
accordingly.
//          If adjacent areas have the same numbers and are both foreground
or background pixels
//          they are combined into one connected component.  Only foreground
pixels are placed
//          into Comps.  If more than 20 components are found, a new Comps is
//          initialized including old values.
//
//Variables:
//          image is a binary image that has foreground and backgroun
elements
//          Comps holds all of the data for the connected components found in
image
//
//Modified: by Sean Begley
//                        - replaced hard #s for img width/hight with soft
values retreived from
//                          passed in IplImage - 2/5/2008
//*********************************************************************
void getConnectedComps(IplImage *image, CvConnectedComp ** Comps)
{
      CvScalar pixval;
      comptot = 0;
      int CurrentCompVal = 0;
      // used if need  to reinitialize components array for more capacity
      CvConnectedComp ** NewComp;

      for (int j = 0; j < image->width*image->height; j++)
      {
            pixval = cvGet2D(image,j/image->width,j%image->width);
            // if this pixel has the value of 255, this component has not yet
been recorded
            if (pixval.val[0] > CurrentCompVal)
            {
                  if (CurrentCompVal >= compmax)
                        Comps[CurrentCompVal] = new CvConnectedComp;
                  // fill this component in with the next lowest value
                  cvFloodFill(image,cvPoint(j%image->width,j/image-
>width),cvScalar(CurrentCompVal +
1),cvScalar(0),cvScalar(0),Comps[CurrentCompVal],4);
                  CurrentCompVal++;
                  // if at capacity reinitialize array to higher capacity
                  if (CurrentCompVal >= compcap)
                  {
                        NewComp = new CvConnectedComp*[compcap + 20];
                        for (int i = 0; i < CurrentCompVal; i++)
                        {
                              // copy component values into new array
```

```
                                NewComp[i] = new CvConnectedComp;
                                NewComp[i]->area = Comps[i]->area;
                                NewComp[i]->value.val[0] = Comps[i]-
>value.val[0];
                                NewComp[i]->rect = Comps[i]->rect;
                                // delete old values
                                delete Comps[i];
                          }
                          // update pointers and capacity
                          compcap = compcap + 20;
                          Comps = NewComp;
                    }
              }
      }
      // update total number of components being used
      comptot = CurrentCompVal;
      // ensure total number of components ever used is up to date (for
deletion)
      if (comptot > compmax)
            compmax = comptot;
      return;
}

//NOT USED
//if the object is far from the center move it a lot, close a medium, really
close, a small amount
void centerCams(int *lX, int *lY, int *rX, int *rY)
{
      double pantilt[4];      //placeholder... real pantilt should be
global... but this function isnt used anymore
      printf("%f\t%f\t%f\t%f\n",pantilt[0],pantilt[1],pantilt[2],pantilt[3]);

      //left cam X (pan)
      if (*lX < 80)
      { pantilt[0] = pantilt[0] + DELTA_B;}
      else if (*lX >= 80 && *lX < 150)
      { pantilt[0] = pantilt[0] + DELTA_M;}
      else if (*lX >= 150 && *lX < 158)
      { pantilt[0] = pantilt[0] + DELTA_S;}
      //else if (*lX = 160) no change;
      else if (*lX > 162 && *lX <= 170)
      { pantilt[0] = pantilt[0] - DELTA_S;}
      else if (*lX > 170 && *lX < 240)
      { pantilt[0] = pantilt[0] - DELTA_M;}
      else
      {pantilt[0] = pantilt[0] - DELTA_B;}

      //left cam Y (tilt)
      if (*lY < 60)
      { pantilt[1] = pantilt[1] + DELTA_B;}
      else if (*lY >= 60 && *lY < 110)
      { pantilt[1] = pantilt[1] + DELTA_M;}
      else if (*lY >= 110 && *lY < 118)
      { pantilt[1] = pantilt[1] + DELTA_S;}
      //else if (*lY = 120) no change;
      else if (*lY >= 122 && *lY <= 130)
      { pantilt[1] = pantilt[1] - DELTA_S;}
```

```
      else if (*lY >= 130 && *lY < 180)
      { pantilt[1] = pantilt[1] - DELTA_M;}
      else
      {pantilt[1] = pantilt[1] + DELTA_B;}

      //right cam X (pan)
      if (*rX < 80)
      { pantilt[2] = pantilt[2] + DELTA_B;}
      else if (*rX >= 80 && *rX < 150)
      { pantilt[2] = pantilt[2] + DELTA_M;}
      else if (*rX >= 150 && *rX < 158)
      { pantilt[2] = pantilt[2] + DELTA_S;}
      //else if (*rX = 160) no change;
      else if (*rX > 162 && *rX <= 170)
      { pantilt[2] = pantilt[2] - DELTA_S;}
      else if (*rX > 170 && *rX < 240)
      {pantilt[2] = pantilt[2] - DELTA_M;}
      else
      {pantilt[2] = pantilt[2] - DELTA_B;}

      //right cam Y (tilt)
      if (*rY < 60)
            pantilt[3] = pantilt[3] + DELTA_B;
      else if (*rY >= 60 && *rY < 110)
            pantilt[3] = pantilt[3] + DELTA_M;
      else if (*rY >= 110 && *rY < 118)
            pantilt[3] = pantilt[3] + DELTA_S;
      //else if (*rY = 120) no change;
      else if (*rY >= 122 && *rY <= 130)
            pantilt[3] = pantilt[3] - DELTA_S;
      else if (*rY > 130 && *rY < 180)
            pantilt[3] = pantilt[3] - DELTA_M;
      else
            pantilt[3] = pantilt[3] - DELTA_B;

      //move cameras to center object on the screen
      hd.MoveHead(pantilt);

      //printf("%f\t%f\t%f\t%f\n\n",pantilt[0],pantilt[1],pantilt[2],pantilt[
3]);


}


//CAMERA TRANSFORM PARAMETERS
//center to camera base = 140mm (baseline = 280mm)
//camera base to rotation base = 91.948mm
//rotation base to camera = 65.5mm
//camera to focal point = 305.25mm
//sigma = 50 pixels per mm
//rotation about z is from dPan
//rotation about y if from dTilt
//effective picture elements: 768x494
//CCD sensing area: 6.4 x 4.8 mm

//currently gives the depth in some unknown unit... if at all...
```

```
//units are unknown, but the bueauty is that I dont care about units... I
just need relative motion.
//the plan is to take the relative motion of the tracked object, and scale it
to be as big as IASC
//can reasonably accomplish in his limited workspace

//may need to ensure that x,y,and z directions all have equal units (equal
rate of change of X Y Z coords
//relative to actual movement)

//to keep with the rest of the programming style, this should probably
void calculateXYZ(CvPoint3D32f *objloc, CvPoint left, CvPoint right)
{
      double f = 15262.5;     //focal length: 305.25 millimeters (50 px/mm) =
15262.5 px
      double b = 14000; //base: millimeters (50 px/mm) = 14000 px
      double sigma = 50; //pixels per mm

      double xri = 0;
      double xli = 0;
      double yli = 0;
      double yri = 0;

      double z = 0;

      double xr = 0;
      double xl = 0;
      double yr = 0;
      double yl = 0;

      double y = 0;
      double x = 0;

      double zft = 0;
      double xft = 0;
      double yft = 0;


      //get pixel coords
      xri = (double)right.x;
      xli = (double)left.x;
      yri = (double)right.y;
      yli = (double)left.y;

      //find z in weird units
      z=f*b/((double)xli-(double)xri);

      //calculate real y and x values in weird units
      yr=yri*z/f;
      yl=yli*z/f;
      xr=xri*z/f;
      xl=xli*z/f;

      //average y
      y=(yl+yr)/2;
```

```
	//average x
	x=(xr+xl)/2;

	//write the values into the objloc to be returned
	objloc->x=x;
	objloc->y=y;
	objloc->z=z;

	//printf("%f\t%f\t%f\n",x,y,z);
}


//function to convert char array to double
//courtesy of a post by Narue at
http://www.daniweb.com/forums/thread80754.html
double to_double ( const char *p )
{
	if (p == "") return NULL;

	//else
	std::stringstream ss ( p );
	double result = 0;

	ss>> result;

	return result;
}

//Function that filters the XYZ coordinates in C:/Temp/coords.csv
//The filtering is accomplished by subtracting Z from X & Y then recursivly
filtering X & Y
//then subtracting the resultant X from Z and recursivly filtering Z.  The
difference filtering
//(subtracting Z from X & Y and X from Z) is necessary to get rid of
artifacts that motion in the Z
//and X directions place in the other directions.  The recursive filter is to
smooth the movement and
//get rid of noise.
void filterCoords(char coords[], char tempcoords[], char filteredcoords[])
{
	FILE * coordsfile;			//file handle to store
unparsed coordinates
	FILE * filteredcoordsfile;		//file handle to store
parsed/filtered coordinates
	char line [512];			//holder for a single line of
coordsfile as it is parsed
	char *token;
	double* linearray = new double[22];			//array of
doubles to hold unfiltered values
	double* currententry = new double[7];			//array to hold
values of the current entry (TIME,X1,Y1,Z1 X2,Y2,Z2)
	double* historybuffer = new double[7];			//history buffer
for X&Y filtering (TIME,X1,Y1,Z1 X2,Y2,Z2)
	double futurebuffer[5][7];				//future
buffer for Z filtering (TIME, X1, Y1, Z1, X2, Y2, Z2)
	CvPoint3D32f faceloc;					//holder
for location of the face
```

```
      int counter=0;                              //counter for time keeping
      int i,j;                                    //random counters



      //*****************************************************************
      //******FILTER PASS 1 (DIFF FILTER & RECURSIVE FILTER of X & Y)******
      //*****************************************************************

      //GET FIRST ENTRY (line 2) FOR FILTERING HISTORY
      //linearray guide
      //[0]=TIME, [1]=PX1L, [2]=PY1L, [3]=PX1R, [4]=PY1R, [5]=X1, [6]=Y1,
[7]=Z1,
      //[8]=PX2L, [9]=PY2L, [10]=PX2R, [11]=PY2R, [12]=X2, [13]=Y2, [14]=Z2,
[15]=FACE_PXL,
      //[16]=FACE_PYL, [17]=FACE_PXR, [18]=FACE_PYR, [19]=FACE_X,
[20]=FACE_Y, [21]=FACE_Z
      coordsfile = fopen(coords, "r");    //open coordsfile (to be filtered)
      fgets(line, 512, coordsfile);                          //get 1st line to
ignore it b/c it is TITLES
      if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
      {
            //tokenize the line
            i=0;
            token=strtok(line, DELIM);
            linearray[0] = to_double(token);
            while((token=strtok(NULL, DELIM))!=NULL)
            {
                  i++;
                  linearray[i]=to_double(token);
            }

            //copy important information into the history buffer
            historybuffer[0] = linearray[0];    //TIME
            historybuffer[1] = linearray[5];    //X1
            historybuffer[2] = linearray[6];    //Y1
            historybuffer[3] = linearray[7];    //Z1
            historybuffer[4] = linearray[12];   //X2
            historybuffer[5] = linearray[13];   //Y2
            historybuffer[6] = linearray[14];   //Z2

            //copy face X, Y, & Z
            faceloc.x=linearray[19];
            faceloc.y=linearray[20];
            faceloc.z=linearray[21];

            //filter faceloc using the same difference filter equation as the
other points
            faceloc.x = faceloc.x - faceloc.z*XY_DIFF;      //X=X-Z*0.008
            faceloc.y = faceloc.y - faceloc.z*XY_DIFF;      //Y=Y-Z*0.008
            faceloc.z = faceloc.z/Z_SCALE - faceloc.x;      //Z=Z/40-X

      }
      fclose(coordsfile);
```

```
      //start back at the beginning
      coordsfile = fopen(coords, "r");
      //open coordsfile (to be filtered)
      filteredcoordsfile = fopen(tempcoords, "w");          //open
filteredcoordsfile (to hold filtered coords)
      fprintf(filteredcoordsfile,"TIME,X1,Y1,Z1,X2,Y2,Z2\n");
      //print titles for filteredcoordsfile
      fgets(line, 512, coordsfile);
            //ignore 1st line of coordsfile b/c it is TITLES
      counter=0;
      while(1)    //loop forever
      {
            if(fgets(line, 512, coordsfile) != NULL)  //get a line for
coordsfile
            {
                  //GET NEXT LINE
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //DIFFERENCE FILTER X & Y
                  //find Xdiff & Ydiff  (Xdiff[i]=X[i]-Z[i]*.008) and save to
filteredcoords
                  //currententry guide
                  //[0]=TIME, [1]=Xdiff1, [2]=Ydiff1, [3]=Z1, [4]=Xdiff2,
[5]=Ydiff2, [6]=Z2
                  currententry[0] = linearray[0];
                  //TIME = TIME
                  currententry[1] = linearray[5] - linearray[7]*XY_DIFF;
      //Xdiff1=X1-Z1*0.008
                  currententry[2] = linearray[6] - linearray[7]*XY_DIFF;
      //Ydiff1=Y1-Z1*0.008
                  currententry[3] = linearray[7];
                  //Z1 = Z1
                  currententry[4] = linearray[12] - linearray[14]*XY_DIFF;
      //Xdiff2=X2-Z2*0.008
                  currententry[5] = linearray[13] - linearray[14]*XY_DIFF;
      //Ydiff2=Y2-Z2*0.008;
                  currententry[6] = linearray[14];
            //Z2 = Z2

                  //RECURSIVE FILTER X & Y
                  //calculate X_rec_diff & Y_rec_diff
(X_rec_diff[i]=0.2*Xdiff[i]+0.8*X_rec_diff[i-1])
                  //currententry guide
                  //[0]=TIME, [1]=X_rec_diff1, [2]=Y_rec_diff1, [3]=Z1,
[4]=X_rec_diff2, [5]=Y_rec_diff2, [6]=Z2
                  /*
                  if (counter < 1)
                  {
```

```
                        currententry[1] = currententry[1];
      //recursivly filter X1
                        currententry[2] = currententry[2];
      //recursivly filter Y1
                        currententry[4] = currententry[4];
      //recursivly filter X2
                        currententry[5] = currententry[5];
      //recursivly filter Y2
                  }
                  else
                  {
                        currententry[1] = A0*currententry[1] +
B0*historybuffer[1];          //recursivly filter X1
                        currententry[2] = A0*currententry[2] +
B0*historybuffer[2];          //recursivly filter Y1
                        currententry[4] = A0*currententry[4] +
B0*historybuffer[4];          //recursivly filter X2
                        currententry[5] = A0*currententry[5] +
B0*historybuffer[5];          //recursivly filter Y2
                  }
                  */

                  //UPDATE HISTORYBUFFER
                  for(j=0;j<7;j++)
                  {
                        historybuffer[j]=currententry[j];
                  }

                  //PRINT LINE TO FILE
                  for(i=0;i<6;i++)
                  {
                        fprintf(filteredcoordsfile, "%f,", currententry[i]);
                  }
                  fprintf(filteredcoordsfile, "%f\n", currententry[6]);
            }
            else        //if we reach the end of the file break out of the
while loop
            {
                  //close files
                  fclose(coordsfile);
                  fclose(filteredcoordsfile);
                  break;
            }
            counter++;
      }

      printf ("****Filter PASS 1 Complete\n");

      //************************************************************
      //******FILTER PASS 2 (DIFFERENCE & RECURSIVE FILTER of Z)******
      //************************************************************

      //FILL FUTURE BUFFER (lines 2-6) FOR FILTERING
      coordsfile = fopen(tempcoords, "r");      //open coordsfile (to be
filtered)
      fgets(line, 512, coordsfile);                        //get 1st line to
ignore it b/c it is TITLES
```

```
	for(i=0;i<5;i++)
	{
		if(fgets(line, 512, coordsfile) != NULL)	//get a line from
coordsfile
		{
			//tokenize the line
			j=0;
			token=strtok(line, DELIM);
			currententry[0] = to_double(token);
			while((token=strtok(NULL, DELIM))!=NULL)
			{
				j++;
				currententry[j]=to_double(token);
			}

			//copy important information into the future buffer
			futurebuffer[i][0] = currententry[0];	//TIME
			futurebuffer[i][1] = currententry[1];	//X1
			futurebuffer[i][2] = currententry[2];	//Y1
			futurebuffer[i][3] = currententry[3];	//Z1
			futurebuffer[i][4] = currententry[4];	//X2
			futurebuffer[i][5] = currententry[5];	//Y2
			futurebuffer[i][6] = currententry[6];	//Z2
		}
	}

