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November 1, 2004

Dr. Andrew Rawicz
School of Engineering Science
Simon Fraser University
Burnaby, BC V5A 1S6

Re: ENSC 340 Design Specification: The CMI Cardiac Action Potential Imaging System (CAPIS)

Dear Dr. Rawicz:

Attached with this letter is the *Design Specification: The CMI Cardiac Action Potential Imaging System,* which was previously described in our project proposal. We are developing an optical mapping tool that will record electrical signals from a small heart for analysis of irregular heart pulses associated with JET arrhythmia.

The purpose of the design specification document is to provide detailed design requirements to be achieved at the end of the proof-of-concept phase. In this document we will describe in detail each of the functional requirements stated in the Function Requirements and test plans for each module.

Concardio Medical Instruments Inc. consists of eight experienced, dedicated, and hard working engineering students who wants to make a difference: Ronnie Chan, Yindar Chuo, Allen Lai, Deanna Lee, Seddrak Luu, Jimmy Tsui, Edwin Wong, and Stephen Wong. Please contact us if there are any questions or concerns via email, ensc-bcri@sfu.ca or by phone through Ronnie Chan at 778-891-3837. Thank you.

Sincerely,

Ronnie Chan

Ronnie Chan
Chief Executive Officer
Concardio Medical Instruments Inc.

Enclosure: *Design Specification for the CMI Cardiac Action Potential Imaging System*

Concardio Medical Instruments Inc.

Design Specifications for the
Cardiac Action Potential Imaging System

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EXECUTIVE SUMMARY

Junctional ectopic tachycardia (JET) is a severe form of arrhythmia frequently seen in babies who have undergone open heart surgery. The pathophysiology of JET is not well understood, and as a result, a cure has not yet been found. Current treatments for the disease are crude and expensive, and finding the cause will become critical in improving the quality and affordability of patient care. Unfortunately, the JET research community currently lacks a research tool capable of mapping electrical signals in a small heart over a period of time. Concardio Medical Instruments Inc. (CMI) aims to fill this need, by constructing a multipurpose imaging system that can help researchers visually track the movement of electrical and chemical signals in a small heart. As a first step toward achieving this vision, CMI would like to introduce the Cardiac Action Potential Imaging System (CAPIS). The purpose of CAPIS is to help cardiologists map the electrical patterns in the heart associated with JET.

Developed with support from our primary client, Dr. Glen Tibbits of the BC Research Institute for Children's and Women's Health (BCRI), CMI's CAPIS will acquire optically mapped potentiometric images and display them in a comprehensive manner suitable for analysis. Currently, CMI is entering the proof-of-concept (POC) phase in the CAPIS development cycle, spanning from September to December of 2004. In the POC stage, a mock-up model for each critical module in CAPIS will be built so that the CMI design team may evaluate the feasibility of constructing an integrated functional prototype. Due to the large size of the project, and lengthy development period, only the mock-up models constructed in the POC stage will constitute the project submitted for ENSC 340.

CAPIS is divided into three critical modules: Image Generation, Image Acquisition, and Image Analysis. The mock-up model for each module has its own set of functionalities to satisfy for evaluation purposes. The basic functions of each module are outlined below:

- **Image Generation Module (IGM):**
  Obtain optical signal from the heart tissues and display them without loss of data.

- **Image Acquisition Module (IAqM):**
  Capture and display live test images of various formats.

- **Image Analysis Module (IAnM):**
  Correct for motion artifacts related to capturing images of a beating heart.

Upon completion of the POC mock-up, the CMI design team will be more equipped to further assess and consolidate with Dr. Glen Tibbits the feasibility and expected functionalities of the CAPIS functional prototype.

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ABBREVIATIONS

BCRI or **BCRICWH**	BC Research Institute for Children's and Women's Health
CAPIS	Cardiac Action Potential Imaging System
CCD camera	charge-coupled device camera
CMI	Concardio Medical Instruments Inc.
DAQ card	data acquisition card
GUI	graphical user interface
IGM	image generation module
IAqM	image acquisition module
IAnM	image analysis module
IEEE	Institute of Electrical and Electronic Engineers
JET	junctional ectopic tachycardia
LED	light-emitting diode
POC	proof-of-concept
PMT	photomultiplier tube
QE	quantum efficiency
TTL	transistor-transistor logic

1 INTRODUCTION

1.1 Purpose Statement

The objective of the CAPIS is to optically map the conduction of action potential in a small heart and generate images for analysis. CAPIS is developed by CMI with support from the BCRI. Designed as a research tool to be used on rabbit hearts, the hope is that CAPIS will be able to help JET researchers track the abnormal heartbeats and locate the cause of JET arrhythmia.

1.2 Intended Audience

This design specifications is intended to be a design guideline for engineers within CMI. This document serves to ensure that the CAPIS development process meets the specified requirements. The Marketing department at CMI will use this document to arrange sales strategies. Any descriptions mentioned herein will be protected as CMI's intellectual property.

1.3 Scope

This document describes the design specifications that must be met by CAPIS, and explains how CAPIS will be designed to meet all the functional requirements as described in the Functional Specification. The design specifications are written for the implementation of the POC models for each module only, as described in the Functional Specifications.

2 SYSTEM OVERVIEW

CAPIS consists of three modules: IGM, IAqM, and IAnM. The final prototype of CAPIS will be an imaging system that uses the IAqM to capture light emitted from a testing rabbit heart through a series of filters and lenses in the IGM. The captured image from the IAqM will be used for research and study by BCRI after the IAnM modifies the captured raw image into useful data.

CMI is currently in the POC stage in the CAPIS development cycle. Since the 4 month stage (from September to December 2004) coincides with ENSC 340, the scope of the ENSC 340 project will be limited to the mock-up models built in the POC stage only. Thus, each individual module will not be integrated and will have its own separate design specifications.

General module descriptions are given as followed. The IGM will use optical filters and dichroic mirrors to separate light emitted from a heart tissue specimen into two specified wavelengths. In addition, a photomultiplier tube (PMT) will be used to count the number of photons from the two separated wavelengths and transmit the relevant information through a data acquisition (DAQ) card to be displayed on a graphical user interface (GUI) via a personal computer. The IAqM will use a Pentium III personal computer to capture test images via a machine vision camera and IEEE 1349a firewire cable, and display and save the images as a streaming video or a still image onto the computer's hard drive. The captured image will be displayed and saved through a GUI, which also allows the user to perform other operations to manipulate the output images for simple analytical display. Finally, the IAnM will use MATLAB and a non-rigid landmark matching program, developed by Dr. Faisel Beg, to perform the necessary correction to restore a series of test images (simulating the artifact from imaging a beating heart) to a comprehensible state for analysis.

3 DESIGN OF THE CAPIS PROOF-OF-CONCEPT MODEL

3.1 Image Generation Module Design

The IGM's high level design consists of a photon capturing component and a photon display/analysis component, as indicated in Figure 1.

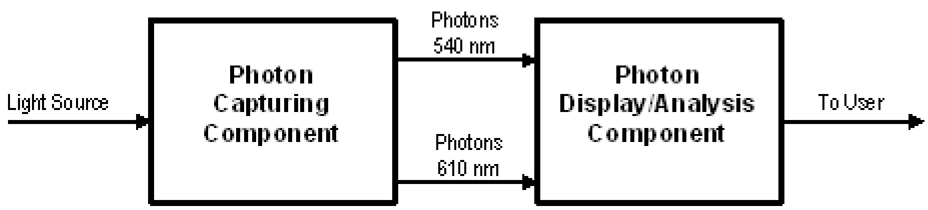


Figure 1: High-level design of the IGM POC model

For more details on the guidelines of the IGM modules, please refer to the functional specification.

