Final Report

A System to Quantify 3D Spatial Deformation of Heart Valve Leaflets

Team #8

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# Table of Contents

Abstract ................................................................................................................................. 4

1. Introduction ......................................................................................................................... 4
   1.1. Background .................................................................................................................. 4
   1.2. Purpose of the Project ............................................................................................... 5
   1.3. Previous Work Done by Others ................................................................................ 5
       1.3.1. Products and patents .......................................................................................... 5
   1.4. Map for the rest of the report .................................................................................... 5

2. Project Design ..................................................................................................................... 6
   2.1. Introduction ................................................................................................................ 6
   2.2. Alternate Design Considerations ............................................................................... 7
       2.2.1. Optical Measurement .......................................................................................... 7
       2.2.2. Apparatus Design .............................................................................................. 7
       2.2.3. Mounting Techniques ....................................................................................... 8
   2.3. Subunits ....................................................................................................................... 9
       2.3.1. Apparatus Design .............................................................................................. 9
       2.3.2. MATLAB Algorithms ....................................................................................... 15
       2.3.3. LabVIEW Programming .................................................................................. 17

3. Realistic Constraints .......................................................................................................... 28

4. Safety Issues ...................................................................................................................... 29

5. Impact of Engineering Solutions ..................................................................................... 30

6. Lifelong Learning .............................................................................................................. 31

7. Budget and Timeline ......................................................................................................... 31
   7.1. Budget ....................................................................................................................... 31
   7.2. Timeline .................................................................................................................... 33

8. Team Member Contributions to the Project .................................................................... 34
   8.1. Group Collaboration .................................................................................................. 34
   8.2. Michael Hahn ........................................................................................................... 34
   8.3. Elizabeth Morgan ....................................................................................................... 34
   8.4. Oskar Perskaas ......................................................................................................... 35
Abstract
Heart valve disease affects about 5 million Americans each year (1), and has become a significant cause of illness and mortality. Such disease typically occurs when heart valves do not function as they should. Improperly functioning valves can cause insufficient blood flow (valvular stenosis) to and from the heart as well as leakage (valvular insufficiency) through the valve, oftentimes the opposite way of the natural flow (regurgitation). The primary treatment for valve disease is to replace the faulty valve with a bioprosthetic one. However, valve replacement, whether invasive (via open-heart surgery) or noninvasive (via percutaneous means), remains a non-ideal solution due to improper valve function and failure.

Our client, Dr. Wei Sun, asked us to design and create a system that is able to measure the strain, calculate the stress, and ultimately visually reconstruct the behavior of several bioprosthetic heart valves under both static and dynamic loading conditions. The design was best broken into three specific aspects: the design and creation of the physical testing apparatus, the development of the LabVIEW programs that are able to track the deformation of the heart valve leaflets, and the development of the MATLAB algorithms that are able to determine the strain, calculate the stress, and visually reconstruct the deformation behavior. Similar systems have been developed in the past; however, all had great limitations and yielded error-ridden results. Therefore, Dr. Sun desired the development of a system that would yield more accurate and reliable data, in order to successfully aid with the creation of optimal heart valve designs.

1. Introduction
Dr. Wei Sun, an Assistant Professor at the University of Connecticut in the Mechanical Engineering department, asked our design team to develop and construct a measurement system that is able to quantify 3D bioprosthetic heart valve deformations during both static and dynamic loading conditions. He would like to obtain behavioral and mechanical data for several different heart valve types, geometries, and sizes.

1.1. Background
According to the American Heart Association, heart valve disease affects about 5 million Americans each year (1), and has become a significant cause of mortality among adults. The two main types of heart valve diseases are valvular stenosis and valvular insufficiency. Valvular stenosis occurs when the valve opening is smaller than normal due to stiff or fused leaflets. Such a narrowed opening can cause the heart to work significantly harder than normal in order to compensate for the reduced blood flow able to pass through. Valvular insufficiency—also called regurgitation—occurs when a heart valve does not close tightly. The insufficient seal can lead to backflow of blood, forcing the heart to work harder to compensate for the leaky valve and lack of blood flow to the rest of the body. Both conditions force the heart to work harder than normal—a behavior that frequently leads to failure. The treatment for such valve diseases is commonly a valve replacement. However, bioprosthetic valves are prone to failure, leading to a need for additional replacements (oftentimes several in a patient’s lifetime). Therefore, it is obvious that an improved bioprosthetic valve design is needed.
1.2. Purpose of the Project
In order to design more successful bioprosthetic heart valves (i.e., longer-lasting, better functioning, etc.), it is imperative that one understands the behavior of the designed valve. Therefore, it has been requested by Dr. Wei Sun, the project sponsor, for a measurement system to be designed and developed that is able to measure the strains and calculate the stresses of bioprosthetic heart valves under both static and dynamic loading conditions, comparable to the heart. Such a system would analyze the behavior of heart valves of different geometries and sizes. Not only is such information useful regarding the testing of existing heart valves, but it would also serve as a new test method for newly developed and innovative valve designs. The system would simulate in vivo conditions, allowing the engineer to foresee the behavior of the valve after implanted in the patient. Any design flaws (i.e., mechanical incompatibility or leakage) would be visible to the engineer before implantation, allowing for design improvement without the risking the patient’s health.