	//FILL HISTORY BUFFER & CURRENT ENTRY
	for(i=0;i<7;i++)
	{
		historybuffer[i]=futurebuffer[0][i];
		currententry[i]=futurebuffer[0][i];
	}

	filteredcoordsfile = fopen(filteredcoords, "w");
	//open filteredcoordsfile2 (to hold filtered coords)
	fprintf(filteredcoordsfile,"TIME,X1,Y1,Z1,X2,Y2,Z2,XF,YF,ZF\n");
	//print titles for filteredcoordsfile

	counter=0;
	while(1)	//loop forever
	{
		if(fgets(line, 512, coordsfile) != NULL)  //get a line for
coordsfile
		{
			//UPDATE CURRENTENTRY
			for(i=0;i<7;i++)
			{
				currententry[i]=futurebuffer[0][i];
			}

			//UPDATE FUTUREBUFFER
			for(i=0;i<4;i++)
			{
				for(j=0;j<7;j++)
				{

					futurebuffer[i][j]=futurebuffer[i+1][j];
```

```
                        }
                  }

                  //GET NEXT LINE
                  //tokenize the line
                  j=0;
                  token=strtok(line, DELIM);
                  futurebuffer[4][0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        j++;
                        futurebuffer[4][j]=to_double(token);
                  }

                  //DIFFERENCE FILTER Z: find Zdiff (Zdiff[i]=Z[i]/40-
X_rec_diff[i+5])
                  //currententry guide
                  //[0]=TIME, [1]=Xdiff1, [2]=Ydiff1, [3]=Z1, [4]=Xdiff2,
[5]=Ydiff2, [6]=Z2
                  currententry[0] = currententry[0];        //TIME = TIME
                  currententry[1] = currententry[1];        //X1 = X1
                  currententry[2] = currententry[2];        //Y1 = Y1
                  currententry[3] = currententry[3]/Z_SCALE -
futurebuffer[0][1];
                  currententry[4] = currententry[4];        //X2 = X2
                  currententry[5] = currententry[5];        //Y2 = Y2
                  currententry[6] = currententry[6]/Z_SCALE -
futurebuffer[0][4];

                  //RECURSIVE FILTER Z: calculate Z_rec_diff
(Z_rec_diff[i]=0.2*Zdiff[i]+0.8*Z_rec_diff[i-1])
                  //currententry guide
                  //[0]=TIME, [1]=X_rec_diff1, [2]=Y_rec_diff1, [3]=Z1,
[4]=X_rec_diff2, [5]=Y_rec_diff2, [6]=Z2
                  if(counter < 1)   //special case for 1st value b/c there is
no history
                  {
                        currententry[3]=currententry[3];          //no filter
                        currententry[6]=currententry[6];          //no filter
                  }
                  else
                  {

      currententry[3]=A0*currententry[3]+B0*historybuffer[3];
      //recursivly filter Z1

      currententry[6]=A0*currententry[6]+B0*historybuffer[6];
      //recursivly filter Z2
                  }

                  //UPDATE HISTORYBUFFER
                  for(i=0;i<7;i++)
                  {
                        historybuffer[i]=currententry[i];
                  }

                  //PRINT LINE TO FILE
```

```
                for(i=0;i<7;i++)
                {
                      fprintf(filteredcoordsfile, "%f,", currententry[i]);
                }
                fprintf(filteredcoordsfile, "%f,%f,%f\n",
faceloc.x,faceloc.y,faceloc.z);
            }
            else        //if we reach the end of the file break out of the
while loop
            {
                //FINISH FILTER ON LAST 5 ENTRIES (held in futurebuffer)
                for(i=0;i<5;i++)
                {
                      //difference filter
                      currententry[0] = futurebuffer[i][0];
                            //TIME = TIME
                      currententry[1] = futurebuffer[i][1];
                            //X1 = X1;
                      currententry[2] = futurebuffer[i][2];
                            //Y1 = Y1
                      currententry[3] = futurebuffer[i][3]/Z_SCALE -
futurebuffer[i][1];     //diff filter Z1
                      currententry[4] = futurebuffer[i][4];
                            //X2 = X2
                      currententry[5] = futurebuffer[i][5];
                            //Y2 = Y2
                      currententry[6] = futurebuffer[i][6]/Z_SCALE -
futurebuffer[i][4];     //diff filter Z1

                      //recursive filter

      currententry[3]=A0*currententry[3]+B0*historybuffer[3];
      //recursivly filter Z1

      currententry[6]=A0*currententry[6]+B0*historybuffer[6];
      //recursivly filter Z2

                      //update history buffer
                      for(j=0;j<7;j++)
                      {
                            historybuffer[j]=currententry[j];
                      }

                      //print line to file
                      for(j=0;j<7;j++)
                      {
                            fprintf(filteredcoordsfile, "%f,",
currententry[j]);
                      }
                      fprintf(filteredcoordsfile, "%f,%f,%f\n",
faceloc.x,faceloc.y,faceloc.z);
                }

                //close files
                fclose(coordsfile);
                fclose(filteredcoordsfile);
                break;
```

```
            }
            counter++;
      }

      printf ("****Filter PASS 2 Complete\n");
      printf ("****All Filtering Complete\n");

      //cleanup
      delete[] linearray;
      delete[] currententry;
      delete[] historybuffer;
}

//function to reduce a set of points down to  as few pnts as possible while
still maintaining the basic flow
//ie: a sine wave of many points would become a triangle wave with points
only at the positive and negative peaks
//this function also splits the single coords file into 2 compressed coords
files so that the fitting function
//can fit the left and right arms maximally and individually.  This splitting
should probably be done in a seperate
//function
void compressCoords(char coords[], char compressedcoords1[], char
compressedcoords2[])
{
      FILE * coordsfile;                        //file handle to store
unparsed coordinates
      FILE * compressedcoordsfile1; //file handle to store parsed/compressed
1 coordinates (TIME, X1, Y1, Z1)
      FILE * compressedcoordsfile2; //file handle to store parsed/compressed
2 coordinates (TIME, X2, Y2, Z2)
      char line [512];                  //holder for a single line of
coordsfile as it is parsed
      char *token;
      double* linearray = new double[10];                  //array to hold
input line
      double* lastpoint = new double[7];                   //array to hold
values of the last saved point (TIME,X1,Y1,Z1 X2,Y2,Z2)
      double* currpoint = new double[7];                   //array to hold
values of the current point (TIME,X1,Y1,Z1 X2,Y2,Z2)
      double* lastsavedpoint1 = new double[4];        //array to hold values
of the last saved point for obj 1 (TIME, X1, Y1, Z1)
      double* lastsavedpoint2 = new double[4];        //array to hold values
of the last saved point for obj 2 (TIME, X2, Y2, Z2);
      double* lastinterimpoint1 = new double[4];           //array to hold
values of the last interrmediate point for obj 1 (TIME, X1, Y1, Z1)
      double* lastinterimpoint2 = new double[4];           //array to hold
values of the last interrmediate point for obj 2 (TIME, X2, Y2, Z2);
      double* pointdiff = new double[7];                   //array to hold
the difference of a point and its predecessor (N/A,X1,Y1,Z1 X2,Y2,Z2)
      int* direction = new int[7];                         //array to hold
the direction of motion for each axis of each object (-1 = down, +1 = up, 0 =
undefined/equal) (X1,Y1,Z1 X2,Y2,Z2)
      int* tempdir = new int[7];                                 //array to
hold the direction of motion for each axis of each object (-1 = down, +1 =
up, 0 = undefined/equal) (X1,Y1,Z1 X2,Y2,Z2)
```

```
      //NOTE: in pointdiff, direction, and tempdir, the 1st element is
ignored and exists only to keep everything simple with regards to the 7
element point arrays
      int changeflag1 = 0;                                          //flag to
indicate a change in direction in obj1
      int changeflag2 = 0;                                          //flag to
indicate a change in direction in obj2
      int i;
      //random counters

      //FILTER FOR CHANGE IN DIRECTION
      coordsfile = fopen(coords, "r");
      //open coordsfile (to be compressed)
      compressedcoordsfile1 = fopen(compressedcoords1, "w");
      //open compressedcoordsfile1 (to hold compressed obj1 coords)
      compressedcoordsfile2 = fopen(compressedcoords2, "w");
      //open compressedcoordsfile2 (to hold compressed obj2 coords)
      fprintf(compressedcoordsfile1,"TIME,X1,Y1,Z1,XF,YF,ZF\n");  //print
titles for compressedcoordsfile1
      fprintf(compressedcoordsfile2,"TIME,X2,Y2,Z2,XF,YF,ZF\n");  //print
titles for compressedcoordsfile2
      fgets(line, 512, coordsfile);
      //ignore 1st line of coordsfile b/c it is TITLES

      //get 1st point, add it to results, save it as last point & last saved
points
      if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
      {
            //tokenize the line
            i=0;
            token=strtok(line, DELIM);
            linearray[0] = to_double(token);
            while((token=strtok(NULL, DELIM))!=NULL)
            {
                  i++;
                  linearray[i]=to_double(token);
            }

            //save lastpoint
            for(i=0;i<7;i++)
            {
                  lastpoint[i]=linearray[i];
            }

            //print to compressed coords files & save to lastsavedpoint &
lastinterimpoint
            fprintf(compressedcoordsfile1, "%f,", lastpoint[0]);
            fprintf(compressedcoordsfile2, "%f,", lastpoint[0]);
            lastsavedpoint1[0]=lastpoint[0];
            lastsavedpoint2[0]=lastpoint[0];
            lastinterimpoint1[0]=lastpoint[0];
            for(i=1;i<3;i++)
            {
                  fprintf(compressedcoordsfile1, "%f,", lastpoint[i]);
                  fprintf(compressedcoordsfile2, "%f,", lastpoint[i+3]);
                  lastsavedpoint1[i]=lastpoint[i];
```

```
                  lastinterimpoint1[i]=lastpoint[i];
                  lastsavedpoint2[i]=lastpoint[i+3];
            }
            fprintf(compressedcoordsfile1, "%f,%f,%f,%f\n",
lastpoint[3],linearray[7],linearray[8],linearray[9]);
            fprintf(compressedcoordsfile2, "%f,%f,%f,%f\n",
lastpoint[6],linearray[7],linearray[8],linearray[9]);
            lastsavedpoint1[3]=lastpoint[3];
            lastinterimpoint1[3]=lastpoint[3];
            lastsavedpoint2[3]=lastpoint[6];

      }

      //get 2nd point, save it as currpoint, and establish directions
      if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
      {
            //tokenize the line
            i=0;
            token=strtok(line, DELIM);
            linearray[0] = to_double(token);
            while((token=strtok(NULL, DELIM))!=NULL)
            {
                  i++;
                  linearray[i]=to_double(token);
            }

            //save currpoint
            for(i=0;i<7;i++)
            {
                  currpoint[i]=linearray[i];
            }

            //set directions
            for(i=1;i<7;i++)
            {
                  pointdiff[i] = currpoint[i] - lastpoint[i];
                  if (pointdiff[i] > 0){ direction[i] = 1; }
                  else if (pointdiff[i] < 0){ direction[i] = -1; }
                  else { direction[i] = 0; }
            }

      }

      while(1)    //loop forever
      {
            //update last point
            for(i=0;i<7;i++)
            {
                  lastpoint[i]=currpoint[i];
            }

            //get new currpoint
            if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
            {
                  //tokenize the line
```

```
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //save currpoint
                  for(i=0;i<7;i++)
                  {
                        currpoint[i]=linearray[i];
                  }

                  //get tempdir
                  for(i=1;i<7;i++)
                  {
                        pointdiff[i] = currpoint[i] - lastpoint[i];
                        if (pointdiff[i] > 0){ tempdir[i] = 1; }
                        else if (pointdiff[i] < 0){ tempdir[i] = -1; }
                        else { tempdir[i] = 0; }
                  }

                  //check for changes in direction for object 1
                  for(i=1;i<3;i++)  //ignore Z (4)
                  {
                        if (tempdir[i] != direction[i])
                        {
                              //ensure that the magnitude
                              if(abs(currpoint[i]-lastsavedpoint1[i]) > 1000)
changeflag1 = 1;
                        }
                  }

                  //check for changes in direction for object 2
                  for(i=4;i<6;i++)  //ignore Z (7)
                  {
                        if (tempdir[i] != direction[i])
                        {
                              //ensure that the magnitude
                              if(abs(currpoint[i]-lastsavedpoint2[i-3]) >
1000) changeflag2 = 1;
                        }
                  }

                  //if a change in direction in obj1 has occurred, print &
save the point
                  if (changeflag1)
                  {
                        //print to compressed coords files & save the point
                        fprintf(compressedcoordsfile1, "%f,", lastpoint[0]);
                        lastsavedpoint1[0] = lastpoint[0];
                        lastinterimpoint1[0] = lastpoint[0];
                        for(i=1;i<3;i++)
                        {
```

```
                              fprintf(compressedcoordsfile1, "%f,",
lastpoint[i]);
                              lastsavedpoint1[i] = lastpoint[i];
                              lastinterimpoint1[i] = lastpoint[i];
                        }
                        fprintf(compressedcoordsfile1, "%f,%f,%f,%f\n",
lastpoint[3],linearray[7],linearray[8],linearray[9]);
                        lastsavedpoint1[3] = lastpoint[3];
                        lastinterimpoint1[3] = lastpoint[3];

                  }
                  //there is no change in direction BUT it has been more then
4 points since our last save, save one
                  /*
                  else if(lastpoint[0] - lastinterimpoint1[0] > 4)
                  {
                        //print to compressed coords files & save the point
                        fprintf(compressedcoordsfile1, "%f,", lastpoint[0]);
                        lastinterimpoint1[0] = lastpoint[0];
                        for(i=1;i<3;i++)
                        {
                              fprintf(compressedcoordsfile1, "%f,",
lastpoint[i]);
                              lastinterimpoint1[i] = lastpoint[i];
                        }
                        fprintf(compressedcoordsfile1, "%f,%f,%f,%f\n",
lastpoint[3],linearray[7],linearray[8],linearray[9]);
                        lastinterimpoint1[3] = lastpoint[3];

                  }
                  */

                  //if a change in direction in obj2 has occurred, print &
save the point
                  if (changeflag2)
                  {
                        //print to compressed coords files & save the point
                        fprintf(compressedcoordsfile2, "%f,", lastpoint[0]);
                        lastsavedpoint2[0] = lastpoint[0];
                        for(i=4;i<6;i++)
                        {
                              fprintf(compressedcoordsfile2, "%f,",
lastpoint[i]);
                              lastsavedpoint2[i-3] = lastpoint[i];
                        }
                        fprintf(compressedcoordsfile2, "%f,%f,%f,%f\n",
lastpoint[6],linearray[7],linearray[8],linearray[9]);
                        lastsavedpoint2[3] = lastpoint[6];

                  }
                  //there is no change in direction BUT it has been more then
4 points since our last save, save one
                  /*
                  else if(lastpoint[0] - lastinterimpoint1[0] > 4)
                  {
                        //print to compressed coords files & save the point
                        fprintf(compressedcoordsfile2, "%f,", lastpoint[0]);
```

```
                        lastinterimpoint2[0] = lastpoint[0];
                        for(i=4;i<6;i++)
                        {
                              fprintf(compressedcoordsfile2, "%f,",
lastpoint[i]);
                              lastinterimpoint2[i] = lastpoint[i];
                        }
                        fprintf(compressedcoordsfile2, "%f,%f,%f,%f\n",
lastpoint[6],linearray[7],linearray[8],linearray[9]);
                        lastinterimpoint2[3] = lastpoint[6];

                  }
                  */

                  //reset changeflags
                  changeflag1 = 0;
                  changeflag2 = 0;

                  //update directions
                  for(i=0;i<7;i++)
                  {
                        direction[i] = tempdir[i];
                  }
            }
            else        //if we reach the end of the file break out of the
while loop
            {
                  //print the last point
                  fprintf(compressedcoordsfile1, "%f,", currpoint[0]);
                  fprintf(compressedcoordsfile2, "%f,", currpoint[0]);
                  for(i=1;i<3;i++)
                  {
                        fprintf(compressedcoordsfile1, "%f,", currpoint[i]);
                        fprintf(compressedcoordsfile2, "%f,",
currpoint[i+3]);
                  }
                  fprintf(compressedcoordsfile1, "%f,%f,%f,%f\n",
lastpoint[3],linearray[7],linearray[8],linearray[9]);
                  fprintf(compressedcoordsfile2, "%f,%f,%f,%f\n",
lastpoint[6],linearray[7],linearray[8],linearray[9]);