In the design specifications, the equipment and parts used for each component are explained in greater detail. Table 1 lists the components in the IGM POC model. Figure 2 shows the pathway of the IGM POC model.

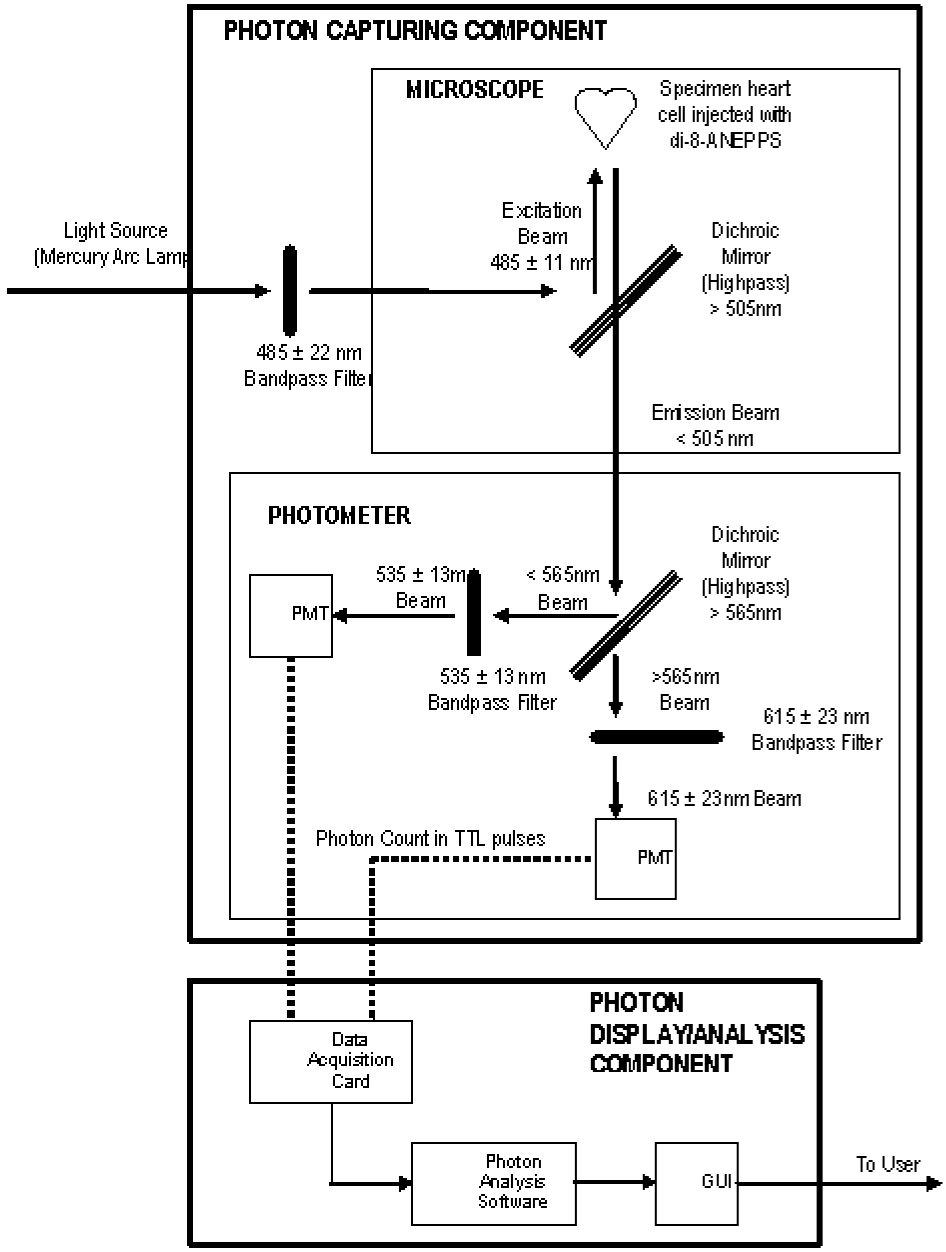


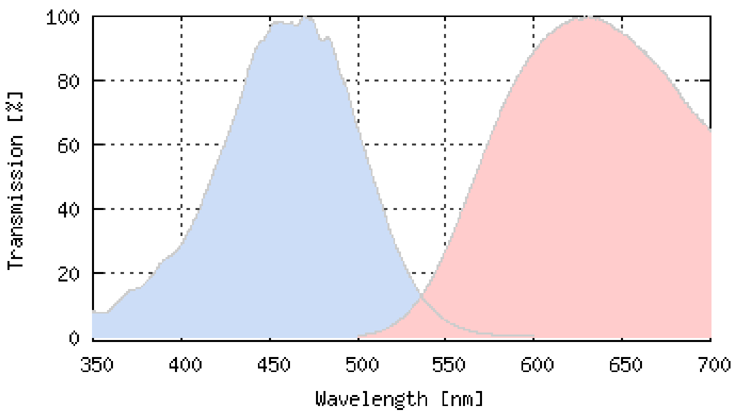
Figure 2: Low-level design of the IGM POC model

Table 1: List of IGM components

Component	Part	Description
Test Specimen	Rabbit heart cells	To be injected by potentiometric dye, so that cells fluoresce under the exposure of certain wavelengths of light
	di-8-ANEPPS	Potentiometric dye to inject into rabbit heart cells
Photon Capturing	Mercury Arc Lamp	Excitation light source component
	Omega Optical 485 ± 11nm bandpass filter	Excitation light source component
	Nikon TE 2000-U biological microscope	Main part of the optical pathway. Magnifies heart cells.
	Omega Optical 505DRLP dichroic mirror	Reflects excitation beam to the specimen cell. Passes emission beam into photometer
	Omega Optical 565DRLP dichroic mirror	Reflects wavelengths < 565nm to one PMT. Passes the rest of the wavelengths to a second PMT
	Omega Optical 535 ± 13nm bandpass filter	Further filters wavelengths < 565nm to only let wavelengths 535 ± 13nm reach the PMT
	Omega Optical 615 ± 23nm bandpass filter	Further filters wavelengths > 565nm to only let wavelengths 615 ± 23nm reach the PMT
Photon Display/Analysis	National Instruments PCI-6602 Data Acquisition Card	Counts TTL pulses
	Labview 6.0	Translates TTL pulses and displays results into in a GUI for the user to analyze

3.1.1 Preparation of Test Specimen

In the POC model, the ratiometric method (in which a comparison between two wavelengths of light are made) is used. As a result, a dye is injected into the cell and will emit light containing a certain number of photons. These photons are emitted after excitation by a mercury arc lamp (see Figure 2), and are captured for analysis in the later modules. The following figure shows the percent transmission of the excitation and emission of di-8-ANEPPS. The goal is to have fluorescence bound to the phospholipid bilayer membranes of the cells, hence reflecting photons with approximately 635nm.



di-8-ANEPPS

Excitation Peak:
468nm

Emission Peak:
635nm

Figure 3: di-8-ANEPPS Transmission Spectrum

The cells observed are collected from the rabbit heart by a laboratory technician at BCRI. The cell will then be placed onto a specimen plate, and injected with di-8-ANEPPS.