1.3. Previous Work Done by Others
Mechanical heart valves are categorized as Class III medical devices. As such, the FDA requires that new mechanical heart valves be tested in a pulse simulator flow loop for 600 million cycles—which is equivalent to about 15 years of real use—before its application for premarket approval is considered. Such a system is similar to the one at hand in that it is able to repeatedly force fluid through a heart valve. However, the main purposes of the two systems are different. The pulse simulator flow loop simply acts as a stress test, with no concern regarding how or why the valve may fail. On the contrary, the system proposed in this report is entirely involved with finding the sources of failure, and trying to understand how the valve can be improved.

1.3.1. Products and patents
Upon literature review, there are currently no commercial devices that perform to the desired design specifications. However, Dr. Wei Sun has worked extensively with the design and testing of an apparatus similar to the one proposed in this report. His work involved quasi-steady state loading of a specific heart valve at 40, 80, and 120 mmHg, using two cameras to track marker deformations. Therefore, Dr. Sun has asked our team to further develop his design, ultimately leading to a system that can yield specific strain and stress results. In addition, note that Dr. Sun tested one particular bioprosthetic heart valve, while this project will involve the testing of several different heart valves, making it possible to directly compare the behaviors of various valves on the market.

While there are numerous patents for new types of heart valves and leaflet designs, no patents exists for anything concerning the strain testing of heart valve leaflets.

1.4. Map for the rest of the report
This report will detail the design process, including the initial designs and how they have evolved into what they are at this moment. The physical apparatus as well as the techniques and programs used to measure strain and 3-dimensionally reconstruct the strains. Budgets, timelines, realistic constraints and the impact this research can have on engineering studies will also be discussed in detail.
2. Project Design

2.1. Introduction
With the design, there will be an option to either apply static and dynamic loadings to the heart valve, as three cameras observe and track the placement changes of graphite markers added to the valve leaflets. LabVIEW will be used to create a Virtual Instrument that will acquire the images from the cameras and analyze the movement of the markers in 3D space. From the relative movements of the markers, strain will be determined, stress will be calculated. From that information, Abaqus will be used to show areas of stress concentration. This information will give insight into the behavior of the geometric design of the valve, and will show the effectiveness of how each valve distributes the strain. The results will analyze the valves, bringing to light certain design characteristics that are more favorable than others, which will aid in the design of better heart valves. Since bioprosthetic heart valves commonly fail, an improved design would reduce the failure rate of implanted valves, and function as a better treatment for aortic heart valve diseases.

The strain measurement system being designed is intended to house and test heart valves, both bioprosthetic and natural tissue, of different sizes and geometries in order to analyze and evaluate form and function. The system will incorporate both physical testing as well as algorithmic analysis of the heart valve being tested. Both static and dynamic loading conditions will be implemented to test both the 3D motion of the valve leaflets as well as the transvalvular pressure.

The proposed strain measurement system will be comprised of a physical testing mechanisms which includes a fluid chamber which houses the heart valve being tested, a strain measurement system to capture the valve deformation, and a pressure transducer to measure the transvalvular pressure. Figure 1 shows an example of a strain measurement system design, similar to the one being proposed. A computer algorithm will numerically constructs all of the acquired data from the physical testing in order to calculate the deformation gradient, stress, and strain that the valve experiences under the different loading conditions.

![Figure 1. A dual camera system to capture leaflet deformation of a bioprosthetic heart valve.](image-url)
The proposed system will allow for stronger heart valve design by allowing the user to test the form and function of the developed heart valve before implantation. It is a readily available method for testing. Developed valves can be mounted to the system in manner similar to that of implantation, while both static and dynamic loading is applied. The numerical analysis then allows the engineer to quantitatively observe the function of the valve. When designing bioprosthetic heart valves, the goal is to reduce high stress concentrations. Since stress concentrations typically lead to failure, by reducing or eliminating them, the valve will show more success after implantation. Ultimately, patients with prosthetic heart valves should be able to live like those without the need for such mechanical aid. Therefore, the design of prosthetic valves should be able to function for years under different physical conditions and behavior. A strain measurement system would allow the testing of newly developed valves, aiding in the development of more efficient, longer-lasting, and all-around better mechanics.