                  //close files
                  fclose(coordsfile);
                  fclose(compressedcoordsfile1);
                  fclose(compressedcoordsfile2);
                  break;
            }

      }

      printf ("****Compression Complete\n");

      //cleanup
      delete[] lastpoint;
      delete[] currpoint;
      delete[] lastsavedpoint1;
      delete[] lastsavedpoint2;
```

```
      delete[] pointdiff;
      delete[] direction;
      delete[] tempdir;
      delete[] linearray;
}

//courtesy of http://www.functionx.com/cpp/examples/abs.htm
double abs(double Nbr)
{
//    return (Nbr >= 0) ? Nbr : -Nbr;
      if( Nbr >= 0 )
            return Nbr;
      else
            return -Nbr;
}

//function that takes compressed coords, and uploads them to a shared drive
location for use by
//the neural network controller.  This is done one point at a time so that
only 1 point is available
//to the NN Controller at a time
void uploadToNN1by1(char uploadL[], char uploadR[], char coordsL[], char
coordsR[])
{
      int counter = 0;                                          //counter
      char lineL [512];                                         //holder for a
single line of coordsfileL as it is parsed
      char lineR [512];                                         //holder for a
single line of coordsfileR as it is parsed
      char *token;                                                    //holder
for tokenizing line
      char *Lout;                                                     //flag to
see if we've reached the end of the file
      char *Rout;                                                     //flag to
see if we've reached the end of the file
      int i;
      //random counter variable
      int updateL = 1;                                          //flag to see if
the point has been uploaded yet
      int updateR = 1;                                          //flag to see if
the point has been uploaded yet
      double* currpointL = new double[4];             //array to hold values
of the current point (TIME,X1,Y1,Z1)
      double* currpointR = new double[4];             //array to hold values
of the current point (TIME,X2,Y2,Z2)
      FILE *uploadfileL;                                              //file
handle for temp upload file to send info to the NN L
      FILE *uploadfileR;                                              //file
handle for temp upload file to send info to the NN R
      FILE *coordsfileL;                                              //file
handle for coords to be uploaded L
      FILE *coordsfileR;                                              //file
handle for coords to be uploaded R

      //open coords files
      coordsfileL = fopen(coordsL, "r");  //coordinates to be uploaded
      coordsfileR = fopen(coordsR, "r");  //coordinates to be uploaded
```

```
	fgets(lineL, 512, coordsfileL); //ignore 1st line of TITLES
	fgets(lineR, 512, coordsfileR); //ignore 1st line of TITLES

	//cycle through a loop where each cycle represents 1 "timestep" from
the input process
	//new coordinates will only be uploaded at the appropriate timestep to
maintain the spacing
	for(;;)
	{
		//get lines from LEFT and RIGHT coordsfiles
		if (updateL == 1) Lout = fgets(lineL, 512, coordsfileL);
		if (updateR == 1) Rout = fgets(lineR, 512, coordsfileR);

		updateL = 0;
		updateR = 0;

		if(Lout != NULL || Rout != NULL)
		{
			//tokenize the LEFT line
			i=0;
			token=strtok(lineL, DELIM);
			currpointL[0] = to_double(token);
			while((token=strtok(NULL, DELIM))!=NULL)
			{
				i++;
				currpointL[i]=to_double(token);
			}

			//tokenize the RIGHT line
			i=0;
			token=strtok(lineR, DELIM);
			currpointR[0] = to_double(token);
			while((token=strtok(NULL, DELIM))!=NULL)
			{
				i++;
				currpointR[i]=to_double(token);
			}

			//if TIME (from currpoint) is equal to or less then the
current iteration of the loop, upload it
			if (lineL != NULL && currpointL[0] <= counter)
			{
				//upload the current time (NN receiver will check to
see if a new point has come in by comparing
				//the timestamp with it's last saved timestamp)
				uploadfileL = fopen(uploadL, "w");
				fprintf(uploadfileL, "%f,%f,%f,%f\n", currpointL[0],
currpointL[1], currpointL[2], currpointL[3]);
				fclose(uploadfileL);
				updateL = 1;
			}

			if (lineR != NULL && currpointR[0] <= counter)
			{
				//upload the current time (NN receiver will check to
see if a new point has come in by comparing
```

```
                        //the timestamp with it's last saved timestamp)
                        uploadfileR = fopen(uploadR, "w");
                        fprintf(uploadfileR, "%f,%f,%f,%f\n", currpointR[0],
currpointR[1], currpointR[2], currpointR[3]);
                        fclose(uploadfileR);
                        updateR = 1;
                  }
            }
            else break;       //if we've reached the end of both files, break
out of the loop
            Sleep(1000);      //sleep for a time representative of the delay
between 2 timesteps (Sleep takes milliseconds as an argument)
            counter++;        //update counter
      }
      fclose(coordsfileL);
      fclose(coordsfileR);

      //cleanup
      delete[] currpointL;
      delete[] currpointR;
}

//function that takes compressed coords, and uploads them to a shared drive
location for use by
//the neural network controller.  It gives all the points the NN Controller
and requires that the NN
//cut them apart and use the points in order.
void uploadToNNbatch(char uploadL[], char uploadR[], char coordsL[], char
coordsR[])
{
      char line [512];                                          //holder for a
single line of a coordsfile as it is parsed
      FILE *uploadfileL;                                              //file
handle for temp upload file to send info to the NN L
      FILE *uploadfileR;                                              //file
handle for temp upload file to send info to the NN R
      FILE *coordsfileL;                                              //file
handle for coords to be uploaded L
      FILE *coordsfileR;                                              //file
handle for coords to be uploaded R

      //open coords files
      coordsfileL = fopen(coordsL, "r");  //coordinates to be uploaded
      coordsfileR = fopen(coordsR, "r");  //coordinates to be uploaded

      //fgets(line, 512, coordsfileL); //ignore 1st line of TITLES
      //fgets(line, 512, coordsfileR); //ignore 1st line of TITLES

      uploadfileL = fopen(uploadL, "w");
      uploadfileR = fopen(uploadR, "w");

      //copy all but the 1st line to a text file on the shared I drive for
use by the Neural Network Controller
      for(;;)
      {
            if(fgets(line, 512, coordsfileL) != NULL)
            {
```

```
                  fprintf(uploadfileL, line);
            }
            else break;       //if we've reached the end of the file, break
out of the loop
      }

      for(;;)
      {
            if(fgets(line, 512, coordsfileR) != NULL)
            {
                  fprintf(uploadfileR, line);
            }
            else break;       //if we've reached the end of the file, break
out of the loop
      }

      printf ("****Upload to Controller Complete\n");

      fclose(uploadfileL);
      fclose(uploadfileR);
      fclose(coordsfileL);
      fclose(coordsfileR);
}

//function to convert the points from their current magic scale to a scale
suitable for ISAC's NN Controller
//also switch axes: X->Y, Y->Z, Z->X
//also, if necessary, mirror image X->Y axis for mirrored motion
void fitCoordsToISAC(char coords[], char fittedcoords[])
{
      FILE *coordsfile;                                    //file handle for
coords to be uploaded
      FILE *fittedcoordsfile;                              //file handle for
the newley fittted coords
      int i,j;
      char line [512];                                     //holder for a
single line of a coordsfile as it is parsed
      double* linearray = new double[7];             //array to values hold
a line of coordsfile
      double* currpoint = new double[4];             //array to hold values
of the current point (TIME,X1,Y1,Z1)
      double* modpoint = new double[4];              //array to hold values
of the current point modified (TIME,X1,Y1,Z1)
      double maxs[2][4];           //2D array to hold max values [0][i]=N/A,
X max TIME, Y max TIME, Z max TIME
                                          //
        [1][i]=N/A, X max, Y max, Z max
      double mins[2][4];           //2D array to hold min values [0][i]=N/A,
X min TIME, Y min TIME, Z min TIME
                                          //
        [1][i]=N/A, X min, Y min, Z min
      double diffs[4];        //array to hold maxs[1][i] - mins[1][i]
      double divs[4];               //array to hold diffs/(ISAC_MAX-
ISAC_MIN);
      double shift[4];        //array to hold shift factors;
      char *token;
```

```
	//initialize maxs/mins
	for(i=0;i<2;i++)
	{
		for(j=0;j<4;j++)
		{
			maxs[i][j]=-999999999999;
			mins[i][j]=999999999999;
		}
	}

	//GET MAX AND MIN FOR X, Y, Z
	//open coords files
	coordsfile = fopen(coords, "r");	//coordinates to be parsed
	fgets(line, 512, coordsfile);		//ignore 1st line of TITLES
	for(;;)
	{
		if(fgets(line, 512, coordsfile) != NULL)	//get a line from
coordsfile
		{
			//tokenize the line
			i=0;
			token=strtok(line, DELIM);
			linearray[0] = to_double(token);
			while((token=strtok(NULL, DELIM))!=NULL)
			{
				i++;
				linearray[i]=to_double(token);
			}

			//save to currpoint
			for(i=0;i<4;i++)
			{
				currpoint[i]=linearray[i];
			}

			//find max/mins
			for(i=1;i<4;i++)
			{
				if(currpoint[i] >= maxs[1][i])
				{
					maxs[0][i] = currpoint[0];	//set new max
time
					maxs[1][i] = currpoint[i];	//set new max
value
				}

				if(currpoint[i] <= mins[1][i])
				{
					mins[0][i] = currpoint[0];	//set new min
time
					mins[1][i] = currpoint[i];	//set new min
value
				}
			}

		}
		else
```

```
            {
                  fclose(coordsfile);
                  break;            //if we've reached the end of the file,
break out of the loop
            }
      }

      //CALCULATE DIFFERENCES
      for(i=1;i<4;i++)
      {
            diffs[i]=maxs[1][i]-mins[1][i];           //get the range of each
axes
      }

      //DIVIDE DIFFERENCE BY ISAC'S RANGE
      divs[1]=diffs[1]/(ISAC_Y_MAX-ISAC_Y_MIN); //our X is ISACs Y
      divs[2]=diffs[2]/(ISAC_Z_MAX-ISAC_Z_MIN); //our Y is ISACs Z
      divs[3]=diffs[3]/(ISAC_X_MAX-ISAC_X_MIN); //our Z is ISACs X

      //CALCULATE SHIFT FACTOR
      shift[1]=(mins[1][1]/divs[1]-ISAC_Y_MIN)*-1;
      shift[2]=(mins[1][2]/divs[2]-ISAC_Z_MIN)*-1;
      shift[3]=(mins[1][3]/divs[3]-ISAC_X_MIN)*-1;

      //REWRITE FILE LINE BY LINE APPLYING SCALE/SHIFT AND REARRANGING AXES
      coordsfile = fopen(coords, "r");                      //coordinates to
be parsed
      fittedcoordsfile = fopen(fittedcoords, "w");    //fitted coordinates
file
      fgets(line, 512, coordsfile);                         //ignore 1st line
of TITLES
      for(;;)
      {
            if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
            {
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //save to currpoint
                  for(i=0;i<4;i++)
                  {
                        currpoint[i]=linearray[i];
                  }


                  modpoint[0]=currpoint[0];
                  for(i=1;i<4;i++)
                  {
```

```
                        modpoint[i]=currpoint[i]/divs[i]+shift[i];
      //scale & shift the point
                  }

                  //write to the new file in ISAC's order
                  fprintf(fittedcoordsfile,
"%f,%f,%f,%f\n",modpoint[0],modpoint[3],modpoint[1],modpoint[2]);

            }
            else
            {
                  fclose(coordsfile);
                  fclose(fittedcoordsfile);
                  break;            //if we've reached the end of the file,
break out of the loop
            }
      }

      printf ("****Fitting to ISAC Complete\n");

      //cleanup
      delete[] linearray;
      delete[] currpoint;
      delete[] modpoint;
}

//file to create many many points in a 3d space to test against an inverse
kinematics program to get a workspace
//format: "count,x,y,z\n"
void testSetForInverseKinematics(char test[], int Xmin, int Xmax, int Ymin,
int Ymax, int Zmin, int Zmax, int stepSize)
{
      FILE *testfile;               //file handle to hold the file to be
written to
      int x,y,z,c;                  //counters

      c=0;

      testfile = fopen(test, "w");

      for(x=Xmin;x<=Xmax;x=x+stepSize)
      {
            for(y=Ymin;y<=Ymax;y=y+stepSize)
            {
                  for(z=Zmin;z<=Zmax;z=z+stepSize)
                  {
                        fprintf(testfile, "%d,%d,%d,%d\n", c,x,y,z);
                        c++;
                  }
            }
      }
      fclose(testfile);
}

//function to create a set of points to be fed through a forward kinematics
program to test for workspace
//format: "count,ang1,ang2,ang3,ang4,ang5,ang6\n"
```

```
void testSetForForwardKinematics(char test[], double maxAngle, double
stepSize)
{
      FILE *testfile;                     //file handle to hold the file to
be written to
      double a0,a1,a2,a3,a4,a5;     //counters (mostly theta angles)
      int c;

      c=0;
      testfile = fopen(test, "w");

      for(a0=0;a0<maxAngle;a0=a0+stepSize)
      {
            for(a1=0;a1<maxAngle;a1=a1+stepSize)
            {
                  for(a2=0;a2<maxAngle;a2=a2+stepSize)
                  {
                        for(a2=0;a2<maxAngle;a2=a2+stepSize)
                        {
                              for(a3=0;a3<maxAngle;a3=a3+stepSize)
                              {
                                    for(a4=0;a4<maxAngle;a4=a4+stepSize)
                                    {

      for(a5=0;a5<maxAngle;a5=a5+stepSize)
                                          {
                                                fprintf(testfile,
"%d,%f,%f,%f,%f,%f,%f\n", c,a0,a1,a2,a3,a4,a5);
                                                c++;
                                          }
                                    }
                              }
                        }
                  }
            }
      }

      fclose(testfile);
}

//function to take a set of coordinates fitted for ISAC and convert them into
Joint Angles
void calcJointAngles(char coords[], char angles[], int rightleft, int EndEff,
int simple)
{
      FILE *coordsfile;                   //file handle for fitted
coordinates to be converted
      FILE *anglesfile;                   //file handle for joint angle
outputs
      char line [512];                    //holder for a single line of
a coordsfile as it is parsed
      char *token;
      double* currpoint = new double[4];  //array to hold values of the
current point (TIME,X1,Y1,Z1)
      CvPoint3D32f point;                 //holder for point to be
passed to simpleInverseKinematics
      double *pdAngles;
```

```
      double pdPos[6]={0.0};              //array to hold the coordinates to
be passed to the Inverse Kinematics
      int i,j;

      if(!simple)
      {
            pdAngles = new double[6];
      }



      coordsfile = fopen(coords, "r");
      anglesfile = fopen(angles, "w");

      if (coordsfile == NULL || anglesfile == NULL)
      {
            printf("WARNING: Could NOT convert fitted coordinates to joint
angles!!!\n");
            return;
      }

      for(;;)
      {
            if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
            {
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  currpoint[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        currpoint[i]=to_double(token);
                  }

                  if(simple)
                  {
                        point.x = currpoint[1];
                        point.y = currpoint[2];
                        point.z = currpoint[3];
                  }
                  else
                  {
                        for(j=0;j<3;j++)  //save the xyz point into our pdPos
holder;
                        {
                              pdPos[j]=currpoint[j+1];
                        }
                  }

                  //INVERSE KINEMATICS
                  if(simple)
                  {
                        pdAngles = simpleInverseKinematics(point, rightleft);
                  }
                  else
```

```
                  {
                        inverseKinematics(pdPos, pdAngles, (short)rightleft,
(short)EndEff);
                        //set last 3 joints to 0 to keep the wrist locked
                        pdAngles[3]=0;
                        pdAngles[4]=0;
                        pdAngles[5]=0;
                  }



                  //write time + joint angles to the new joint angles file
                  fprintf(anglesfile,
"%f,%f,%f,%f,%f,%f,%f\n",currpoint[0],pdAngles[0],pdAngles[1],pdAngles[2],pdA
ngles[3],pdAngles[4],pdAngles[5]);