3.1.2 Magnification of Specimen Cells

The prepared rabbit heart cells will need to be magnified in such a way that we can isolate one of these cells on the photometer in order to capture the die's fluorescence. Specifically,we will be using a Nikon TE 2000-U inverted research-grade biological microscope, depicted in Figure 4.

Figure 4: Nikon TE 2000-U biological microscope

The Nikon TE 2000-U is particularly useful for the design of the POC model since all the optical components of the IGM can either be secured directly inside the microscope or can be conveniently attached to it. Thus, besides its magnification abilities, the microscope also serves as the main component for the module.

3.1.3 Excitation Light Source

In order to capture the die's fluorescence of a single specimen cell, incident light in a certain range of wavelengths is required. For the IGM, a mercury arc lamp is used to emit a spectrum of light which includes this wavelength range. In addition, an Omega Optical 485 ± 11 nm bandpass filter is used to allow the dye to absorb only a narrow range of these wavelengths. This combination is chosen because it meets the following requirements for our excitation light source:

- The light source consists of wavelengths 485 ± 11 nm, which optimally excites the di-8-ANEPPS dye.

3.1.4 Optical Filtering Component

After the potentiometric dye in the cell fluoresces upon exposure to the excitation light source, the emission beam from the dye needs to be filtered so that photons of specific wavelengths can be isolated and counted. The filtering component comprises of a series of mirrors and filters (as seen in Figure 2) to accomplish this task. A dichroic mirror filters out light from the excitation light source and thus only passes wavelengths greater than 505nm, which contains the beam emitted from di-8-ANEPPS. This dichroic mirror is encased in a cube and is secured inside the microscope.

3.1.5 Data Capture

We will use a photomultiplier detection system to capture data as seen in Figure 5 below.

Figure 5: The Photomultiplier Detection System

The goal for this module is to identity the range of intensities for the released photons and the frequency of photons captured. For the capturing of the released photons we have the photomultiplier detection system, manufactured by Photon Technology International. The photomultiplier detection system is a PMT that is extremely sensitive and allows the measurement of very low levels of light. The PMT can detect with high-voltage power supply, digital display, and discriminator—and capture photons in either analog or digital mode.

3.1.6 Counting Photons

The PMT will be set at photon counting mode, triggering a pulse (or a count) at the output, thus generating a transistor-transistor logic (TTL) curve. As a result, the number of pulses or counts per second is directly proportional to the light impinging the PMT. The PMT is virtually a noiseless amplifier. The counting of photons becomes non-linear when the counts per second rises above 1 to 1.5 million counts per second. Since we expect only five to ten thousand counts per second in CAPIS, the photon count should be linear.

3.1.7 Light Splitting

Light splitting is accomplished by microscope photometers manufactured by Photon Technology International, as shown in Figure 6.

Figure 6: The Microscope Photometers

The emission beam will exit the microscope and enter the photometer (attached to the microscope), where another dichroic mirror splits the beam—such that a beam of wavelengths less than 565nm will be directed at one PMT, and a beam of wavelengths greater than 565nm will be directed at a second PMT. Each of these two beams is further narrowed by a bandpass filter to wavelengths 535 ± 13 nm and 615 ± 23 nm before the photons reach the PMTs.

The dichroic mirrors and filters are selected such that they meet the following criteria:

- Separation of excitation beam and emission beam. That is, a mirror is needed to such that the excitation beam is reflected to the specimen cells, while the emission beam from the cells is passed through the mirror into a photometer.
- IGM is able to separate photons of 540nm and 610nm, with an error margin of ± 20nm.

3.1.8 Analog to Digital Conversion

The goal in this section is to process the data obtained from the two photomultiplier tubes. Since the PMTs generate TTL pulses as described in section 3.1.6, using a counter to record the number of pulses is one convenient method to capture data. National Instruments manufactures data acquisition tools that allow us to fetch data from the PMTs and store the data into a computer. This means of acquiring data requires minimal setup adjustment; moreover, information is readily saved in the computer for future processing and review. This acquisition is done by a DAQ card located on the acquisition computer.

3.1.8.1 Interface Tool

A DAQ card is installed in a computer to capture data; however, an interface tool is required to form a communication bridge between the PMTs output and the DAQ card's input, allowing simultaneous streaming of data of two different channels. National instrument's BNC-2121 connector block can act as the interface medium, as shown in Figure 7.

Figure 7: National Instruments BNC-2121 Connector Block

This connector block has the following specifications that meet our requirements:

- BNC and spring terminal connections
- Easy connection of I/O signals to National Instruments' PCI-660x devices (DAQ cards)
- Generates pulse train, trigger, and quadrature encoder signals for testing

This interface connector block allows us to get easy access to all the signal channels via wire or cable connections. The connector block also includes digital I/O light-emitting diode (LED) state indicators, connectors for counters, frequency adjustment and various other connectors and functions. We can make best use of the connector block's capability to provide information of the state of our system, thereby reducing the time needed to test and debug our module throughout the development stage.

3.1.8.2 Data Acquisition (DAQ) Card

The National Instrument PCI-6602 data acquisition card, as shown in Figure 8, captures data from the PMTs to the computer as described previously.

Figure 8: National Instruments PCI-6602 Data Acquisition Card

We need to capture data from two channels simultaneously (since two wavelengths is observe in the end), and the TTL pulses we expect to capture are approximately 5 to 10kHz, through observation of previous optical setups.

This data acquisition card has the following specifications that meet our requirement:

- 8 up/down, 32-bit counter/timers
- 80 MHz maximum source frequency (125 MHz with prescalers)
- Available for PCI compatible computers
- Can perform three simultaneous high-speed DMA transfers
- Digital debouncing filters
- Up to 32 digital I/O lines (5 V/TTL)

The PCI-6602 device has eight 32-bit counter channels and up to 32 lines of TTL/CMOS-compatible digital I/O. Meeting the channel and frequency requirements, we will use this data acquisition card to count the number of TTL pulses generated from the two channels of the PMTs concurrently.

3.1.8.3 Data Acquisition and User Interface

A program must be written to acquire data using the PCI-6602 data acquisition card, and display data collected to the users. We will write our program in National Instruments' LabVIEW, because this programming environment is compatible with National Instruments' hardware that we are using. Furthermore, this programming environment allows easy creation of GUIs.

The user interface we create will clearly display the frequency of the photons captured from the two PMTs. The software will also allow users to save the streaming data upon a button click. Figure 9 shows the preliminary layout of the graphical user interface.