2.2. Alternate Design Considerations

2.2.1. Optical Measurement
To capture the 3D motion of the leaflets, an inflation method corresponding to thin-walled tissues will be utilized. Such a method requires small markers and several high-speed digital cameras. In order to see the strain, 60-90 marks will be placed on each leaflet. The cameras then record the displacement of each marker, allowing for the precise calculation of inflation and strain. There were two possible approaches to designing the optimal measurement system, a two camera system, and a three camera system. The advantages and disadvantages of both designs are discussed below.

2.2.1.1. Two Camera System
At least two cameras are needed to follow all of the markers and to give stereoscopic vision. Using only two cameras is the cheapest option, but can result in experimental limitations. In some leaflet deformation situations, it is possible that only one of the two cameras will be able to see the markers around the boundaries, which could lead to a loss of information in that region.

2.2.1.2. Three Camera System
Three cameras can be used in to ensure all markers are in the field of view, especially near the boundaries, and the third camera can act to increase accuracy when calculating marker positions. However, with an additional camera, several aspects of the system such as the algorithm used to analyze the gathered data will need to be altered in order to incorporate the additional information. There will also be additional financial costs for a third camera.

2.2.2. Apparatus Design
The project can be broken down into two parts, static loading and dynamic loading, each calling for special accommodations in its testing apparatus. The static loading apparatus was initially thought to require a simple water column placed on the heart valve, to be filled with varying amounts of water. Each valve will be tested under 0, 20, 40, 60, 80, 100, and 120 mmHg. The dynamic loading apparatus is a bit more complex, and requires the use of a closed pump system to force saline through the valve.
2.2.2.1. Static Apparatus
The original static apparatus design (Figure 2) was comprised of a clear acrylic glass housing chamber, a mounting post, and a loading hopper. The hopper was to be filled with saline in order to reach the desired transvalvular pressures. This open bath type of design is appealing because it is simple and easily built.

![Figure 2. Original static apparatus design.](image)

2.2.2.2. Dynamic Apparatus
As opposed to the static loading device, the dynamic apparatus will have a hydraulic pump to change the transvalvular pressure over time by cycling saline at different rates through the valve. The design will differ from the static apparatus in that it will have closed-loop tubing with a pump integrated. The hopper in the static conformation was to be detachable to allow the testing mode to be switched between static and dynamic. Heart Valve Mounting

2.2.3. Mounting Techniques
Heart valves come in an assortment of sizes with varying exterior surfaces. We need to make sure we can accurately test, at the very least, the most common types of heart valves. Leaking fluid will result in inaccurate results, and therefore, the mounting design is imperative. A tight seal must be made between the system and valve tissue in order to eliminate any fluid leakage. Sutures and mechanical fits are two different ways to achieve a seal.
2.2.3.1. Sutures
If sutures are used we would have to suture the valve into the apparatus so that it was fixed into position. Sutures are appealing because they do not require the creation of customized mounting plates for every new valve that is being tested. However, the process of suturing and then removing sutures for each valve will be a time consuming process and damage the valve.

2.2.3.2. Mechanical Fit
Mechanical fits are appealing because they do not cause damage to the valve and can be quickly interchanged. This allows for the testing of multiple valves in a shorter period of time and the ability to reuse the same valves for far longer than one could when using a suture method. The disadvantage of mechanical fits is that each heart valve will likely require the creation of its own mounting plate. This means that Dr. Sun will likely have to create his own plates if he wants to test new valves after the conclusion of our project.

2.3. Subunits
There are several aspects to the developed strain measurement system: a fluid chamber that houses a bioprosthetic heart valve, an optical strain measurement system to capture 3D leaflet cusp deformations under a variety of hydrostatic loading conditions, and a pressure transducer that simultaneously measures the transvalvular pressure. The system is computer controlled with automatic data visualization and analysis. In addition, the motion of the leaflets is numerically constructed.

2.3.1. Apparatus Design
A major requirement for the system is the ability to test heart valves under both static and dynamic loading conditions. In order to best accommodate for this, a single apparatus was designed that can be switched between testing modes with just a few alterations. The heart of the apparatus, the fluid chamber, can be seen below in figure 1.