            }
            else
            {
                  fclose(coordsfile);
                  fclose(anglesfile);
                  break;            //if we've reached the end of the file,
break out of the loop
            }
      }

      printf ("****Conversion to Joint Angles Complete\n");

      //cleanup
      delete[] currpoint;
      delete[] pdAngles;
}

//function to interface with Kinematics.cpp for Inverse Kinematics
//calculates joint angles from a set of XYZ coords
//written by Juan Rojas
void inverseKinematics(double * pdPos, double * pdAngles, short m_sLeftArm,
short m_sEndEffector)
{
      int i;
      double            M[16];
      Kinematics  *m_pKMArm;

      //for (i=0;i<16;i++)
      //    M[i]=0.0;

      // Create Arm Class
      m_pKMArm = new Kinematics(m_sLeftArm, m_sEndEffector);

      //m_pKMArm->m_sRightHand = m_sLeftArm;
      // Tells which side end-effector information we will use

      // Tranform: Subtract the base-tranform from the center of the eyes to
get the coords at the base of the shoulder
      pdPos[0]-=m_pKMArm->m_pdBaseXform[0];
      pdPos[1]-=m_pKMArm->m_pdBaseXform[1];
      pdPos[2]-=m_pKMArm->m_pdBaseXform[2];
```

```
      // Initialization calls necessary to get parameters right
      m_pKMArm->SetRPYMatrix(m_pKMArm->m_pdEndEffXform,M);              //
Build W2E Transformation
      m_pKMArm->SetW2ETransform(M);

      // Call that actually computes the inverse kinematics and returns the
angles
      // Give it the XYZ to compute the new position
      m_pKMArm->SetXYZRPY(pdPos);
      // Get the angles of the new position
      m_pKMArm->GetAngles(pdAngles);

      for (i=0;i<6;i++)
            if(fabs(pdAngles[i]) < 0.0001)
                  pdAngles[i] = 0.0000;
}

//function to create an empty file called Start.Now that tells the controller
to go.  The controller sits in
//a loop searching for this file which indicates that new joint angles have
been uploaded.  When it finds the
//file the loop exits and the controller begins moving the arm to points
specified by uploadL.txt and uploadR.txt
void uploadGoFlag(char loc[])
{
      FILE *flagfile;                                    //file handle for our
upload flag

      //open flag file for writing
      flagfile = fopen(loc, "w");

      //close flag file
      fclose(flagfile);

      printf ("****Upload of \"Go Flag\" Complete\n");
}


//function to detect the person's face based on the c facedetect demo that
comes with OpenCV
void haarFaceDetect(IplImage* img, CvTarget *tar)
{
      int radius;
    double scale = 1.3;

    IplImage* gray = cvCreateImage( cvSize(img->width,img->height), 8, 1 );
    IplImage* small_img = cvCreateImage( cvSize( cvRound (img->width/scale),
                        cvRound (img->height/scale)),
                  8, 1 );
    int i;

    cvCvtColor( img, gray, CV_BGR2GRAY );
    cvResize( gray, small_img, CV_INTER_LINEAR );
    cvEqualizeHist( small_img, small_img );
    cvClearMemStorage( storage );
```

```
    if( cascade )
    {
        CvSeq* faces = cvHaarDetectObjects( small_img, cascade, storage,
                                            1.1, 2,
0/*CV_HAAR_DO_CANNY_PRUNING*/,
                                            cvSize(30, 30) );

            tar->r = 0; //initialize the target radius to 0
            //cycle through detected faces to find the largest
        for( i = 0; i < (faces ? faces->total : 0); i++ )
        {
            CvRect* r = (CvRect*)cvGetSeqElem( faces, i );
            radius = cvRound((r->width + r->height)*0.25*scale);

                  //if the radius of the detected face is larger then prev
saved radius, save the loc
                  if (radius > tar->r)
                  {
                        tar->r = radius;
                        tar->x = cvRound((r->x + r->width*0.5)*scale);
                        tar->y = cvRound((r->y + r->height*0.5)*scale);
                  }

        }
    }

    cvReleaseImage( &gray );
    cvReleaseImage( &small_img );
}

//function to get an average of the location of the face in the images,
calculate the 3D location of it
//and then write it to the coords file
void avgFaceLoc(char coords[], char out[])
{
      FILE *coordsfile;                         //file handle for coords file
w/ face locations
      FILE *outputfile;                         //file handle for modified
output file
      char line [512];                          //holder for a single line of
a coordsfile as it is parsed
      char *token;
      double* linearray = new double[22]; //array to hold values of the
current line

      double XLtotal=0,YLtotal=0,XRtotal=0,YRtotal=0; //holders for total
values in each direction

      CvPoint left;                                   //CvPoint to hold the
left averages
      CvPoint right;                                  //CvPoint to hold the
right averages
      CvPoint3D32f faceloc;                     //3D CvPoint to hold the
average adjusted 3D location

      int count=0;                                    //holder for total # of
entries analyzed
```

```
      int i;

      //linearray guide
      //[0]=TIME, [1]=PX1L, [2]=PY1L, [3]=PX1R, [4]=PY1R, [5]=X1, [6]=Y1,
[7]=Z1,
      //[8]=PX2L, [9]=PY2L, [10]=PX2R, [11]=PY2R, [12]=X2, [13]=Y2, [14]=Z2,
[15]=FACE_PXL,
      //[16]=FACE_PYL, [17]=FACE_PXR, [18]=FACE_PYR, [19]=FACE_X,
[20]=FACE_Y, [21]=FACE_Z

      //currpoint guide
      //[0]=FACE_PXL, [1]=FACE_PYL, [2]=FACE_PXR, [3]=FACE_PYR

      coordsfile = fopen(coords, "r");

      if (coordsfile == NULL)
      {
            printf("WARNING: Could NOT average and rewrite face
locations!!!\n");
            return;
      }

      fgets(line, 512, coordsfile);       //IGNORE 1st line b/c it is TITLES
      for(;;)     //loop forever
      {
            if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
            {
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //update totals
                  XLtotal+=linearray[15];
                  YLtotal+=linearray[16];
                  XRtotal+=linearray[17];
                  YRtotal+=linearray[18];
                  count++;

            }
            else
            {
                  fclose(coordsfile);
                  break;            //if we've reached the end of the file,
break out of the loop
            }
      }

      //calculate averages
      left.x = XLtotal/count;
```

```
      left.y = YLtotal/count;
      right.x = XRtotal/count;
      right.y = YRtotal/count;

      //calculate XYZ location;
      calculateXYZ(&faceloc, left, right);


      //rewrite the coords file
      coordsfile = fopen(coords, "r");
      outputfile = fopen(out, "w");

      //write titles line to outputfile
      fprintf(outputfile,"TIME,PX1L,PY1L,PX1R,PY1R,X1,Y1,Z1,PX2L,PY2L,PX2R,PY
2R,X2,Y2,Z2,FACE_PXL,FACE_PYL,FACE_PXR,FACE_PYR,FACE_X,FACE_Y,FACE_Z\n");

      if (coordsfile == NULL || outputfile == NULL)
      {
            printf("WARNING: Could NOT average and rewrite face
locations!!!\n");
            return;
      }

      fgets(line, 512, coordsfile);       //IGNORE 1st line b/c it is TITLES
      for(;;)     //loop forever
      {
            if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
            {
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //print the line to our output file with the adjusted face
values
                  fprintf(outputfile,
"%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%d,%d,%d,%d,%f,%f,%f\n",

      linearray[0],linearray[1],linearray[2],linearray[3],linearray[4],linear
ray[5],linearray[6],

      linearray[7],linearray[8],linearray[9],linearray[10],linearray[11],line
array[12],linearray[13],

      linearray[14],left.x,left.y,right.x,right.y,faceloc.x,faceloc.y,faceloc
.z);
            }
            else
            {
                  fclose(coordsfile);
                  fclose(outputfile);
```

```
                  break;            //if we've reached the end of the file,
break out of the loop
            }
      }

      printf ("****Averaging of Face Location and Rewrite Complete\n");

      //cleanup
      delete[] linearray;
}

//function to do simple inverse kinematics.  in this case ISAC's arm is
represented as a 3 angle 2 link
//manipulator.  we will only use angles 0, 1 and 2, and will lock the wrist
in place.
//this function takes in a 3D point as input and returns joint angles for
ISAC to reach to it.
//calculations of Theta 1 & 2 taken from page 69 of Modelling and Control of
Robotic Manipulators by
//L. Sciavicco & B. Siciliano
double* simpleInverseKinematics(CvPoint3D32f point, int rightleft)
{
      //T = Theta = Angle
      //X, Y, & Z are relative to ISAC's workspace thus: X= front to back,
Y=right to left, X=top to bottom
      double T0, T1, T2, T4;                    //Theta 0, 1, 2, & 4 refer to
angles 0, 1, 2, & 4
      double a, b, u, f, h;                     //holders for constant values
      double Ta, Tb, v1, v2;                    //intermediate angle
calculations
      double n,o;                                     //intermediate values
for calculation of T0
      double c2;                                      //intermediate values
for calculation of T1 & T2
      double x,y,z;                                   //holder for absoulte
values of incoming point
      double* ret = new double[6];        //return array for angles {T0, T1,
T2, 0, 0, 0}
      double alpha, beta;

      //set constant holders
      a = CENTER_TO_ANGLE_0;
      b = SHOULDER_OFFSET;
      u = UPPERARM;
      f = FOREARM;
      h = HAND_L;

      //adjust x, y, z for math
      x = point.x;
      if (rightleft == RIGHT_ARM)
      {
            y = -point.y;
      }
      else
      {
            y = point.y;
      }
```

```
z = -point.z;

//Calculate Theta 0 (shoulder X Y)
if (y >= a)
{
      Ta = atan(x/(y - a));
      Tb = acos(b*sin(Ta)/x);

      T0 = Tb - Ta;
}
else
{
      n  = a - y;
      Tb = atan(x/n);
      o  = x/sin(Tb);
      Ta = acos(b/o);
      T0 = -(PI - Ta - Tb);
}

if (rightleft == RIGHT_ARM)
{
      T0 = -T0;
}

//Calculate Theta 1 (elbow) & Theta 2 (shoulder X Z)
//**** current assumption that 0 on the Z axis is at shoulder level
//geometric solution
alpha = atan2(z,x);
beta = acos((x*x+z*z+u*u-(f+h)*(f+h))/(2*u*sqrt(x*x+z*z)));

c2 = (x*x + z*z - u*u - (f+h))/(2*u*(f+h));

//angles according to the book
v1 = alpha + beta;
v2 = acos(c2);

//conversion to ISAC's frame
T1 = v1;
T2 = -v2 - PI/2;

//Calculate Theta 4 (wrist up/down)
T4 = -(PI + T1 + T2);

//Convert to Degrees
T0=T0*R2D;
T1=T1*R2D;
T2=T2*R2D;
T4=T4*R2D;

//Ensure that final Theta values do not exceed ISAC's Range of Motion
if (rightleft == RIGHT_ARM)
{
      if(T0 > ANG_R_0_MAX) T0 = ANG_R_0_MAX;
      if(T0 < ANG_R_0_MIN) T0 = ANG_R_0_MIN;
      if(T1 > ANG_R_1_MAX) T1 = ANG_R_1_MAX;
      if(T1 < ANG_R_1_MIN) T1 = ANG_R_1_MIN;
      if(T2 > ANG_R_2_MAX) T2 = ANG_R_2_MAX;
```

```
            if(T2 < ANG_R_2_MIN) T2 = ANG_R_2_MIN;
            if(T4 > ANG_R_4_MAX) T4 = ANG_R_4_MAX;
            if(T4 < ANG_R_4_MIN) T4 = ANG_R_4_MIN;
      }
      else
      {
            if(T0 > ANG_L_0_MAX) T0 = ANG_L_0_MAX;
            if(T0 < ANG_L_0_MIN) T0 = ANG_L_0_MIN;
            if(T1 > ANG_L_1_MAX) T1 = ANG_L_1_MAX;
            if(T1 < ANG_L_1_MIN) T1 = ANG_L_1_MIN;
            if(T2 > ANG_L_2_MAX) T2 = ANG_L_2_MAX;
            if(T2 < ANG_L_2_MIN) T2 = ANG_L_2_MIN;
            if(T4 > ANG_L_4_MAX) T4 = ANG_L_4_MAX;
            if(T4 < ANG_L_4_MIN) T4 = ANG_L_4_MIN;
      }

      //populate return array in degrees
      ret[0]=T0;
      ret[1]=T1;
      ret[2]=T2;
      ret[3]=0;
      ret[4]=T4;
      ret[5]=0;

      return ret;
}

//function to convert the points from their current magic scale to a scale
suitable for ISAC's NN Controller
//also switch axes: X->Y, Y->Z, Z->X
//different approach then fitCoordstoISAC
void fitCoordsToISAC2(char coords[], char fittedcoords[], int rightleft)
{
      FILE *coordsfile;                                    //file handle for
coords to be uploaded
      FILE *fittedcoordsfile;                              //file handle for
the newley fittted coords
      int i,j;
      char line [512];                                     //holder for a
single line of a coordsfile as it is parsed
      double* linearray = new double[7];             //array to values hold
a line of coordsfile
      double* currpoint = new double[4];             //array to hold values
of the current point (TIME,X1,Y1,Z1)
      double* modpoint = new double[4];              //array to hold values
of the current point modified (TIME,X1,Y1,Z1)
      double maxs[2][4];           //2D array to hold max values [0][i]=N/A,
X max TIME, Y max TIME, Z max TIME
                                          //
        [1][i]=N/A, X max, Y max, Z max
      double mins[2][4];           //2D array to hold min values [0][i]=N/A,
X min TIME, Y min TIME, Z min TIME
                                          //
        [1][i]=N/A, X min, Y min, Z min
      double diffs[4];        //array to hold maxs[1][i] - mins[1][i]
      double div;                   //holder for the scale factor
      double shift[4];        //array to hold shift factors
```

```
      double armshift;        //holder for the amount to shift the series1
(right arm) points by
      int no_move=0;                //flag to signify that no important
movement has been see
      char *token;

      //initialize maxs/mins
      for(i=0;i<2;i++)
      {
            for(j=0;j<4;j++)
            {
                  maxs[i][j]=-999999999999;
                  mins[i][j]=999999999999;
            }
      }

      //GET MAX AND MIN FOR X, Y, Z (dont use Z but get it anyways)
      //open coords files
      coordsfile = fopen(coords, "r");    //coordinates to be parsed
      fgets(line, 512, coordsfile);       //ignore 1st line of TITLES
      for(;;)
      {
            if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
            {
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //save to currpoint
                  for(i=0;i<4;i++)
                  {
                        currpoint[i]=linearray[i];
                  }

                  //find max/mins
                  for(i=1;i<4;i++)
                  {
                        if(currpoint[i] >= maxs[1][i])
                        {
                              maxs[0][i] = currpoint[0];    //set new max
time
                              maxs[1][i] = currpoint[i];    //set new max
value
                        }

                        if(currpoint[i] <= mins[1][i])
                        {
                              mins[0][i] = currpoint[0];    //set new min
time
```

```
                              mins[1][i] = currpoint[i];    //set new min
value
                        }
                  }

            }
            else
            {
                  fclose(coordsfile);
                  break;            //if we've reached the end of the file,
break out of the loop
            }
      }

      //CALCULATE DIFFERENCES
      for(i=1;i<4;i++)
      {
            diffs[i]=maxs[1][i]-mins[1][i];           //get the range of each
axes
      }

      //FIND BIGGEST RANGE & DIVIDE DIFFERENCE BY ISAC'S RANGE
      if(diffs[1] > diffs[2])
      {
            if (diffs[1] > MIN_MOVEMENT)
                  div = diffs[1]/(ISAC_Y_MAX-ISAC_Y_MIN); //our X is ISAC's Y
            else
                  no_move = 1;
      }
      else
      {
            if (diffs[2] > MIN_MOVEMENT)
                  div = diffs[2]/(ISAC_Z_MAX-ISAC_Z_MIN); //our Y is ISAC's Z
            else
                  no_move = 1;
      }

      //CALCULATE SHIFT FACTOR based on Face Location
      shift[1]=(mins[1][1]/div-FACE_Y)*-1;
      shift[2]=(maxs[1][2]/div-FACE_Z)*-1;

      //IF RIGHT ARM :: GET LARGEST LEFT/RIGHT (X->Y) VALUE
      armshift = maxs[1][1]/div+shift[1];