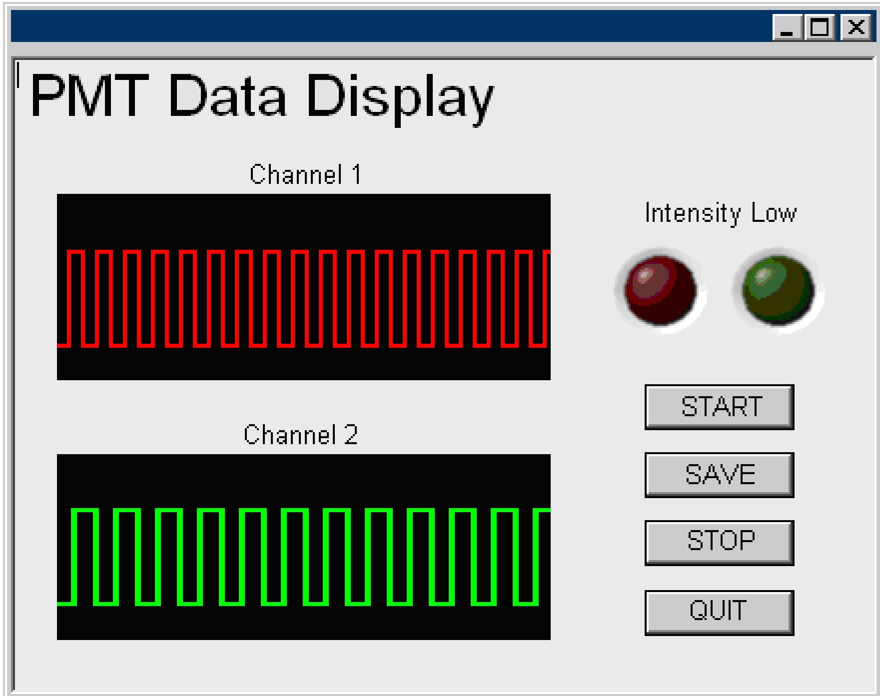


Figure 9: GUI of the IGM module

3.1.8.4 Real-Time Data Streaming Display

The real-time data streaming display will display the frequency of the TTL signals received from the PMTs. Both channels are displayed simultaneously and updated in real time. The streaming data can be triggered upon pressing on the START button.

The PCI-6602 data acquisition card can only support digital I/O; therefore, we are unable to display the TTL curves as required in the functional specifications. However, this card has the capability of measuring frequency and pulse width of the received signal as described. Using this data collected, we may be able to simulate received TTL curves in the GUI. Displaying TTL curves will provide better visualization to the user.

3.1.8.5 Signal Intensity

The signal intensity LED shows warning to user that the intensity is too low by switching on an LED on the GUI. Since we are expecting data from 5 to 10kHz, the LED will lit when the signal is lower than 4kHz. User should stop the test and check if there is any connection problem or hardware failure.

3.1.8.6 Data Saving

Intensity of a particular wavelength observed, the number of photons received at a particular wavelength, will be saved upon user's desire. On the GUI display, user can pick which criteria are required in order to acquire and save the particular pieces of data.

3.1.8.7 Program Exit

The program is exited upon clicking the QUIT button. All data being monitored and displayed will be stopped and lost.

3.2 Image Acquisition Module Design

3.2.1 General Overview of Image Acquisition Module Design

The IAqM is the second stage of CAPIS. The IAqM POC model is designed to satisfy the functional specifications for this phase of the project. The IAqM POC model will be implemented using an image capturing device interfaced to a computer that would provide control over the image capturing device, and display and analysis of the captured images as shown in the system block diagram in Figure 10.

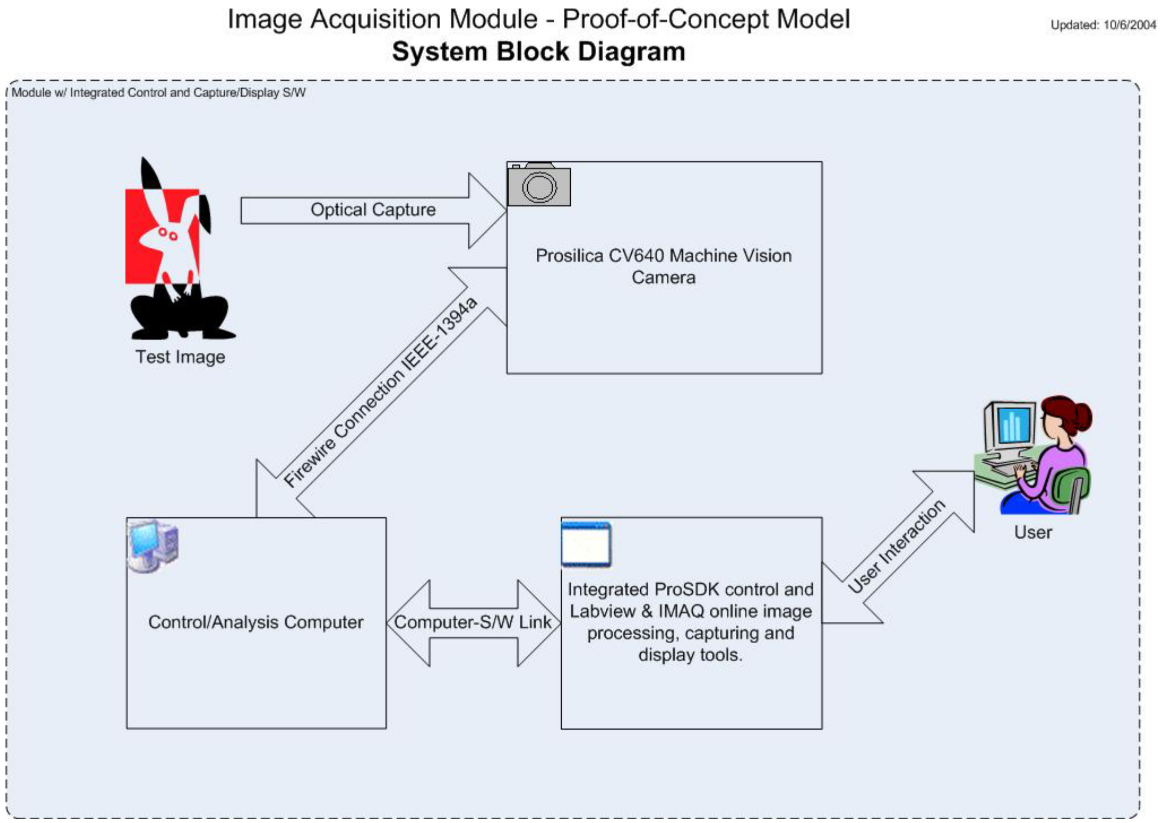


Figure 10: Image Acquisition Module - POC model - System Block Diagram

IAqM can avoid lengthy development of the image capturing device by using a conventional off-the-shelf machine imaging device (such as a digital camera) interfaced to a computer in a manner as described in the above figure. Interfacing the computer to control and obtain image data is made simpler by the device driver provided by the imaging device manufacturers. Furthermore, imaging analysis and display software development packages (readily available in the market) reduces the design complexity of the display output requirements as outlined in the functional specification. Lastly, the use of a computer as the central interface for image capturing and output display is a sound choice simply because of its versatility in supporting various forms of digital inputs, hardware device control, graphical analysis, and display formats.

Many of the various components that integrate to form this module are provided by the project team's research client/sponsor, Dr. Glen Tibbits and his cardio-physiology research team. Having development equipment sponsorship alleviates the financial burden on the team; however, it also imposes various design constraints that, unfortunately, calls for some sacrifices in meeting some minor functional goals. Both the implementation of the IAqM and functional changes due to enforced device constraints will be discussed in the following subsections.

The following list outlines the devices and software that are provided to the design team:

1. Prosilica CV640 Machine Image Camera (CMOS technology, IEEE 1394A firewire connection)
2. Pentium III 800MHz computer with monitor
3. National Instruments' LabVIEW Graphical Development Environment
4. National Instruments' Advanced IMAQ Vision for LabVIEW
5. NI-IMAQ IEEE 1394 Machine Vision Support Package

These devices and software are chosen by Dr. Tibbits as resources to develop this system as the team proposed, but in the same time are devices that have value to future applications as well.