![Figure 1. The fluid chamber.](image-url)
It has 4 unique openings, each with its own specific role, and a mounting post in the center where the heart valve will be held. Depending on the testing mode, various openings on the fluid chamber are connected or sealed. For static loading conditions, please refer to figure 2 below.

![Figure 2. The fluid chamber (static loading).](image)

While testing static loading conditions pressure is applied opposite the direction blood would normally flow through the heart valve in the body. It is essentially measuring the strain caused by backflow against the valve leaflets. For this testing mode, connection B is closed, connection C is left open to the atmosphere, connection A (i) and (ii) are connected to a hand pump and pressure transducer respectively, and connection D is where the borescopes enter the system. The valve itself is sutured into a mounting plate, which is mechanically attached just above E.

Different size mounting plates were made to hold different types and sizes of heart valves. Each plate contains four bolt holes to allow for easy attachment to the top of the mounting post and an annulus hole with a suture ring in its center. Once the valve is sutured into the plate, the plate is attached to the mounting post via bolts and wing nuts. Saline is then added to the chamber until it’s above the plate, but below connection B. The pressure from the saline is enough to close the heart valve leaflets. The hand pump attached to connection A (i) is then used to further pressurize the system, generating transvalvular pressures up to the desired 120 mmHg. Two borescopes were mounted into the fluid chamber lid in order to get a close view of the heart valve leaflets while recording their deformation. Each leaflet will be marked with graphite markers in a 3-1-3-1-3 pattern as shown below in figure 4.
The coordinates of these markers will be tracked. Their layout is essential in determining strain as will be discussed later.

The second testing mode, using dynamic loading conditions, requires a more complicated system. Figure 5 below depicts its use.

In dynamic testing the saline will flow through the valve just as it would in the body, opening and closing as the fluid is pumped through it. In order to accomplish this, connection A(i) will be sealed and connections B and C will be connected to form a closed loop system. Inside the closed loop between connection B and C with be a pneumatic pump, which will create pressure in a pulsing manner similar to the heart. Once again a pressure transducer will be used to measure the transvalvular pressures and ensure testing is being done at the appropriate pressure levels. The borescopes will still be inserted in the same fashion to digitally capture the deformation.
For both tests, a calibration cube is used in order to define the coordinate system that MATLAB would later. This involves simply placing the calibration cube which is attached to a long flexible piece of welding wire into the field of view of both cameras just above the valve.

2.3.1.1. Valve Mounting
Heart valves come in an assortment of sizes with varying exterior surfaces. We need to make sure we can accurately test, at the very least, the most common types of heart valves. The goal is to mount the valves in a manner similar to when being implanted in the patient. Therefore, the tissue will be sutured onto a plate, which will then be mounted into the system. It is extremely important for each plate to be designed specifically for each type valve in order to ensure proper testing.

During the flow, leakage will yield inaccurate results, and therefore, the mounting plate design is imperative. A tight seal must be made between the plate and valve tissue in order to eliminate any fluid leakage. Several plates will be machined for different types of valves (aortic, mitral, etc.) as well as different sizes. Figure 5 shows the four different valves in the heart, while Figure 6 shows several different heart valves. As can be observed, the geometry, design, and size of the valves are very different; the need for specifically designed mounting plates is apparent. Note that since the goal of the measurement system is to simply test the form and function of the actual valve structure, there is no need to incorporate the entire environmental system of the heart (i.e., aortic arch).

![Figure 5. The four heart valves (2)](image)

The four heart valves are located at the entry and exit points of the heart chambers. They act as door which open and close in concert to keep the blood flowing in one direction. Valves affected by disease can compromise the flow of blood through the heart, and therefore, bioprosthetic valves are implanted. In a lifetime, heart valves will open and close more than two billion times, with the heart beating approximately 100,000 times a day (2). Therefore, the importance of a properly functioning bioprosthetic valve is of dire concern.
(a) Some valves, such as the Edwards SAPIEN Transcatheter Heart Valve, are part of a stent structure, and therefore, require, not only a specialized mounting plate, but also a specialized mounting technique. Since a stented valve is not sutured in place when implanted, when testing, it should also not be sutured. Therefore, a tube-like device will be used as the mounting device when testing stented valves.

(b) Biological valves come in many shapes, sizes, and are made of several natural and prosthetic materials. For this proposed system, porcine valves will be primarily used for testing. However, bovine and even human tissue is oftentimes used in biological valves. In addition, synthetic materials are also used to create such structures.

Figure 6. Different types of bioprosthetic heart valves: (a) Edwards SAPIEN Transcatheter Heart Valve (26 mm and 23 mm sizes) (3) and (b) biological valves (4).