      //REWRITE FILE LINE BY LINE APPLYING SCALE/SHIFT AND REARRANGING AXES
AND SET ISAC_X = 400
      coordsfile = fopen(coords, "r");                        //coordinates to
be parsed
      fittedcoordsfile = fopen(fittedcoords, "w");    //fitted coordinates
file
      fgets(line, 512, coordsfile);                           //ignore 1st line
of TITLES
      for(;;)
      {
            if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
```

```
            {
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //save to currpoint
                  for(i=0;i<4;i++)
                  {
                        currpoint[i]=linearray[i];
                  }


                  modpoint[0]=currpoint[0];
                  for(i=1;i<4;i++)
                  {
                        modpoint[i]=currpoint[i]/div+shift[i];    //scale &
shift the point
                  }

                  if (rightleft == RIGHT_ARM)
                  {
                        modpoint[1]=modpoint[1]-armshift;
                  }

                  //SAFTEY SHIFT
                  //shift the points further from the center to ensure ISAC
wont hit his own hands together
                  if (rightleft == RIGHT_ARM)
                  {
                        modpoint[1]=modpoint[1]-SAFTEY_SHIFT;
                  }
                  else
                  {
                        modpoint[1]=modpoint[1]+SAFTEY_SHIFT;
                  }

                  //write to the new file in ISAC's order
                  if (no_move)
                        fprintf(fittedcoordsfile,
"%f,%f,%f,%f\n",modpoint[0],FOREARM+HAND_L,CENTER_TO_ANGLE_0+SHOULDER_OFFSET,
-UPPERARM);
                  else
                        fprintf(fittedcoordsfile,
"%f,%f,%f,%f\n",modpoint[0],CONST_X,modpoint[1],modpoint[2]);

            }
            else
            {
                  fclose(coordsfile);
                  fclose(fittedcoordsfile);
```

```
                  break;            //if we've reached the end of the file,
break out of the loop
            }
      }

      printf ("****Fitting to ISAC Complete\n");

      //cleanup
      delete[] linearray;
      delete[] currpoint;
      delete[] modpoint;
}

void flipY(char coords[], char flippedYcoords[])
{
      FILE * coordsfile;                        //file handle to store
unparsed coordinates
      FILE * flippedfile;                       //file handle to store
flipped Y coords
      char line [512];                    //holder for a single line of
coordsfile as it is parsed
      char *token;
      double* linearray = new double[22];                  //array of
doubles to hold unfiltered values
      double Y1tot=0,Y2tot=0,Yftot=0;
      double Y1avg,Y2avg,Yfavg;
      double count=0;
      int i;


      //**********************************
      //****** Get Y1 & Y2 AVERAGES ******
      //**********************************

      //GET FIRST ENTRY (line 2) FOR FILTERING HISTORY
      //linearray guide
      //[0]=TIME, [1]=PX1L, [2]=PY1L, [3]=PX1R, [4]=PY1R, [5]=X1, [6]=Y1,
[7]=Z1,
      //[8]=PX2L, [9]=PY2L, [10]=PX2R, [11]=PY2R, [12]=X2, [13]=Y2, [14]=Z2,
[15]=FACE_PXL,
      //[16]=FACE_PYL, [17]=FACE_PXR, [18]=FACE_PYR, [19]=FACE_X,
[20]=FACE_Y, [21]=FACE_Z
      coordsfile = fopen(coords, "r");    //open coordsfile (to be filtered)
      fgets(line, 512, coordsfile);                        //get 1st line to
ignore it b/c it is TITLES
      if(fgets(line, 512, coordsfile) != NULL)        //get a line from
coordsfile
      {
            //tokenize the line
            i=0;
            token=strtok(line, DELIM);
            linearray[0] = to_double(token);
            while((token=strtok(NULL, DELIM))!=NULL)
            {
                  i++;
                  linearray[i]=to_double(token);
            }
```

```
            Y1tot=Y1tot+linearray[6];
            Y2tot=Y2tot+linearray[13];
            Yftot=Yftot+linearray[20];
            count++;
      }
      fclose(coordsfile);

      //calculate average Y value
      Y1avg=Y1tot/count;
      Y2avg=Y2tot/count;
      Yfavg=Yftot/count;

      //**************************************
      //****** REWRITE Y1 & Y2 (FLIPPED) ******
      //**************************************

      //start back at the beginning
      coordsfile = fopen(coords, "r");                        //open coordsfile
(to be flipped)
      flippedfile = fopen(flippedYcoords, "w");       //open flippedycoords
(to hold flipped Y coords)
      fprintf(flippedfile,"TIME,PX1L,PY1L,PX1R,PY1R,X1,Y1,Z1,PX2L,PY2L,PX2R,P
Y2R,X2,Y2,Z2,FACE_PXL,FACE_PYL,FACE_PXR,FACE_PYR,FACE_X,FACE_Y,FACE_Z\n");
      fgets(line, 512, coordsfile);
            //ignore 1st line of coordsfile b/c it is TITLES
      while(1)    //loop forever
      {
            if(fgets(line, 512, coordsfile) != NULL)  //get a line for
coordsfile
            {
                  //GET NEXT LINE
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  linearray[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        linearray[i]=to_double(token);
                  }

                  //print to new file

      fprintf(flippedfile,"%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f
,%f,%f,%f,%f,%f\n",

      linearray[0],linearray[1],linearray[2],linearray[3],linearray[4],linear
ray[5],
                        2*Y1avg-
linearray[6],linearray[7],linearray[8],linearray[9],linearray[10],linearray[1
1],
                        linearray[12],2*Y2avg-
linearray[13],linearray[14],linearray[15],linearray[16],linearray[17],
                        linearray[18],linearray[19],2*Yfavg-
linearray[20],linearray[21]);
            }
```

```
            else        //if we reach the end of the file break out of the
while loop
            {
                  //close files
                  fclose(coordsfile);
                  fclose(flippedfile);
                  break;
            }
      }

      printf ("****Y Flipping Complete\n");

      //cleanup
      delete[] linearray;
}

void interpolateAngles(char anglesIn[], char anglesOut[])
{

      FILE *anglesInFile;
      FILE *anglesOutFile;

      char line [512];                        //holder for a single line of
anglesIn as it is parsed
      char *token;
      double* currangles = new double[7]; //array of doubles to hold current
angles
      double* lastangles = new double[7]; //array to hold the last angles
      double span;
      double* increments = new double[7]; //array to hold the increments for
the interpolation ([0] unused)
      int i;

      //linearray guide
      //[0]=TIME, [1]=Ang0, [2]=Ang1, [3]=Ang2, [4]=Ang3, [5]=Ang4, [6]=Ang5

      anglesInFile = fopen(anglesIn, "r");            //open file with angles
to be interpolated
      anglesOutFile = fopen(anglesOut, "w");          //open file to write
interpolated angles to

      //get 1st line from anglesIn
      if(fgets(line, 512, anglesInFile) != NULL)
      {
            //tokenize the line
            i=0;
            token=strtok(line, DELIM);
            lastangles[0] = to_double(token);
            while((token=strtok(NULL, DELIM))!=NULL)
            {
                  i++;
                  lastangles[i]=to_double(token);
            }
      }

      while(1)
      {
```

```
            //get a line from anglesIn
            if(fgets(line, 512, anglesInFile) != NULL)
            {
                  //tokenize the line
                  i=0;
                  token=strtok(line, DELIM);
                  currangles[0] = to_double(token);
                  while((token=strtok(NULL, DELIM))!=NULL)
                  {
                        i++;
                        currangles[i]=to_double(token);
                  }

                  span = currangles[0] - lastangles[0];     //get the time
between 2 sets of angles

                  //calculate increments for interpolation
                  for(i=1;i<7;i++)
                  {
                        increments[i]=(currangles[i] - lastangles[i])/span;
                  }

                  //write original point + new interpolated points
                  for(i=0;i<span;i++)
                  {
                              fprintf(anglesOutFile,"%f,%f,%f,%f,%f,%f,%f\n",
                              lastangles[0]+i,
                              lastangles[1]+i*increments[1],
                              lastangles[2]+i*increments[2],
                              lastangles[3]+i*increments[3],
                              lastangles[4]+i*increments[4],
                              lastangles[5]+i*increments[5],
                              lastangles[6]+i*increments[6]);
                  }
            }
            else  //break out of the loop if we have reached the end of the
file
            {
                  break;
            }

            //update lastpoint
            for(i=0;i<7;i++)
            {
                  lastangles[i]=currangles[i];
            }
      }

      //print out the last point
      fprintf(anglesOutFile,"%f,%f,%f,%f,%f,%f,%f\n",lastangles[0],lastangles
[1],lastangles[2],lastangles[3],
            lastangles[4],lastangles[5],lastangles[6]);


      //close files
      fclose(anglesInFile);
      fclose(anglesOutFile);
```

```
	//cleanup
	delete[] currangles;
	delete[] lastangles;
	delete[] increments;
}
```

A.2. TrackColor.h (Vision & Processing Header)

```
//Sean Begley
//Imitation Learning
//Hand Following
//1/23/2008


/************************/
/*******             *******/
/*******   NOTES   *******/
/*******             *******/
/************************/

//HUE RANGE
//135-155 : purple bean bag                          *works ok
//80-100 : light blue bean bag                       *works well
//40-80 : big green ball / green lego lid *works very well

//CAMERA TRANSFORM PARAMETERS
//center to camera base = 140mm
//camera base to rotation base = 91.948mm
//rotation base to camera = 65.5mm
//camera to focal point = 39mm
//rotation about z is from dPan
//rotation about y if from dTilt
//effective picture elements: 768x494
//CCD sensing area: 6.4 x 4.8 mm

//OBJECT 1 is the TEAL BEAN BAG and goes in the human's RIGHT HAND
//This motion is then translated to ISAC's RIGHT ARM
//OBJECT 2 is the GREEN LID and goes in the human's LEFT HAND
//This motion is then translated to ISAC's LEFT ARM




/************************/
/*******             *******/
/******* INCLUDES  *******/
/*******             *******/
/************************/

//openCV
#include "cv.h"
#include "highgui.h"
```

```
//standard headers
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include <float.h>
#include <time.h>
#include <sstream>
#include <iostream>

//ISAC specific
#include "PXck_FG.h"          //framegrabbers (cameras)
#include "CameraHead.h"       //head object (pan/tilt bases)



/************************/
/*******              *******/
/******* CONSTANTS *******/
/*******              *******/
/************************/

//big/medium/small changes for camera angles
const double DELTA_B = 2;           //large movement coefficient
const double DELTA_M = .5;          //medium movement coefficient
const double DELTA_S = .01;         //small movement coefficient

//hue ranges for detection
const int HUE_LIGHT_BLUE_BAG[2]     ={80,100};        //light blue bean bag
const int HUE_PURPLE_BAG[2]         ={135,155};       //purple bean bag
const int HUE_BIG_GREEN_BALL[2]     ={40,80};         //big green ball / lego
lid

//color array
const int NUM_COLORS = 8;           //number of colors in the COLORS array
const static CvScalar COLORS[] =
            {
                  {{0,0,255}},            //red
                  {{0,128,255}},          //orange
                  {{0,255,255}},          //yellow
                  {{0,255,0}},            //green
                  {{255,128,0}},          //royal blue
                  {{255,255,0}},          //aquamarine
                  {{255,0,0}},            //dark blue
                  {{255,0,255}}           //purple
            };

//constants for filtering operations
const double XY_DIFF = 0.008; //used by difference filter to scale Z
const double A0 = 0.2;              //used by recursive filter
const double B0 = 0.8;              //used by recursive filter
const double Z_SCALE = 40;          //used by difference filter to futher
scale Z
const int X_SHIFT = 5;              //used by difference filter to shift X
const char DELIM[] = ",\t";         //used by most all file parsing to
tokenize lines
```

```
//constants related to ISAC's
const double ISAC_X_MIN = 400;      //ISAC's left arm workspace
const double ISAC_X_MAX = 400;
const double ISAC_Y_MIN = 100;
const double ISAC_Y_MAX = 500;
const double ISAC_Z_MIN = -400;
const double ISAC_Z_MAX = 300;

const double FACE_X = 0;      //FACE_X is not used
const double FACE_Y = 0;
const double FACE_Z = 300;

const double ANG_L_0_MIN = -30;//-58.372; //the min/max angles for the left
arm joints
const double ANG_L_0_MAX = 14.995;
const double ANG_L_1_MIN = 35.760;
const double ANG_L_1_MAX = 120.25;
const double ANG_L_2_MIN = -210.378;
const double ANG_L_2_MAX = -144.212;
const double ANG_L_4_MIN = -40;
const double ANG_L_4_MAX = 40;

const double ANG_R_0_MIN = -14.995;       //the min/max angles for the right
arm joints
const double ANG_R_0_MAX = 30;//58.372;
const double ANG_R_1_MIN = 35.760;
const double ANG_R_1_MAX = 120.25;
const double ANG_R_2_MIN = -210.378;
const double ANG_R_2_MAX = -144.212;
const double ANG_R_4_MIN = -40;
const double ANG_R_4_MAX = 40;

const double CONST_X = 300;               //constant depth for ignoring depth

const double CENTER_TO_ANGLE_0 = 246;     //various lengths on ISAC
const double SHOULDER_OFFSET = 200;
const double UPPERARM = 325;
const double FOREARM = 290;
const double HAND_L = 250;


//constants for Program Usages
const int LEFT_ARM = 1;
const int RIGHT_ARM = 0;
const int END_EFF_YES = 1;
const int END_EFF_NO = 0;
const int SIMPLE_INV_KIN = 1;
const int COMPLEX_INV_KIN = 0;
const int VISION_TIME = 400;        //max time it takes to complete a
detection cycle
const int MIN_MOVEMENT = 5000;            //minium amount of movement in the
X & Y directions that will be counted
const int SAFTEY_SHIFT = 100;       //amount to move ISAC's hands away from
the center (0) to ensure they dont hit

//general constants
```

```
const double PI = 3.14159265359;
const double R2D = (180.0 / PI);
const double D2R = (PI / 180.0);




/************************/
/*******              *******/
/*******  GLOBAL   *******/
/******* VARIABLES *******/
/*******              *******/
/************************/

//variables for getConnectedComps
int compmax=0;
int compcap=40;         //should be the same size as the length of Comps
below
int maxcomp=0;
int comptot=0;
double maxarea=0;
static CvConnectedComp ** Comps = new CvConnectedComp*[40];       //holder
for Connected Components

//variables for pan/tilt units
CameraHead hd;                //head object (pan/tilts)

//Haar face detection
static CvMemStorage* storage = 0;
static CvHaarClassifierCascade* cascade = 0;

void detect_and_draw( IplImage* image );

const char* cascade_name =
    "haarcascade_frontalface_alt.xml";
/*    "haarcascade_profileface.xml";*/




/************************/
/*******              *******/
/*******  CLASSES  *******/
/*******              *******/
/************************/

//CvTarget: an extension of the CvPoint class... basically just a point (int
x, int y) with a radius (int r)
class CvTarget : public CvPoint
{
      public:
      CvTarget();
      CvTarget(int xi, int yi, int ri);
      int r;
```

```
};

CvTarget::CvTarget () {       //default constructor
      x=0;
      y=0;
      r=0;
}

CvTarget::CvTarget (int xi, int yi, int ri) {   //constructor with user input
  x = xi;
  y = yi;
  r = ri;
}




/*************************/
/*******               *******/
/*******  FUNCTION  *******/
/******* PROTOTYPES *******/
/*******               *******/
/*************************/

void detectObject(IplImage* img, CvTarget *tar, int low, int high);
void drawTarget(IplImage* img, CvTarget obj, int clr);
void getConnectedComps(IplImage *image, CvConnectedComp ** Comps);
void centerCams(int *lX, int *lY, int *rX, int *rY);
void calculateXYZ(CvPoint3D32f *objloc, CvPoint left, CvPoint right);
double to_double ( const char *p );
void filterCoords(char coords[], char tempcoords[], char filteredcoords[]);
void compressCoords(char coords[], char compressedcoords1[], char
compressedcoords2[]);
double abs(double Nbr);
void uploadToNN1by1(char uploadL[], char uploadR[], char coordsL[], char
coordsR[]);
void uploadToNNbatch(char uploadL[], char uploadR[], char coordsL[], char
coordsR[]);
void fitCoordsToISAC(char coords[], char fittedcoords[]);
void testSetForInverseKinematics(char test[], int Xmin, int Xmax, int Ymin,
int Ymax, int Zmin, int Zmax, int stepSize);
void testSetForForwardKinematics(char test[], double maxAngle, double
stepSize);
void calcJointAngles(char coords[], char angles[], int rightleft, int EndEff,
int simple);
void inverseKinematics(double * pdPos, double * pdAngles, short m_sLeftArm,
short m_sEndEffector);
void uploadGoFlag(char loc[]);
void haarFaceDetect(IplImage* img, CvTarget *tar);
void avgFaceLoc(char coords[], char out[]);
double* simpleInverseKinematics(CvPoint3D32f point, int rightleft);
void fitCoordsToISAC2(char coords[], char fittedcoords[], int rightleft);
void flipY(char coords[], char flippedYcoords[]);
void interpolateAngles(char anglesIn[], char anglesOut[]);
```

B. Control Code Listing

B.3. main.cpp (main Control loop code)