Given the devices specified above, the basic design of the IAqM thus includes a Prosilica CV640 camera connected via IEEE 1394A firewire to the Pentium III computer. The camera can be controlled by the hardware driver provided by the manufacturer or provided by National Instruments' IMAQ IEEE 1394 Machine Vision Support Package. A GUI developed under the LabVIEW and IMAQ software packages will provide all necessary display and image manipulation functions. Particularly, LabVIEW and IMAQ software development packages were provided to the development team because of its compatibility with the camera drivers.

A system physical diagram is shown in Figure 11, illustrating the physical layout of the IAqM and the direction of the image data flow as desired.

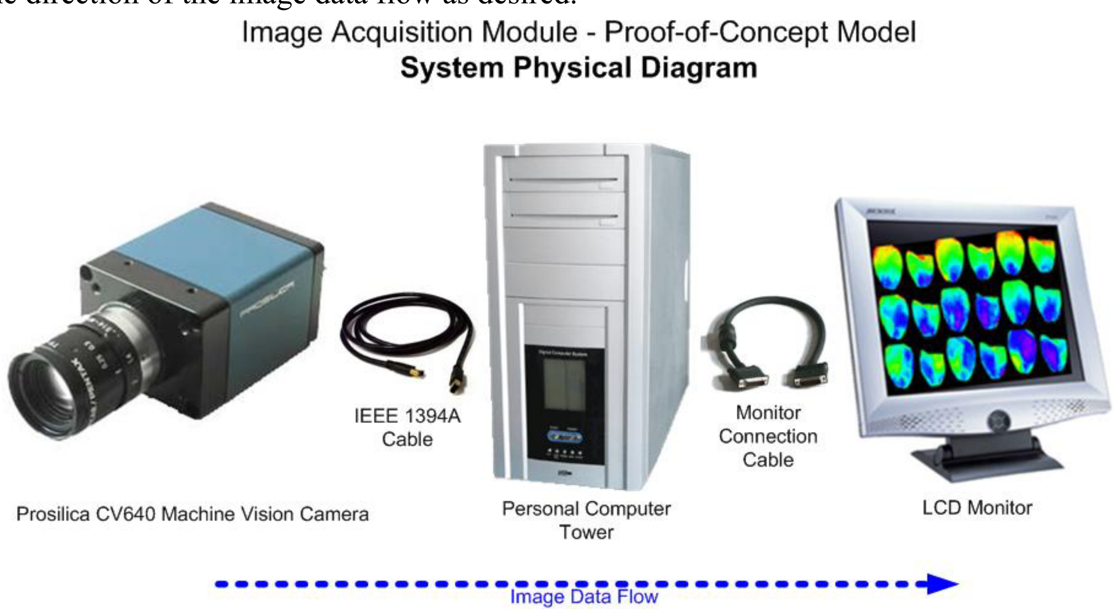


Figure 11: Acquisition Module – POC model – System Physical Diagram

3.2.2 Image Capturing

As the name of this module suggests, the main purpose of the IAqM is to acquire an image and thus an imaging device will be needed. The imaging device cannot be just any digital camera. The camera needs to capture low intensity light between 300nm to 800nm, high frame rates to capture the electrical changes in the heart, and high enough resolution to see capillary sized detail. Cameras that would suffice our purpose would be, for example, charged coupled device (CCD) cameras and machine vision cameras. We will be using a machine vision camera, Prosilica CV640, provided to us by our sponsor Dr. Glen Tibbits. Table 2 below compares the requirements that we set in the functional specifications document and the information about the camera provided to us by Prosilica.

Table 2: Comparison of Procilica camera specifications to required specifications [4]

	Module Requirement from Functional Specifications	Information of Prosilica CV640
Quantum Efficiency (QE)	21% to 90% for 300 to 800nm light	21% to 35% for 400 to 800nm light
Imaging frames per second at full resolution	0.91 to 4194	120 fps
Imaging pixel array (resolution)	128 x 128 pixels to 1920 x 1080 pixels	659 x 494 pixels
Imaging pixel size	6.35 x 7.4 μm to 16 x 16 μm	9.9 x 9.9 μm

As shown, Prosilica CV640 matches quite well with our imaging device requirement. Notice the difference between the QE wavelength ranges of the functional requirements and the camera information. We are limited to use the Prosilica CV640 camera due to the restrictions described in the introduction of this IAqM module, even though the camera does not perfectly match our functional specification requirements. However, we believe that we can perform the POC experiments that we planned (to be outlined in the "Test Plan" section later).

3.2.3 Image Capturing Control

The Prosilica CV640 camera uses IEEE 1394A firewire data interface connection. The camera is thus connected to the computer via the firewire cable. The firewire interface provides both camera powering and data transferring as designed by the camera manufacturer. To implement the low-level hardware interaction in the IAqM, the team uses camera drivers. As described earlier, several drivers are available for interfacing the camera and computer. The team will use the NI-IMAQ IEEE 1394 camera driver because of its compatibility with the LabVIEW and IMAQ software development environments, which is critically necessary in order to facilitate image data read and camera control data writes when the GUI developed under LabVIEW/IMAQ is communicating to the camera hardware.

3.2.4 Output Display

After the camera captures the image or streaming the video, we need some means of displaying the information and giving controls for performing simple operations on the captured image/video to the user. Thus, we will attempt to develop a GUI, using LabVIEW/IMAQ, that will possibly have the layout as shown in Figure 12 below.