```
#include "Headers\stdafx.h"
#include <windows.h>
#include <windef.h>
#include <string.h>
#include <stdlib.h>
#include <stdio.h>
#include <conio.h>
#include <stdarg.h>
#include <math.h>
#include <IOSTREAM>
#include <sstream>
#include "Headers\winmotenc.h"
#include "Headers\Control.h"
#include "Headers\NNMuscleClass.h"
#include "Headers\MahirKinematics.h"
#include "Headers\PID.h"
#include "Headers\commport.h"
#include "Headers\GripControl.h"

#ifdef _ATL_STATIC_REGISTRY
#include <statreg.h>
#include <statreg.cpp>
#endif

#include <atlimpl.cpp>

using namespace std;

double leftValvesOutputs[12]={0};
double leftValvesInputs[12]={0};
double InitialleftValvesOutputs[12];
long leftEncoders[6]={0};
double leftAngles[6]={0};

double rightValvesOutputs[12]={0};
double rightValvesInputs[12]={0};
double InitialrightValvesOutputs[12];
long rightEncoders[6]={0};
double rightAngles[6]={0};

double
LPID0_output=0.0,LPID1_output=0.0,LPID2_output=0.0,LPID3_output=0.0,LPID4_out
put=0.0,LPID5_output=0.0;

//Kinematic variables
#define PI 3.14159265

/*double lengthOfEndEff;
double *alpha,*a,*d,*theta;
```

```
double **rotation;
double **limitsOfThetas;

double **T01;
double **T12;
double **T23;
double **T34;
double **T45;
double **T56;

double **T02;
double **T03;
double **T04;
double **T05;
double **T06;

double *j1Pos;
double *j2Pos;
double *j3Pos;
double *j4Pos;
double *j5Pos;
double *j6Pos;
double *endEffPos;
*/
double* optimumRotations( double *desPos, double *prevThetas, double alpha,
double beta, double gamma);
double to_double( const char *p);

const char DELIM[]=",\t";

void main()
{
      int count=0,numb=0;
      float desiredangleL0 =0.0, desiredangleL1 =0.0, desiredangleL2 =0.0,
desiredangleL3 =0.0, desiredangleL4 =0.0, desiredangleL5 =0.0;
      float desiredangleR0 =0.0, desiredangleR1 =0.0, desiredangleR2 =0.0,
desiredangleR3 =0.0, desiredangleR4 =0.0, desiredangleR5 =0.0;
      float incrementalVoltage0 = 0.0, incrementalVoltage1 =
0.0,incrementalVoltage2 = 0.0,incrementalVoltage3 = 0.0,incrementalVoltage4 =
0.0, incrementalVoltage5 = 0.0;
      double gamma = 0, beta = 0.0, alpha = 0.0;
      double *desPos = (double*)malloc(3*sizeof(double));
      double *prevThetasL = (double*)malloc(6*sizeof(double));
      double *prevThetasR = (double*)malloc(6*sizeof(double));
      double *thetas = (double*)malloc(6*sizeof(double));
      int solutionexist = 0;
      double timevalL;
      double timevalR;
      char lineL[512];
      char lineR[512];
      int i;
      char *token;
      double *currangsL = new double[6];
      double *currangsR = new double[6];
      int totalstep = 50;
      FILE *anglesfileL;
      FILE *anglesfileR;
```

```
      int waitL = 0;
      int waitR = 0;
      double *anglesL = new double[6];
      double *anglesR = new double[6];
      int Ldone=0;
      int Rdone=0;
      FILE *StartNowFile;

      //TEST VARIABLES: Set these to 1 for use, 0 for no use
      int usecontrol=1, useleft=1, useright=1, useStartNow=0;

      //GripControl gripper;
      // Left Arm Objects
      CNNMuscles
LeftNNMusclesAngle0F(1,0,1);LeftNNMusclesAngle0F.Allocator();CNNMuscles
LeftNNMusclesAngle0B(1,0,-1);LeftNNMusclesAngle0B.Allocator();
      CNNMuscles
LeftNNMusclesAngle1F(1,1,1);LeftNNMusclesAngle1F.Allocator();CNNMuscles
LeftNNMusclesAngle1B(1,1,-1);LeftNNMusclesAngle1B.Allocator();
      CNNMuscles
LeftNNMusclesAngle2F(1,2,1);LeftNNMusclesAngle2F.Allocator();CNNMuscles
LeftNNMusclesAngle2B(1,2,-1);LeftNNMusclesAngle2B.Allocator();
      //CNNMuscles
LeftNNMusclesAngle3F(1,3,1);LeftNNMusclesAngle3F.Allocator();CNNMuscles
LeftNNMusclesAngle3B(1,3,-1);LeftNNMusclesAngle3B.Allocator();
      CNNMuscles
LeftNNMusclesAngle4F(1,4,1);LeftNNMusclesAngle4F.Allocator();CNNMuscles
LeftNNMusclesAngle4B(1,4,-1);LeftNNMusclesAngle4B.Allocator();
      //CNNMuscles
LeftNNMusclesAngle5F(1,5,1);LeftNNMusclesAngle5F.Allocator();CNNMuscles
LeftNNMusclesAngle5B(1,5,-1);LeftNNMusclesAngle5B.Allocator();

      // Right Arm Objects
      CNNMuscles
RightNNMusclesAngle0F(0,0,1);RightNNMusclesAngle0F.Allocator();CNNMuscles
RightNNMusclesAngle0B(0,0,-1);RightNNMusclesAngle0B.Allocator();
      CNNMuscles
RightNNMusclesAngle1F(0,1,1);RightNNMusclesAngle1F.Allocator();CNNMuscles
RightNNMusclesAngle1B(0,1,-1);RightNNMusclesAngle1B.Allocator();
      CNNMuscles
RightNNMusclesAngle2F(0,2,1);RightNNMusclesAngle2F.Allocator();CNNMuscles
RightNNMusclesAngle2B(0,2,-1);RightNNMusclesAngle2B.Allocator();
      //CNNMuscles
LeftNNMusclesAngle3F(1,3,1);LeftNNMusclesAngle3F.Allocator();CNNMuscles
LeftNNMusclesAngle3B(1,3,-1);LeftNNMusclesAngle3B.Allocator();
      //CNNMuscles
LeftNNMusclesAngle4F(1,4,1);LeftNNMusclesAngle4F.Allocator();CNNMuscles
LeftNNMusclesAngle4B(1,4,-1);LeftNNMusclesAngle4B.Allocator();
      //CNNMuscles
LeftNNMusclesAngle5F(1,5,1);LeftNNMusclesAngle5F.Allocator();CNNMuscles
LeftNNMusclesAngle5B(1,5,-1);LeftNNMusclesAngle5B.Allocator();

      if (usecontrol)   InitializeCards();
      if (usecontrol && useleft)
{InitializeLeftValves();/*gripper.SimpleOpen()*/;Sleep(1500);}
      if (usecontrol && useright)
{InitializeRightValves();/*gripper.SimpleOpen()*/;Sleep(1500);}
```

```
	Sleep(3000);
	// Precise Sampling Time Initialization
	LARGE_INTEGER ticksPerSecond,start_ticks, end_ticks, cputime,tick;
	if (!QueryPerformanceFrequency(&ticksPerSecond))
		if (!QueryPerformanceCounter(&tick) )
			printf("no go counter not installed");

	// Data File Initialization
	FILE *outputdata;
	if((outputdata = fopen(".\\MatlabWork\\MatlabWork.txt","w")) == NULL)
		printf("Can't Open File MatlabWork.txt\n");

	// Homing & Reset Encoders Left
	if (usecontrol){Sleep(100);/*gripper.SimpleOpen()*/;Sleep(500);}
	if (usecontrol && useleft) { ResetLeftEncoders();vitalSelectBoard(0);}
	if (usecontrol && useright) {
ResetRightEncoders();vitalSelectBoard(1);}

	//set angles in radians
	alpha = 0*PI/180; //Hold z of base frame (deg*PI/180)
	beta =  -90*PI/180; //Hold y of rotated base frame (deg*PI/180)
	gamma = 0*PI/180;  //Hold x of rotated base frame (deg*PI/180)

	thetas[0] = 10.0;

	while(1)
	{
		//check to see if the Start.Now files exists to see if it is time
go
		while(1)
		{
			if (useStartNow==0) break;    //if we are ignoring the
start file, break out
			else StartNowFile = fopen("I:/Temp/Start.Now","r");
			if (StartNowFile != NULL) break;    //if we find a start
file break out
			if (kbhit()) break;           //if someone hits a key,
break out
			Sleep(10);
		}

		if (kbhit()) break;           //if someone hits a key, break out

		//setup variables for another run
		waitL=0;
		waitR=0;
		Ldone=0;
		Rdone=0;
		count=0;
		//set prevThetas to home position
		prevThetasL[0] = 0.0;
		prevThetasL[1] = 90;//PI/2.0;
		prevThetasL[2] = -180;//-PI;
		prevThetasL[3] = 0.0;
		prevThetasL[4] = 0;//PI/50.0; //For left arm
		prevThetasL[5] = 0.0;
```

```
            prevThetasR[0] = 0.0;
            prevThetasR[1] = 90;//PI/2.0;
            prevThetasR[2] = -180;//-PI;
            prevThetasR[3] = 0.0;
            prevThetasR[4] = 0;
            prevThetasR[5] = 0.0;
            //open files with joint angles to goto
            anglesfileL = fopen("I:/Temp/uploadL.txt", "r");
            anglesfileR = fopen("I:/Temp/uploadR.txt", "r");

            //loop through all points in the uploadL & uploadR files
            printf("Control Loop Starts!!\n");
            for(;;)
            {

                  QueryPerformanceCounter(&start_ticks);

                  //LEFT
                  //get angles from file
                  if (waitL == 0)
                  {
                        if(fgets(lineL, 512, anglesfileL) != NULL)
                        {
                              i=0;
                              token=strtok(lineL, DELIM);
                              timevalL = to_double(token);
                              while((token=strtok(NULL, DELIM))!=NULL)
                              {
                                    currangsL[i]=to_double(token);
                                    i++;
                              }
                        }
                        else
                        {
                              Ldone=1;    //if we reach the end of the file
set the Left done flag
                        }
                  }

                  //if the timeval (in our file) is <= the current count then
goto the point
                  //otherwise wait until timevalL is equal to count
                  if(timevalL <= count)
                  {
                        waitL = 0;
                        for(i=0;i<6;i++)
                              anglesL[i]=currangsL[i];
                  }
                  else
                  {
                        waitL=1;
                  }

                  //RIGHT
                  //get angles from file
                  if (waitR == 0)
                  {
```

```
                        if(fgets(lineR, 512, anglesfileR) != NULL)
                        {
                              i=0;
                              token=strtok(lineR, DELIM);
                              timevalR = to_double(token);
                              while((token=strtok(NULL, DELIM))!=NULL)
                              {
                                    currangsR[i]=to_double(token);
                                    i++;
                              }
                        }
                        else
                        {
                              Rdone=1;    //if we reach the end of the file
set the Right done flag
                        }
                  }

                  //if the timeval (in our file) is <= the current count then
goto the point
                  //otherwise wait until timevalL is equal to count
                  if(timevalR <= count)
                  {
                        waitR = 0;
                        for(i=0;i<6;i++)
                              anglesR[i]=currangsR[i];
                  }
                  else
                  {
                        waitR=1;
                  }

                  //printf("**THETAS: %f, %f, %f, %f, %f, %f\n",
thetas[0],thetas[1],thetas[2],thetas[3],thetas[4],thetas[5]);

                  if(anglesL && anglesR == NULL)
                  //if (!solutionexist)
                  {
                        printf("No Solution Exists!\n");
                        // Closing the Controls
                        if (usecontrol)
      {/*gripper.GrabSomething()*/;CloseValves();Sleep(500);vitalQuit();Sleep
(500);}
                        fclose(outputdata);
                        return;
                  }

                  //Control loop

                  //printf("%d :: ",(int)timevalL);

                  //if we're done then get us back to the home position
                  if (Ldone == 1 && Rdone == 1)
                  {
                        Sleep(4000);
                        desiredangleL0 = 0;
                        desiredangleL1 = 90;
```

```
                        desiredangleL2 = -180;
                        desiredangleL3 = 0;
                        desiredangleL4 = 0;
                        desiredangleL5 = 0;

                        desiredangleR0 = 0;
                        desiredangleR1 = 90;
                        desiredangleR2 = -180;
                        desiredangleR3 = 0;
                        desiredangleR4 = 0;
                        desiredangleR5 = 0;
                  }
                  //otherwise set the desired angles to the retrieved angles
                  else
                  {
                        desiredangleL0 = anglesL[0];
                        desiredangleL1 = anglesL[1];
                        desiredangleL2 = anglesL[2];
                        desiredangleL3 = anglesL[3];
                        desiredangleL4 = anglesL[4];
                        desiredangleL5 = anglesL[5];

                        desiredangleR0 = anglesR[0];
                        desiredangleR1 = anglesR[1];
                        desiredangleR2 = anglesR[2];
                        desiredangleR3 = anglesR[3];
                        desiredangleR4 = 0;//anglesR[4];
                        desiredangleR5 = anglesR[5];
                  }

                  if(kbhit()) break;

                  // Left Arm
                  //ANGLE 0
                  if( prevThetasL[0] > desiredangleL0 )

      LeftNNMusclesAngle0B.Process(&desiredangleL0,&incrementalVoltage0);
                  else if( prevThetasL[0] < desiredangleL0 )

      LeftNNMusclesAngle0F.Process(&desiredangleL0,&incrementalVoltage0);
                  leftValvesOutputs[0] = InitialleftValvesOutputs[0] -
incrementalVoltage0;
                  leftValvesOutputs[1] = InitialleftValvesOutputs[1] +
incrementalVoltage0;

                  //ANGLE 1
                  if( prevThetasL[1] < desiredangleL1 )

      LeftNNMusclesAngle1F.Process(&desiredangleL1,&incrementalVoltage1);
                  else if( prevThetasL[1] > desiredangleL1 )

      LeftNNMusclesAngle1B.Process(&desiredangleL1,&incrementalVoltage1);
                  leftValvesOutputs[2] =
InitialleftValvesOutputs[2]+incrementalVoltage1;
                  leftValvesOutputs[3] = InitialleftValvesOutputs[3]-
incrementalVoltage1;
```

```
                //ANGLE 2
                if( prevThetasL[2] > desiredangleL2 )

      LeftNNMusclesAngle2B.Process(&desiredangleL2,&incrementalVoltage2);
                else if( prevThetasL[2] < desiredangleL2 )

      LeftNNMusclesAngle2F.Process(&desiredangleL2,&incrementalVoltage2);
                leftValvesOutputs[4] = InitialleftValvesOutputs[4] +
incrementalVoltage2 - incrementalVoltage3;
                leftValvesOutputs[5] = InitialleftValvesOutputs[5] -
incrementalVoltage2 - incrementalVoltage3;
                leftValvesOutputs[6] = InitialleftValvesOutputs[6] -
incrementalVoltage2 + incrementalVoltage3;
                leftValvesOutputs[7] = InitialleftValvesOutputs[7] +
incrementalVoltage2 + incrementalVoltage3;

                //ANGLE 4
                if( prevThetasL[4] > desiredangleL4 )

      LeftNNMusclesAngle4B.Process(&desiredangleL4,&incrementalVoltage4);
                else if( prevThetasL[4] < desiredangleL4 )

      LeftNNMusclesAngle4F.Process(&desiredangleL4,&incrementalVoltage4);
                leftValvesOutputs[8] = InitialleftValvesOutputs[8] -
incrementalVoltage4 - incrementalVoltage5 ;
                leftValvesOutputs[9] = InitialleftValvesOutputs[9] +
incrementalVoltage4 + incrementalVoltage5;
                leftValvesOutputs[10]= InitialleftValvesOutputs[10] -
incrementalVoltage4 + incrementalVoltage5;
                leftValvesOutputs[11]= InitialleftValvesOutputs[11] +
incrementalVoltage4 - incrementalVoltage5;

                // Right Arm
                //ANGLE 0
                if( prevThetasR[0] > desiredangleR0 )
                {

      RightNNMusclesAngle0B.Process(&desiredangleR0,&incrementalVoltage0);
                }
                else if( prevThetasR[0] < desiredangleR0 )
                {

      RightNNMusclesAngle0F.Process(&desiredangleR0,&incrementalVoltage0);
                }
                rightValvesOutputs[0] = InitialrightValvesOutputs[0] -
incrementalVoltage0;
                rightValvesOutputs[1] = InitialrightValvesOutputs[1] +
incrementalVoltage0;

                //ANGLE 1
                if( prevThetasR[1] < desiredangleR1 )
                {

      RightNNMusclesAngle1F.Process(&desiredangleR1,&incrementalVoltage1);
                }
                else if( prevThetasR[1] > desiredangleR1 )
                {
```

```
      RightNNMusclesAngle1B.Process(&desiredangleR1,&incrementalVoltage1);
                  }
                  rightValvesOutputs[2] =
InitialrightValvesOutputs[2]+incrementalVoltage1;
                  rightValvesOutputs[3] = InitialrightValvesOutputs[3]-
incrementalVoltage1;

                  //ANGLE 2
                  if( prevThetasR[2] > desiredangleR2 )
                  {

      RightNNMusclesAngle2B.Process(&desiredangleR2,&incrementalVoltage2);
                  }
                  else if( prevThetasR[2] < desiredangleR2 )
                  {

      RightNNMusclesAngle2F.Process(&desiredangleR2,&incrementalVoltage2);
                  }
                  rightValvesOutputs[4] = InitialrightValvesOutputs[4] +
incrementalVoltage2 - incrementalVoltage3;
                  rightValvesOutputs[5] = InitialrightValvesOutputs[5] -
incrementalVoltage2 - incrementalVoltage3;
                  rightValvesOutputs[6] = InitialrightValvesOutputs[6] -
incrementalVoltage2 + incrementalVoltage3;
                  rightValvesOutputs[7] = InitialrightValvesOutputs[7] +
incrementalVoltage2 + incrementalVoltage3;

                  if (usecontrol && useleft && !waitL) SetLeftArmPressures();
                  if (usecontrol && useright && !waitR)
SetRightArmPressures();

                  QueryPerformanceCounter(&end_ticks); //printf("time
pass:%f\n",(float)(end_ticks.QuadPart-
start_ticks.QuadPart)/ticksPerSecond.QuadPart*1000);
                  while(((float)(end_ticks.QuadPart-
start_ticks.QuadPart)/ticksPerSecond.QuadPart*1000) < (float) 50)
                  QueryPerformanceCounter(&end_ticks); cputime.QuadPart =
end_ticks.QuadPart- start_ticks.QuadPart;

                  // Reading the Angles
                  printf("LEFT: %d ",(int)timevalL);
                  if (usecontrol &&
useleft){ReadLeftEncoders();RealLeftAngles();}
                  printf("RIGHT: %d ",(int)timevalR);
                  if (usecontrol &&
useright){ReadRightEncoders();RealRightAngles();}

                  // Update the voltage output references
                  fprintf(outputdata,"%d %.2f %.2f %.2f\n",count,
desiredangleL0, leftAngles[0], incrementalVoltage0);

                  //update prevThetas
                  for(i=0;i<6;i++)
                  {
                        prevThetasL[i]=leftAngles[i]; //leftAngles global and
updated by RealLeftAngles
```

```
                        prevThetasR[i]=rightAngles[i];      //rightAngles
global and updated by RealRightAngles
                  }
                  Sleep(400);
                  count++;

                  //if we have gotten through all the files and gone back to
the home position, then break out
                  if (Ldone == 1 && Rdone == 1)
                  {
                        if(useStartNow) fclose(StartNowFile);
                        fclose(anglesfileL);
                        fclose(anglesfileR);
                        remove("I:/Temp/Start.Now");
                        StartNowFile = NULL;
                        break;
                  }
            }
            if (useStartNow == 0) break;
      }
      // Closing the Controls
      Sleep(1000);
      if (usecontrol)
      {/*gripper.GrabSomething()*/;CloseValves();Sleep(500);vitalQuit();Sleep
(500);}
      fclose(outputdata);
}

double* optimumRotations( double *desPos, double *prevThetas, double alpha,
double beta, double gamma)
{
      double *thetas;
      int different = 0;
      double rangeAlpha = 30;
      double rangeBeta  = 20;
      int solutionexist = 0;

      for( int i = 0; i < 20; i++ )
      {
            //printf("**************************** %d\n",i);
            thetas = inverseKinematics(desPos, alpha+i, beta+i, gamma,
prevThetas, &solutionexist); if (solutionexist) break;
            thetas = inverseKinematics(desPos, alpha-i, beta-i, gamma,
prevThetas, &solutionexist); if (solutionexist) break;
            thetas = inverseKinematics(desPos, alpha-i, beta+i, gamma,
prevThetas, &solutionexist); if (solutionexist) break;
            thetas = inverseKinematics(desPos, alpha+i, beta-i, gamma,
prevThetas, &solutionexist); if (solutionexist) break;

      }
      if (!solutionexist) return NULL;
      return thetas;
}

//courtesy of a post by Narue at
http://www.deniweb.com/forums/thread80754.html
double to_double( const char *p)
```

```
{
	if (p == "") return NULL;

	//else
	std::stringstream ss ( p );
	double result = 0;

	ss>> result;
	return result;
}
```

B.4. NNMuscleClass.cpp (individual muscle class)

```
// Train.cpp: implementation of the CTrain class.
//
//////////////////////////////////////////////////////////////////////

#include "Headers\NNMuscleClass.h"
#include <iostream>
#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <conio.h>
#include <malloc.h>
#include <time.h>

#define PI 3.141592653589
#define Rate 8

//////////////////////////////////////////////////////////////////////
// Construction/Destruction
//////////////////////////////////////////////////////////////////////

CNNMuscles::CNNMuscles(int leftrightarmvalue, int anglenumbervalue, int
forwardbackwardvalue)
{
	leftrightarm=  leftrightarmvalue; // if leftrightarmvalue = 1 --> left
arm
	anglenumber = anglenumbervalue; // if anglevalue = 0 --> angle0 & =1 --
> Angle1 ...6
	forwardbackward = forwardbackwardvalue; // if forwardbackwardvalue = 1
-->forward
}

CNNMuscles::~CNNMuscles()
{

	delete vfuture_th;
	delete vpast_th;
	delete vpresent_th;
	delete z;
	delete z_in;

	for(j=0;j<nNeuron;j++)
```

```
	{
		free(*(wpresent+j));
		free(*(wpast+j));
		free(*(wfuture+j));
		free(*(deltaw+j));
	}
	free(wpresent);
	free(wpast);
	free(wfuture);
	free(deltaw);

	for(i=0;i<nInput;i++)
	{
		free(*(vpresent+i));
		free(*(vpast+i));
		free(*(vfuture+i));
		free(*(deltav+i));
	}
	free(vpresent);
	free(vpast);
	free(vfuture);
	free(deltav);

	for(t=0;t<m;t++)
	free(*(inputx+t));
	free(inputx);
}

void CNNMuscles::Allocator(void)
{

	using namespace std;
	nInput = 1;nNeuron=50;
	int sillybuffer1;
	float sillybuffer2;

	FILE *weights;

	// Left Arm Files
	if (leftrightarm ==1 && anglenumber == 0 && forwardbackward == 1)
		if((weights =
fopen(".\\NNWeights\\LeftNNmuscle01FWeights.txt","r")) == NULL)
			printf("Can't Open File LeftNNmuscle01FWeights.txt\n");
	if (leftrightarm ==1 && anglenumber == 0 && forwardbackward == -1)
		if((weights =
fopen(".\\NNWeights\\LeftNNmuscle01BWeights.txt","r")) == NULL)
			printf("Can't Open File LeftNNmuscle01FWeights.txt\n");

	if (leftrightarm ==1 && anglenumber == 1 && forwardbackward == 1)
		if((weights =
fopen(".\\NNWeights\\LeftNNmuscle23FWeights.txt","r")) == NULL)
			printf("Can't Open File LeftNNmuscle23FWeights.txt\n");
	if (leftrightarm ==1 && anglenumber == 1 && forwardbackward == -1)
		if((weights =
fopen(".\\NNWeights\\LeftNNmuscle23BWeights.txt","r")) == NULL)
			printf("Can't Open File LeftNNmuscle23BWeights.txt\n");
```

```
      if (leftrightarm ==1 && anglenumber == 2 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle4567Angle2FWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle4567Angle2FWeights.txt\n");
      if (leftrightarm ==1 && anglenumber == 2 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle4567Angle2BWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle4567Angle2BWeights.txt\n");

      if (leftrightarm ==1 && anglenumber == 3 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle4567Angle3FWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle4567Angle3FWeights.txt\n");
      if (leftrightarm ==1 && anglenumber == 3 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle4567Angle3BWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle4567Angle3BWeights.txt\n");

      if (leftrightarm ==1 && anglenumber == 4 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle891011Angle4FWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle891011Angle4FWeights.txt\n");
      if (leftrightarm ==1 && anglenumber == 4 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle891011Angle4BWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle891011Angle4BWeights.txt\n");

      if (leftrightarm ==1 && anglenumber == 5 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle891011Angle5FWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle891011Angle4FWeights.txt\n");
      if (leftrightarm ==1 && anglenumber == 5 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\LeftNNmuscle891011Angle5BWeights.txt","r")) == NULL)
                  printf("Can't Open File
LeftNNmuscle891011Angle5BWeights.txt\n");

      // Right Arm Files
      if (leftrightarm ==0 && anglenumber == 0 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle01FWeights.txt","r")) == NULL)
                  printf("Can't Open File RightNNmuscle01FWeights.txt\n");
      if (leftrightarm ==0 && anglenumber == 0 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle01BWeights.txt","r")) == NULL)
                  printf("Can't Open File RightNNmuscle01FWeights.txt\n");

      if (leftrightarm ==0 && anglenumber == 1 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle23FWeights.txt","r")) == NULL)
```

```
                printf("Can't Open File RightNNmuscle23FWeights.txt\n");
      if (leftrightarm ==0 && anglenumber == 1 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle23BWeights.txt","r")) == NULL)
                printf("Can't Open File RightNNmuscle23BWeights.txt\n");

      if (leftrightarm ==0 && anglenumber == 2 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle4567Angle2FWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle4567Angle2FWeights.txt\n");
      if (leftrightarm ==0 && anglenumber == 2 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle4567Angle2BWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle4567Angle2BWeights.txt\n");

      if (leftrightarm ==0 && anglenumber == 3 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle4567Angle3FWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle4567Angle3FWeights.txt\n");
      if (leftrightarm ==0 && anglenumber == 3 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle4567Angle3BWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle4567Angle3BWeights.txt\n");

      if (leftrightarm ==0 && anglenumber == 4 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle891011Angle4FWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle891011Angle4FWeights.txt\n");
      if (leftrightarm ==0 && anglenumber == 4 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle891011Angle4BWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle891011Angle4BWeights.txt\n");

      if (leftrightarm ==0 && anglenumber == 5 && forwardbackward == 1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle891011Angle5FWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle891011Angle4FWeights.txt\n");
      if (leftrightarm ==0 && anglenumber == 5 && forwardbackward == -1)
            if((weights =
fopen(".\\NNWeights\\RightNNmuscle891011Angle5BWeights.txt","r")) == NULL)
                printf("Can't Open File
RightNNmuscle891011Angle5BWeights.txt\n");

      fscanf(weights,"%d\n",&nNeuron);
      fscanf(weights,"%f\n",&sillybuffer2);
      fscanf(weights,"%f\n",&sillybuffer2);
      fscanf(weights,"%d\n",&sillybuffer1);
      fscanf(weights,"%d\n",&sillybuffer1);
      fscanf(weights,"%d\n",&nInput);
```

```
srand( (unsigned)time( NULL ) );

//1*10
z_in = (float*)malloc(nNeuron*sizeof(float));

//1*10
z = (float*)malloc(nNeuron*sizeof(float));

//1*10
delta_in = (float*)malloc(nNeuron*sizeof(float));

//1*10
delta_hidden = (float*)malloc(nNeuron*sizeof(float));

//1*10
deltav_th = (float*)malloc(nNeuron*sizeof(float));

// 14*10
deltav = (float**)malloc(nInput*sizeof(float*));
for(i=0;i<nInput;i++)
      *(deltav+i) = (float*)malloc(nNeuron*sizeof(float));

//10*2
deltaw = (float**)malloc(nNeuron*sizeof(float*));
for(i=0;i<nNeuron;i++)
      *(deltaw+i) = (float*)malloc(2*sizeof(float));

//random 10*2
wpresent = (float**)malloc(nNeuron*sizeof(float*));
for(i=0;i<nNeuron;i++)
      *(wpresent+i) = (float*)malloc(2*sizeof(float));

//random 10*2
wpast = (float**)malloc(nNeuron*sizeof(float*));
for(i=0;i<nNeuron;i++)
      *(wpast+i) = (float*)malloc(2*sizeof(float));

//random 10*2
wfuture = (float**)malloc(nNeuron*sizeof(float*));
for(i=0;i<nNeuron;i++)
      *(wfuture+i) = (float*)malloc(2*sizeof(float));

//random 1*10
vpresent_th = (float*)malloc(nNeuron*sizeof(float));

//random 1*10
vpast_th = (float*)malloc(nNeuron*sizeof(float));

//random 1*10
vfuture_th = (float*)malloc(nNeuron*sizeof(float));

//random 14*10
vpresent = (float**)malloc(nInput*sizeof(float*));
for(i=0;i<nInput;i++)
      *(vpresent+i) = (float*)malloc(nNeuron*sizeof(float));

//random 14*10
```

```
	vpast = (float**)malloc(nInput*sizeof(float*));
	for(i=0;i<nInput;i++)
		*(vpast+i) = (float*)malloc(nNeuron*sizeof(float));

	//random 14*10
	vfuture = (float**)malloc(nInput*sizeof(float*));
	for(i=0;i<nInput;i++)
		*(vfuture+i) = (float*)malloc(nNeuron*sizeof(float));

	m=1;
	//***********************READING WEIGHTS NINPUTS AND
NEURONS*************************

	for (k=0;k<1;k++)
	{
		for (j=0;j<nNeuron;j++)
			fscanf(weights,"%f\n",&wfuture[j][k]);
		fscanf(weights,"%f\n",&wfuture_th[k]);
	}

	for(j=0;j<nNeuron;j++)
	{
		for(i=0;i<nInput;i++)
			fscanf(weights,"%f\n",&vfuture[i][j]);
	}

	for(j=0;j<nNeuron;j++)
		fscanf(weights,"%f\n",&vfuture_th[j]);

	//***************END OF
READING*****************************************

	inputx = (float**)malloc(m*sizeof(float*));
	for(i=0;i<m;i++)
		*(inputx+i) = (float*)malloc(nInput*sizeof(float));

	fclose(weights);
}

void CNNMuscles::Process(float *input,float *output)
{
	inputx[0][0] = *input;

	if (leftrightarm ==1 && anglenumber == 0)
		// Here Normalizing the Angles. Forward changes between -65 & +25
to 0-1
		inputx[0][0] = (inputx[0][0] + 65) / 90;
	if (leftrightarm ==0 && anglenumber == 0)
		// Here Normalizing the Angles. Forward changes between -25 & +55
to 0-1
		inputx[0][0] = (inputx[0][0] + 25) / 80;

	if (anglenumber == 1 )
		// Normalizing the input 40-125 to 0-1
		inputx[0][0] = (inputx[0][0] - 40) / 85;
	if (anglenumber == 2)
		// Normalizing the input -215 & -130 to 0-1
```