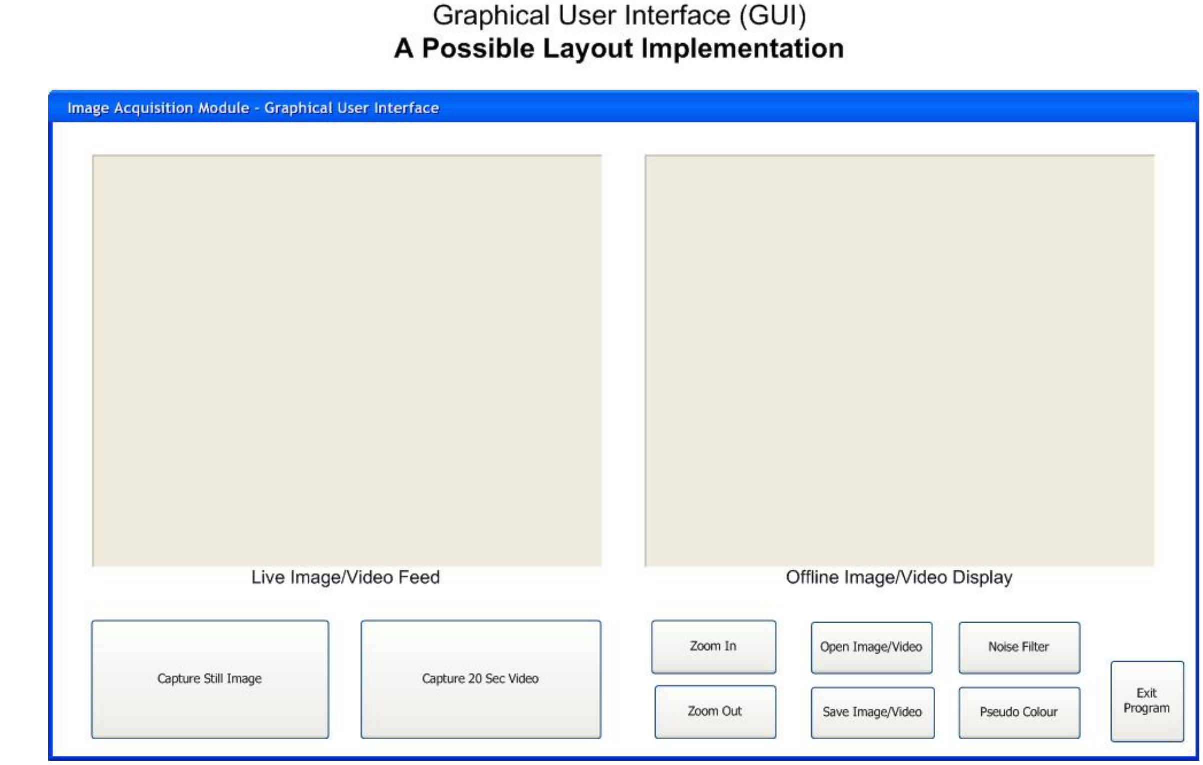


Figure 12: A model of a possible layout of the graphical user interface

The GUI can perform operations on live streaming video or saved offline image/video. In this proposed GUI layout, the live image display panel on the left will constantly display the live streaming video input from the camera. The user will have the option to capture a still image or a 20 second video of the camera input. The captured image or video will then be displayed in the offline image/video display panel on the right after the image or video has been captured. Alternatively, the user may open a previously saved image or video that will be displayed in the offline display panel, assuming that the image or video chosen by the user is in one of the supported file formats. The supported file formats will be determined later.

Once the user has an image or video displayed offline on the right display panel, (either by opening and image or capturing an image), the user then can perform operations on the offline image or video such as digital zoom in, digital zoom out, saving the displayed image or video, pseudo colouring, and noise filtering. All of these operations can be implemented using the virtual instrument (VI) functions and controls provided by LabVIEW. LabVIEW VIs are basically functional blocks that are portrayed in graphical formats that the programmer can connect together.

In terms of the functionality of each operation, all operations are very self explanatory and straight forward except for the saving operation. Two implementations are possible for the saving operation. One implementation is to ask the user to choose between saving the displayed image/video as a new image/video, or overwriting the existing image/video if this displaying image/video is from a saved file. Another implementation is to save the image/video (displayed in the right display panel) as a new image/video. The way we will implement the save operation will be determined later depending on the time constraints and the functionalities of LabVIEW.

Finally, the GUI has an option for the user to exit the program. Another possibility that we will explore is whether it is possible to package the GUI into an executable program. This will need further investigation and thus we present this idea as a possibility.

3.3 Image Analysis Module Design

3.3.1 Functional Overview

The purpose of the POC model for the IAnM is to demonstrate the different possible techniques for correcting motion artifact and evaluate their performance to select the optimal solution. We begin our discussion of the IAnM implementation by revisiting the motion artifact problem.

3.3.1.1 The Problem – Motion Artifacts

Since the CAPIS is intended to image a moving, beating heart, motion artifact is a problem that must be addressed, thus the POC model for the IAnM is dedicated to motion artifact correction. Motion artifact describes the distortion in images as a result of capturing a moving object. By selecting a CCD camera (in the IAqM) with a sufficiently high frame rate, we can avoid blurriness within the images. However, the heart will have a different shape in each image as the heart is contracts and relaxes, making it difficult for researchers to analyze the propagation of action potential. Thus, our task in the IAnM is to restore the heart images to a standardized shape.

3.3.1.2 The Strategy – Two-Part Landmark-based Non-Rigid Registration

The IAnM team at CMI plans to correct for motion artifact with a two-part landmark-based non-rigid registration technique. Registration is the process of aligning an input image (template) with a given reference image (target). Non-rigid means the mapping between a template pixel and a target pixel is not uniform for all pixels. Landmarks are pairs of control points that link a pixel in the template with a corresponding pixel in the target, where both pixels describe a common feature in the images. So, landmark-based non-rigid registration is the process of warping images into a standardized shape with the user inputting landmarks interactively.

Our landmark-based non-rigid registration concept contains two parts, which are two different implementation of landmark-based non-rigid registration. One implementation is based on image processing functions in MATLAB, and the other is based on the image matching program that Dr. Faisel Beg developed in his research. The reason for this two-tier approach is to give engineers at CMI a chance to evaluate performance and choose and optimize our motion artifact correction software. These two approaches will be discussed in detail in the following sections.

3.3.2 Implementation in MATLAB

Figure 13 presents the flow diagram for the landmark-based non-rigid registration program implemented in MATLAB.

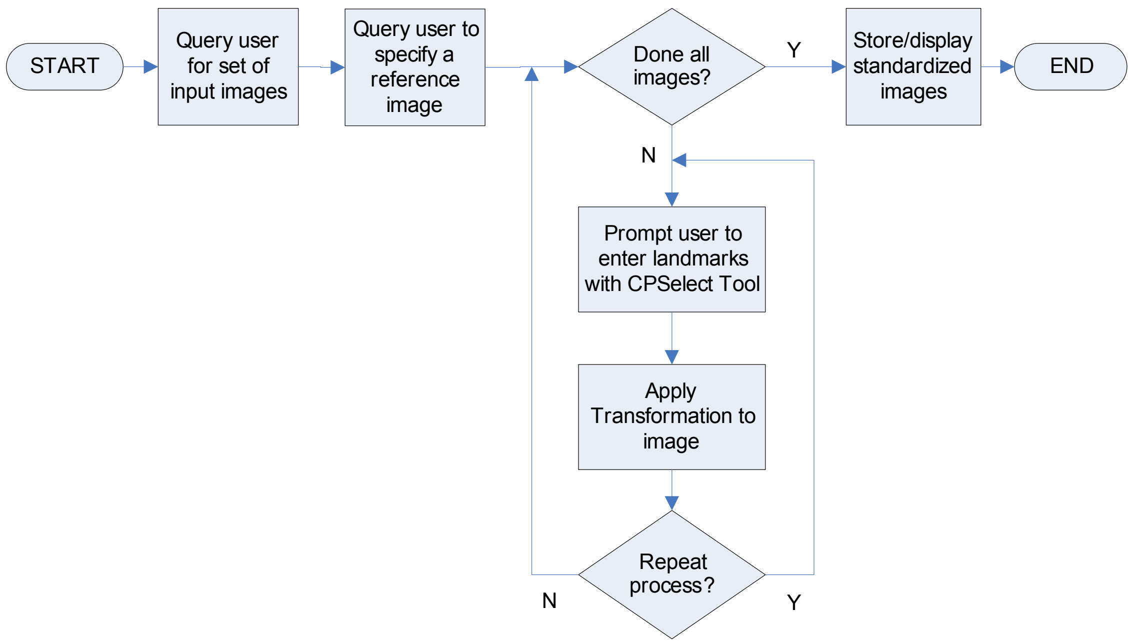


Figure 13: Flowchart of the landmark-based non-rigid registration program implemented in MATLAB

At the start of execution, we impose three assumptions on the input images:

1. Input images have the same dimension and same data format,
2. Input images have been filtered to remove noise,
3. Input images have been pseudo-coloured.

The program begins by querying the user for a set of input images and a reference image, to which all input images will be aligned. Then, the program proceeds to iterate through all the input images. For each input image, the program will prompt the user to manually select the control points using the CPSelect Tool in MATLAB's Image Processing Toolbox. Figure 14 shows the interface of the CPSelect Tool.