```
            inputx[0][0] = (inputx[0][0] + 215) / 75;
      if (anglenumber == 3)
            // Normalizing the input -40 & 30 to 0-1
            inputx[0][0] = (inputx[0][0] + 40) / 70;
      if (anglenumber == 4)
            // Normalizing the input -40 && 40 to 0-1
            inputx[0][0] = (inputx[0][0] +40) / 80;
      if (anglenumber == 5)
            // Normalizing the input -70 & 70 to 0-1
            inputx[0][0] = (inputx[0][0] +70)/ 140;

      for(t=0;t<1;t++) // m =1 m is the data number
      {
            y_in[0] = wfuture_th[0];
            for(j=0;j<nNeuron;j++)
            {
                  z_in[j] = vfuture_th[j];
                  for(i=0;i<1;i++)  // nInput yerine 1 yazýyoruz , nInput
data sayýsý
                        z_in[j] += inputx[t][i] * vfuture[i][j];
                        z[j]= 2/(1+exp(-2*z_in[j]))-1;// activation function:
tansig   n = 2/(1+exp(-2*n))-1
                        y_in[0] += z[j] * wfuture[j][0];
            }
                  *output = y_in[0];
      }
}
```

B.5. Control.h (code for controlling valves/encoders)

```
#ifndef _Control_h
#define _Control_h

#include "stdafx.h"
#include <windows.h>
#include <windef.h>
#include <string.h>
#include <stdlib.h>
#include <stdio.h>
#include <stdarg.h>
#include <math.h>
#include <IOSTREAM>
#include "winmotenc.h"

extern double leftValvesOutputs[12];
extern double InitialleftValvesOutputs[12];
extern double leftValvesInputs[12];
extern long leftEncoders[6];
extern double leftAngles[6];

extern double rightValvesOutputs[12];
extern double InitialrightValvesOutputs[12];
extern double rightValvesInputs[12];
extern long rightEncoders[6];
extern double rightAngles[6];
```

```
void InitializeLeftValves()
{
	printf("Initializing Left Arm!!\n");
	double bufferVoltage=0.1;
	int i=0,j=0,k=0;

	leftValvesOutputs[0]=2.3;
	leftValvesOutputs[1]=1.7;
	leftValvesOutputs[2]=2.0;
	leftValvesOutputs[3]=2.0;
	leftValvesOutputs[4] =0.0;
	leftValvesOutputs[5] =2.2;
	leftValvesOutputs[6] =2.4;
	leftValvesOutputs[7] =0.0;
	leftValvesOutputs[8]  =2.3;
	leftValvesOutputs[9]  =1.7;
	leftValvesOutputs[10] =1.7;
	leftValvesOutputs[11] =2.3;

	for(i=0;i<25;i++) // 25x100 ms = 2.5 sec makes the muscles blow up
	{
		vitalSelectBoard(0);
		for(j=0;j<8;j++) // giving reference to each channel of board 0
		{
			if(j==0)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
			if (j==1)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
			if (j==2)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
			if (j==3)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
			if (j==4)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
			if (j==5)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
			if (j==6)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
			if (j==7)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j, bufferVoltage);}
		}
		vitalSelectBoard(1);
		for(j=8;j<12;j++) // giving reference to each channel of board 0
		{
			if (j==8)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
					vitalDacWrite(j-8, bufferVoltage);}
			if (j==9)
				if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
```

```
                              vitalDacWrite(j-8, bufferVoltage);}
                  if (j==10)
                        if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-8, bufferVoltage);}
                  if (j==11)
                        if(bufferVoltage <= leftValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-8, bufferVoltage);}
            }
            bufferVoltage +=0.1; // Increasing the ref voltage slowly not to
harm
            Sleep(100); // Wait 100 ms at each step
      }
      for(int s=0;s<12;s++)
            InitialleftValvesOutputs[s] = leftValvesOutputs[s];

      vitalSelectBoard(0);
}

void InitializeRightValves()
{
      printf("Initializing Right Arm!!\n");
      double bufferVoltage=0.1;
      int i=0,j=0,k=0;

      rightValvesOutputs[0]=2.2;
      rightValvesOutputs[1]=1.8;
      rightValvesOutputs[2]=2.2;
      rightValvesOutputs[3]=1.8;
      rightValvesOutputs[4] =0.0;
      rightValvesOutputs[5] =2.1;
      rightValvesOutputs[6] =1.9;
      rightValvesOutputs[7] =0.0;
      rightValvesOutputs[8]  =2.0;
      rightValvesOutputs[9]  =2.0;
      rightValvesOutputs[10] =2.0;
      rightValvesOutputs[11] =2.0;

      for(i=0;i<25;i++) // 25x100 ms = 2.5 sec makes the muscles blow up
      {
            vitalSelectBoard(1);
            for(j=0;j<4;j++) // giving reference to each channel of board 0
            {
                  if (j==0)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j+4, bufferVoltage);}
                  if (j==1)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j+4, bufferVoltage);}
                  if (j==2)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j+4, bufferVoltage);}
                  if (j==3)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j+4, bufferVoltage);}
            }
            vitalSelectBoard(2);
            for(j=4;j<12;j++) // giving reference to each channel of board 0
```

```
            {
                  if(j==4)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
                  if (j==5)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
                  if (j==6)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
                  if (j==7)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
                  if (j==8)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
                  if (j==9)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
                  if (j==10)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
                  if (j==11)
                        if(bufferVoltage <= rightValvesOutputs[j] + 0.05){
                              vitalDacWrite(j-4, bufferVoltage);}
            }

            bufferVoltage +=0.1; // Increasing the ref voltage slowly not to
harm
            Sleep(100); // Wait 100 ms at each step
      }
      for(int s=0;s<12;s++)
            InitialrightValvesOutputs[s] = rightValvesOutputs[s];

      vitalSelectBoard(1);
}

void SetLeftArmPressures()
{
      int channel=0;

      vitalSelectBoard(0);
      for(channel=0;channel<8;channel++) // giving reference to each channel
of board 0
      {
            if (leftValvesOutputs[channel] < 0.0 ){
                  printf("negative pressure!\n");
                  leftValvesOutputs[channel] = 0.0;
            }
            if (leftValvesOutputs[channel] > 3.6 )
            {
                  leftValvesOutputs[channel] = 3.6;
                  printf("Too Maiac Pressure!!\n");
            }
            vitalDacWrite( channel, leftValvesOutputs[channel] );
      }
      vitalSelectBoard(1);
```

```
      for(channel=0;channel<4;channel++) // giving reference to first 4
channel of board 1
      {
            if (leftValvesOutputs[channel+8] < 0.0 ){
                  printf("negative pressure!\n");
                  leftValvesOutputs[channel+8] = 0.0;
            }
            if (leftValvesOutputs[channel+8] > 3.6 )
            {
                  leftValvesOutputs[channel+8] = 3.6;
                  printf("Too Maiac Pressure!!\n");
            }

            vitalDacWrite( channel, leftValvesOutputs[channel+8] );
      }
}

void SetRightArmPressures()
{
      int channel=0;

      vitalSelectBoard(1);
      for(channel=4;channel<8;channel++) // giving reference to each channel
of board 0
      {
            if (rightValvesOutputs[channel-4] < 0.0 ){
                  printf("negative pressure!\n");
                  rightValvesOutputs[channel-4] = 0.0;
            }
            if (rightValvesOutputs[channel-4] > 3.6 )
            {
                  rightValvesOutputs[channel-4] = 3.6;
                  printf("Too Maiac Pressure!!\n");
            }
            vitalDacWrite( channel, rightValvesOutputs[channel-4] );
      }
      vitalSelectBoard(2);
      for(channel=0;channel<8;channel++) // giving reference to first 4
channel of board 1
      {
            if (rightValvesOutputs[channel+4] < 0.0 ){
                  printf("negative pressure!\n");
                  rightValvesOutputs[channel+4] = 0.0;
            }
            if (rightValvesOutputs[channel+4] > 3.6 )
            {
                  rightValvesOutputs[channel+4] = 3.6;
                  printf("Too Maiac Pressure!!\n");
            }
            vitalDacWrite( channel, rightValvesOutputs[channel+4] );
      }
}

void CloseValves()
{
      double bufferVoltage=0.1;
      int i=0,j=0,k=0;
```

```
	printf("Closing Valves!!\n");

	for(i=0;i<36;i++) // 36x100 ms = 3.6 sec makes the muscles blow up
	{
		// For the Left Arm
		vitalSelectBoard(0);
		for(j=0;j<8;j++) // giving reference to each channel of board 0
		{
			if( leftValvesOutputs[j]-bufferVoltage >0 )
				vitalDacWrite( j, leftValvesOutputs[j]-
bufferVoltage);
		}
		vitalSelectBoard(1);
		for(j=0;j<4;j++) // giving reference to first 4 channel of board
1
		{
			if( leftValvesOutputs[j+8]-bufferVoltage >0 )
				vitalDacWrite( j, leftValvesOutputs[j+8]-
bufferVoltage);
		}
		// For the Right Arm
		for(j=4;j<8;j++) // giving reference to first 4 channel of board
1
		{
			if( rightValvesOutputs[j-4]-bufferVoltage >0 )
				vitalDacWrite( j, rightValvesOutputs[j-4]-
bufferVoltage );
		}
		vitalSelectBoard(2);
		for(j=0;j<8;j++) // giving reference to first 4 channel of board
1
		{
			if( rightValvesOutputs[j+4]-bufferVoltage >0 )
				vitalDacWrite( j, rightValvesOutputs[j+4]-
bufferVoltage );
		}
		Sleep(200); // Wait 100 ms at each step
		bufferVoltage += 0.1;
	}
}

void ReadLeftEncoders()
{
	//Read Encoder Values
	vitalSelectBoard(0);
	for(int channel=0;channel<4;channel++)
		vitalEncoderRead(channel, &leftEncoders[channel]);
	vitalSelectBoard(1);
	for(channel=0;channel<2;channel++)
		vitalEncoderRead(channel, &leftEncoders[channel+4]);

	leftEncoders[2]*=-1;
	leftEncoders[5]*=-1;
```

```
      //printf("Enc1: %d Enc2: %d Enc3: %d Enc4: %d Enc5: %d Enc6:
%d\n",leftEncoders[0],leftEncoders[1],leftEncoders[2],leftEncoders[3],leftEnc
oders[4],leftEncoders[5]);
}

void ReadRightEncoders()
{
      //Read Encoder Values
      vitalSelectBoard(1);
      //!!!First two encoders are flipped!!! (The readings show that)
      vitalEncoderRead(2, &rightEncoders[1]);
      vitalEncoderRead(3, &rightEncoders[0]);

      vitalSelectBoard(2);
      // This part is changed in Sean master
      //for(int channel=0;channel<4;channel++)
      //    vitalEncoderRead(channel, &rightEncoders[channel+2]);
      vitalEncoderRead(0, &rightEncoders[2]);
      vitalEncoderRead(1, &rightEncoders[3]);
      vitalEncoderRead(2, &rightEncoders[4]);
      vitalEncoderRead(3, &rightEncoders[5]);

      rightEncoders[1]*=-1;
      rightEncoders[2]*=-1;

      //printf("Enc1: %d Enc2: %d Enc3: %d Enc4: %d Enc5: %d Enc6:
%d\n",rightEncoders[0],rightEncoders[1],rightEncoders[2],rightEncoders[3],rig
htEncoders[4],rightEncoders[5]);
}

void ResetLeftEncoders()
{
      vitalSelectBoard(0);
      for(int channel=0;channel<4;channel++)
            vitalResetCounter(channel);
      vitalSelectBoard(1);
      for(channel=0;channel<2;channel++)
            vitalResetCounter(channel);
}

void ResetRightEncoders()
{
      vitalSelectBoard(1);
      for(int channel=2;channel<4;channel++)
            vitalResetCounter(channel);
      vitalSelectBoard(2);
      for(channel=0;channel<4;channel++)
            vitalResetCounter(channel);
}

void RealLeftAngles()
{
      //Encoder Parameters =  -5092 5092 -4244 4244 636.6 -636.6
      leftAngles[0] =  (double) leftEncoders[0] / -5092.0 /6.28 * 360;
      leftAngles[1] =  (double) -1*leftEncoders[1] / 5092.0 /6.28 * 360 + 90;
      leftAngles[2] =  ((double) leftEncoders[3] / -4244.0 /2 /6.28 * 360 -
(double) leftEncoders[2] / 4244 /2 /6.28 * 360) -180 ;
```

```
	leftAngles[3] =  ((double) -leftEncoders[3] / - 4244.0 /6.28 * 360 -
(double) leftEncoders[2] /  4244 /6.28 * 360 ) ;
	leftAngles[4] =  ((double) -leftEncoders[4] / 636.6 /2 /6.28 * 360 -
(double) leftEncoders[5] / 636.6 /2 /6.28 * 360);
	leftAngles[5] =  ((double) leftEncoders[4] / - 636.6 /6.28 * 360 +
(double) leftEncoders[5] / 636.6 /6.28 * 360);

	printf("a0: %.2f a1: %.2f a2: %.2f a3: %.2f a4: %.2f a5:
%.2f\n",leftAngles[0],leftAngles[1],leftAngles[2],leftAngles[3],leftAngles[4]
,leftAngles[5]);
}

void RealRightAngles()
{
	//Encoder Parameters =  -5092 5092 -4244 4244 636.6 -636.6
	rightAngles[0] =  (double) rightEncoders[0] / -5092.0 /6.28 * 360;
	rightAngles[1] =  (double) -1*rightEncoders[1] / 5092.0 /6.28 * 360 +
90;
	rightAngles[2] =  ((double) -rightEncoders[3] / -4244.0 /2 /6.28 * 360
+ (double) rightEncoders[2] / 4244 /2 /6.28 * 360) -180 ;
	rightAngles[3] =  ((double) -rightEncoders[3] / - 4244.0 /6.28 * 360 -
(double) rightEncoders[2] /  4244 /6.28 * 360 ) ;
	rightAngles[4] =  ((double) -rightEncoders[4] / 636.6 /2 /6.28 * 360 -
(double) rightEncoders[5] / 636.6 /2 /6.28 * 360);
	rightAngles[5] =  ((double) rightEncoders[4] / - 636.6 /6.28 * 360 +
(double) rightEncoders[5] / 636.6 /6.28 * 360);

	printf("a0: %.2f a1: %.2f a2: %.2f a3: %.2f a4: %.2f a5:
%.2f\n",rightAngles[0],rightAngles[1],rightAngles[2],rightAngles[3],rightAngl
es[4],rightAngles[5]);
}

void ReadLeftPressure()
{
	double leftPressures[4]={0};

	//Filtering
	for(int i=0;i<5;i++)
	{
		if( i == 0 ){
			vitalSelectBoard(0);
			vitalReadAnalogInputs( 0, leftPressures);
			for(int channel=0; channel<4;channel++)
				leftValvesInputs[channel]= leftPressures[channel];

			vitalReadAnalogInputs( 1, leftPressures);
			for(channel=4;channel<8;channel++)
				leftValvesInputs[channel]= leftPressures[channel-4];

			vitalSelectBoard(1);
			vitalReadAnalogInputs( 0, leftPressures);
			for(channel=8;channel<12;channel++)
				leftValvesInputs[channel]= leftPressures[channel-8];

			Sleep(1);
		}else{
			vitalSelectBoard(0);
```

```
                  vitalReadAnalogInputs( 0, leftPressures);
                  for(int channel=0; channel<4;channel++)
                        leftValvesInputs[channel]+= leftPressures[channel];

                  vitalReadAnalogInputs( 1, leftPressures);
                  for(channel=4;channel<8;channel++)
                        leftValvesInputs[channel]+= leftPressures[channel-4];

                  vitalSelectBoard(1);
                  vitalReadAnalogInputs( 0, leftPressures);
                  for(channel=8;channel<12;channel++)
                        leftValvesInputs[channel]+= leftPressures[channel-8];

                  Sleep(1);
            }
      }

      for(i=0;i<12;i++)
            leftValvesInputs[i]/=5;

      // there is a problem with the 10th muscle
      leftValvesInputs[9]-=100;

      vitalSelectBoard(0);

}

void InitializeCards()
{
      printf("Initializing Cards!!\n");
      int numb =0;
      //Initializing the Cards
      if( numb=vitalInit() )
            printf("%d board(s) detected\n",numb);
      else
            printf( "Error initializing WinMotenc library\n" );
}

#endif
```