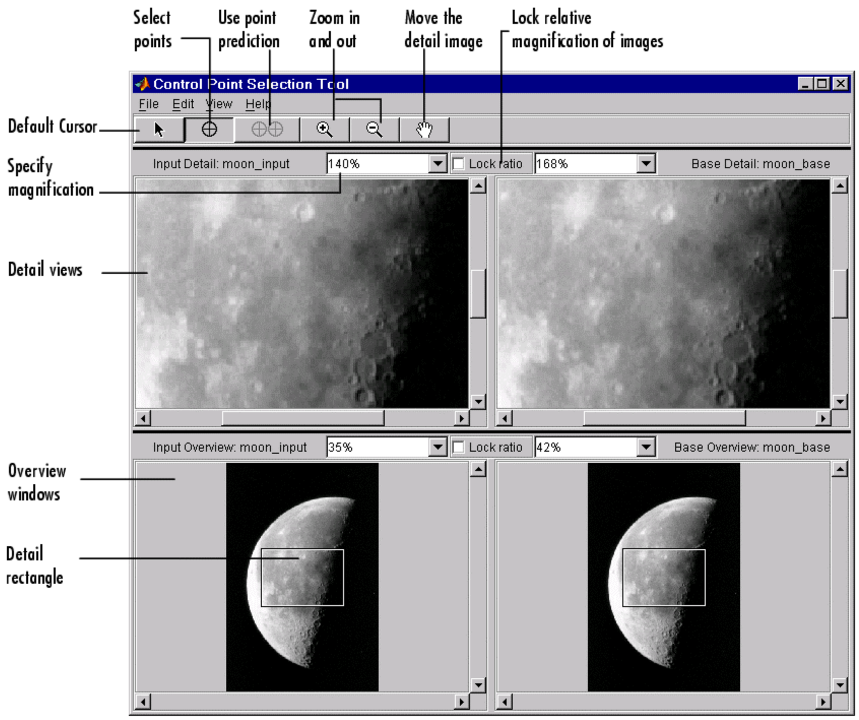
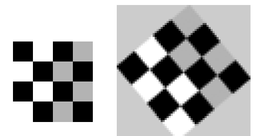
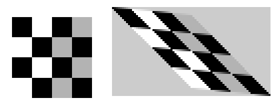
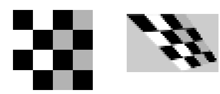
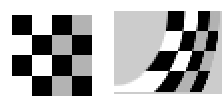
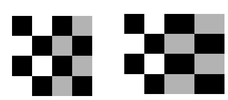
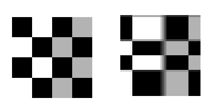


Figure 14: CPSelect Tool interface for selecting control points

The user can select pairs of control points by clicking on a landmark in the input image and then selecting the corresponding landmark on the reference (base) image. After the landmarks have been entered and saved, the input image will be mapped to the reference image by an affine transform. The quality of the transformation will depend on the number and accuracy of the control points. So, when the transformation is completed, the user will have a chance to observe the result of the transformation and decide whether another transformation is needed. If so, then the program will take the result from the previous transformation as the input image and prompt the user to enter new control points. We believe this iterative approach will allow us to improve transformation results. This process will be applied to each input image. When completed, the program will display the results and save them to a location specified by the user.

The affine transform we use to align the input and reference images is one of several transforms supported by the Image Processing Toolbox in MATLAB. Table 3 shows a list of transforms supported by MATLAB. We choose the affine transform for our application because it can accommodate rotation, translation, and shearing. Another transform of interest to us is the lwm transform, which can accommodate local distortions. Depending on performance, we will use one or both of these transforms to improve our results.

Table 3: Types of transformations supported by MATLAB [3]

Transformation Type	Description	Minimum Control Points	Example
`'linear conformal'`	Use this transformation when shapes in the input image are unchanged, but the image is distorted by some combination of translation, rotation, and scaling. Straight lines remain straight, and parallel lines are still parallel.	2 pairs	
`'affine'`	Use this transformation when shapes in the input image exhibit shearing. Straight lines remain straight, and parallel lines remain parallel, but rectangles become parallelograms.	3 pairs	
`'projective'`	Use this transformation when the scene appears tilted. Straight lines remain straight, but parallel lines converge toward vanishing points (which might or might not fall within the image).	4 pairs	
`'polynomial'`	Use this transformation when objects in the image are curved. The higher the order of the polynomial, the better the fit, but the result can contain more curves than the base image.	6 pairs (order 2) 10 pairs (order 3) 16 pairs (order 4)	
`'piecewise linear'`	Use this transformation when parts of the image appear distorted differently.	4 pairs	
`'lwm'`	Use this transformation (local weighted mean), when the distortion varies locally and piecewise linear is not sufficient.	6 pairs (12 pairs recommended)	

3.3.3 Non-rigid Landmark Matching Using Geodesic Splines

The second implementation of motion artifact reduction will use a method of landmark matching developed by one of our project associates, Dr. Faisel Beg. Adaptation of the geodesic splines method into CAPIS will bring expertise in the new field of medical image analysis for our motion artifact reduction. In this section we will discuss the algorithm involved and how the algorithm will be used in the IAnM.

3.3.3.1 General Description

Because the code was developed off-site, specifics of the mathematical terminology will be briefly stated.

The non-rigid landmark matching algorithm performs a transformation between two sets of landmark data. Three main points that are focused in this algorithm include:

1. Interpolating splines [2],
2. Representation of the mapping as a flow; as a solution to an ordinary differential equation governing the system [2], and
3. Putting constraints on the minimum path (geodesic path) on landmark data [2].

The algorithm can provide exact landmark matching or inexact matching, where the tradeoff is smoothness of the mapping [1].

3.3.3.2 Adaptation

Integration of the non-rigid landmark matching algorithm will be done to accommodate the input and output requirements of the IAnM. That is, we need to make all the necessary conversions of data (inputs and outputs) from the algorithm supported formats to the IAnM supported formats. A block diagram of the IAnM with the non-rigid landmark matching algorithm is as follows.

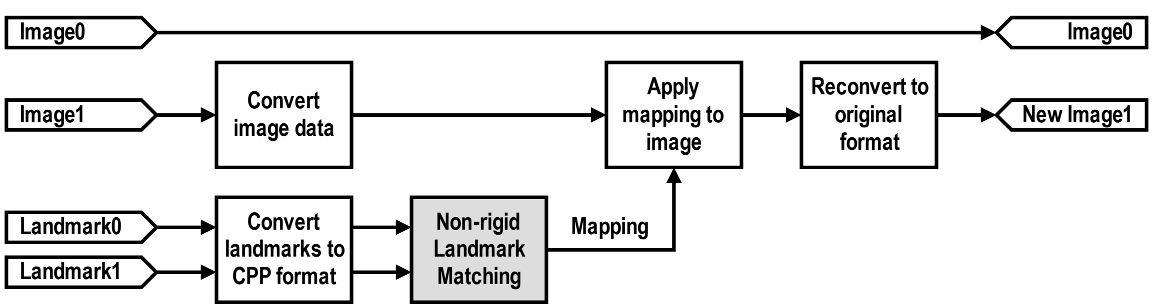


Figure 15: Block diagram for adaptation of algorithm to the Image Analysis module

In the diagram, *Image0* represents the image which every subsequent image will be mapped to. We can refer to this image as the stationary image, or the image that does not suffer from motion artifacts. An image containing motion artifacts is denoted *Image1*, or the moving image. Landmarks *Landmark0* and *Landmark1* correspond to images *Image0* and *Image1*. As depicted, a conversion from the landmark format to "CPP format" is required—this format is required for the current implementation of the landmark matching using geodesic splines.

Once the algorithm produces a plausible mapping of the image based on landmark data, the image must now be transformed. To do so, we use a program such as MATLAB to apply the mapping to the moving image, *Image1*. Finally, we produce the transformed image. Note that conversions of image might be necessary, as shown in Figure 15.

Tailoring the IAnM to the inputs and outputs of the system clearly identifies the data conversions required. In this manner, we can easily replace components of the module—for instance, the mapping module or the landmark matching algorithm.

4 TEST PLAN FOR THE CAPIS PROOF-OF-CONCEPT MODEL

The POC models for CAPIS will each have specific test plans to verify their respective designs to meet their functionalities. These test plans are detailed in the subsections below.

4.1 Image Generation Module

Photon Emission

- Determine whether or not the photons from the potentiometric agent are emitted greater than a wavelength of 510 nm.

Photon Separation

- Determine whether or not IGM will isolate photons of wavelengths 540 nm and 610 nm within error margin as described in the system requirements of this module.

Data Collection

- Ensure the collected photons generate transistor-transistor logic (TTL) pulses on the photometer properly.

Quality of Signal

- Visually inspect whether the clarity of the TTL curves is acceptable for submission to the photon analysis component.

Photon Counting and Display

- Count the number of TTL pulses for each of the two wavelengths, and display the results, in the form of light intensity emitted from these two wavelengths.

Preparation for Integration

- The photometer and the photon display/analysis component is part of the POC model, and thus they will only be used to test and demonstrate the working ability of the IGM.
- Once the model has been tested and the IGM is ready for integration with the other modules, the photometer and the display/analysis component are no longer needed.
- To prepare for integration, ensure the two different wavelengths of light from the photon capturing component can be properly projected into the IAqM, where further analysis will occur.

4.2 Image Acquisition Module

The following is an outline of how we are to test the module to confirm that it is operating properly and experiments that we are going to run on the module to satisfy our POC objectives.

4.2.1 Test Plans

Confirm Camera Operations

- Install the Prosilica camera driver and plug the camera via the firewire to the computer. Test to see if there is a live feed displayed by the camera's driver.

Confirm LabVIEW GUI Operations

- Capture a test image, using the GUI created in LabVIEW, in normal room lighting, display the image, save the image, open the image, and perform pseudo-coloring and digital zooming on the image.
- Capture a 20 second streaming video, using the GUI created in LabVIEW, in normal room lighting, display the image, save the image, open the image, and perform pseudo-coloring and digital zooming on the image.

Noise Reduction

- After visual inspection of the captured images on the GUI, the images are distorted by noise and not acceptable to perform our experiments, we will implement noise removal algorithms.

After we have confirmed that our IAqM's basic display features are functioning properly, we will proceed with verifying that the image capturing functionalities are met by implementing our POC experiments. Each of these POC experiments will attempt to emulate the conditions the camera will be under in when the system is completed.

4.2.2 Proof-of-Concept Experiments

Frame Rate

- Have a LED blink at the rate that emulates a typical cardiac action signal to test if the IAqM can capture the information without loosing any data.

Intensity

- Capture a still image and 20 second streaming video of a low intensity light image source that emulates the low intensity light to be seen through the optical pathway.

Wavelength

- Capture a still image and 20 second streaming video of a light source composed of wavelengths between 300 to 800nm to emulate the light emitted by the florescent dye.

Resolution

- Capture a still image and 20 second streaming video of a calibration grid to emulate the desired level of detail to be seen on the heart.

The above test plan and experiments addresses most of the performance and general functionalities proposed. The experiments are briefly outlined to allow possible changes to implementation due to available resources that had not be finalized yet.

4.3 Image Analysis Module

We have two main tests to perform in the Image Analysis module. These tests are to

1. Determine quantitatively which landmark matching algorithm performs better for the input images supplied, and
2. Determine qualitatively documentation and usability of the developed software.

As mentioned in the functional specifications, in testing usability, we will have beta users operate the software without prior knowledge. These users will have the resource of our documentation provided. The result desire is simply qualitative—that is, whether documentation is clear and concise such that others can continue work beyond the POC model.

Our main attention focuses on testing of the two separate algorithms for landmark matching. We opted to develop a quantitative test, because we place importance in identifying how well each landmark matching algorithm performs, *and to what degree* the algorithms perform against each other.

The following block diagram outlines the basic testing procedure for landmark matching algorithms. The procedure in Figure 16 below is an extension of Figure 15. Using one dataset for both algorithms, we define the *image matching error percentage* as the image intensity difference divided by the total image intensity of the stationary image (*Image0*). This figure accurately represents how close the transformed moving image matches the stationary image.

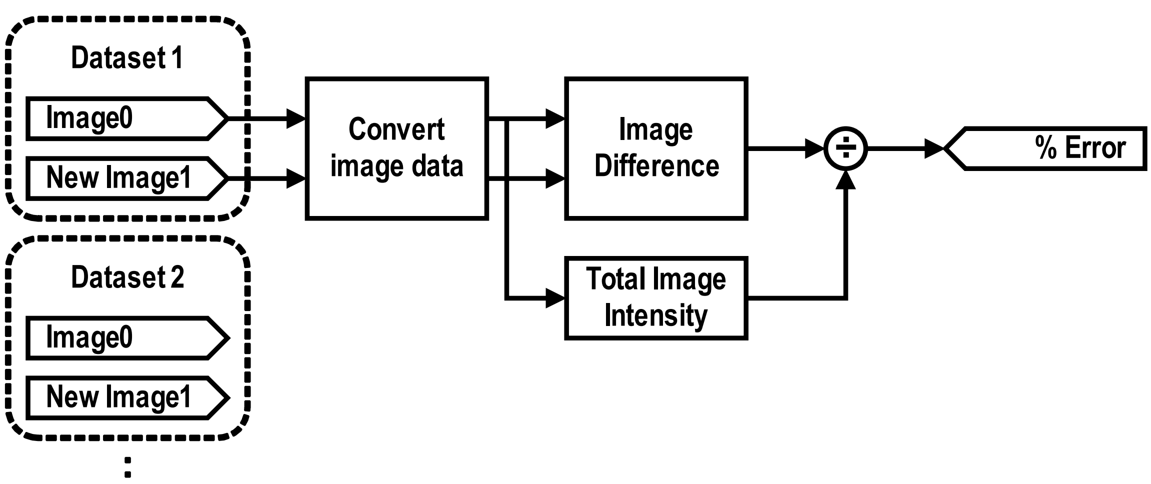


Figure 16: Block diagram, testing module for IAnM

Primitively, the algorithm producing the lowest image matching error percentage will be the better algorithm for CAPIS. A more elaborate testing module would examine multiple datasets, consisting of a large variety of image and landmark data, and look at the consistency of the error percentage obtained. In this manner, we avoid the possibility of an algorithm performing better on a specific dataset.

Finally, the testing module can be performed in any location—the image conversion block in Figure 16 accommodates the required conversion for the image difference/intensity computer. Examples of possible testers include MATLAB or custom C++ code available through Dr. Faisel Beg (as a part of the landmark matching algorithm).

5 CONCLUSION

The design approach towards the implementation of the CAPIS POC model provides a preliminary proposal to how the project team hopes to develop a device that satisfies the functionalities described in the Functional Specification Proposal. At the end of the POC phase, ending in December 2004, through the design and testing as described in this document, the CAPIS POC model should be able to demonstrate each of the previously stated requirement. When completed, the team hopes that the CAPIS POC model will serve as a basis for developing a functional tool to provide medical researchers a method in identifying the physiology of the JET-disease.

6 REFERENCES

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