The final mounting plate design features four bolt holes to allow for easy attachment to the top of the mounting post and an annulus hole with a suture lip in its center. Dr. Sun was going to order a size 25 mitral valve from Edwards Lifesciences. This has a 36 mm suture ring outer diameter and an annulus outer diameter of 28 mm. The first plate was machined to stick the annulus all the way through, and catch the suture ring on the suture lip. This lip had 20 suture holes milled through it as shown below in figure 7.
A System to Quantify 3D Spatial Deformation of Heart Valve Leaflets

Figure 7. A mounting plate.

A rubber ring was created to fit under the suture lip to ensure a watertight mount. The valve suture ring sits on top of the lip. We implemented a continuous stitch while suturing. The suture first goes through the valve suture ring, then the plate suture lip, and finally the rubber ring. The process repeats, going up and down until the valve and rubber are firmly attached to the plate.

2.3.1.2. Optical Measurement

The purpose of the proposed measurement system is to test and analyze the physical deformation of the mounted heart valve under inspection. Several methods must be implemented in order to capture such deformation. To capture the 3D motion of the leaflets, an inflation method corresponding to thin-walled tissues will be utilized. Such a method requires small markers and several digital cameras to trace the marker motion to infer the associated inflation and membrane strain. In order to determine the strain, 11 markers will be placed on each leaflet. Two borescopes fitted with CCDs cameras will record the displacement of each marker, allowing for the precise calculation of inflation and strain. A calibration cube will also be made. It will have 4 points of known location on 3 faces. Capturing these points on camera is an essential part of the 3D reconstruction process, which will be discussed in more detail later.

2.3.1.3. Transvalvular Pressure

A pressure transducer will also be utilized to measure the transvalvular pressure. When heart valves are closed, they experience the highest pressure. The bearing load at that point is the highest, and acts on the valve at a pressure of about 120 mmHg (for the average, healthy adult). In the closed state, the chamber is static and backflow and backpressure will be mimicked. The left ventricle has about 7 mmHg of pressure in the closed state. Therefore, the difference between the bearing side of the valve and the left ventricle side of the valve will be used to calculate the transvalvular pressure. With static testing, only one pressure transducer is needed to track the pressure valves acting on the valve (in the chamber). However, since the other side of the valve is exposed to the atmosphere (atmospheric pressure), the pressure reading from the transducer is the pressure used in further calculations of stress.

In addition to the static testing mode, a dynamic loading mode will be analyzed. During dynamic loading conditions saline will be pumped through the valve, and the resulting deformation will be analyzed. Unlike the static loading, which only requires one pressure transducer to measure the pressure in the apparatus, the dynamic loading requires two pressure transducers, one on each side of the valve. The transvalvular pressure is then calculated by taking the difference between the two readings.
2.3.2. MATLAB Algorithms
The third step to the system developed is to take the entire image data acquired in the LabView programs and input it into MATLAB for further analysis. Thus described so far, the system simulates static (or dynamic) loading on the mounted bioprosthetic heart valves, while two cameras capture and track, via LabView, the deformations of the markers placed on the valve leaflets. At this point, raw 2D coordinate data from LabView has been gathered and written to a text file. In order for the analysis to reach completion, however, MATLAB must sort the data, create 3D coordinate from the 2D LabVIEW coordinates, and output the mechanical information of the heart valve, such as stress and strain.

All of the data gathered from the physical testing of the mounted heart valves will be reconstructed and analyzed through four previously developed MATLAB algorithms. A DLT (direct linear transformation) standard algorithm will be utilized to reconstruct the 3D motion of the leaflets. The system will also calculate and analyze the stresses and strains of the valve under both static and dynamic loading conditions. Since similar strain measurement systems have been previously developed in other research labs, the standard DLT algorithm already exists and will be utilized and manipulated to fit the proposed design. Each algorithm is responsible for a different task, all relating to the final program which will determine and calculate the information desired. The main algorithm that calls all other functions is described in detail below.

2.3.2.1. Inflation Testing with Marker Technique and DLT Method
This MATLAB algorithm is the final step in the system, and functions as the post-processing data analysis tool. It compiles all of the information gathered through the testing and LabVIEW program and constructs 3D coordinates of each marker in each frame in order to determine strains and calculate stresses acting on the valve. More specifically, the program performs a 3D reconstruction with the DLT method for each marker, as well as performs a stress-strain analysis for the inflation test.

The algorithm can be divided into three steps, each utilizing several functions built in to the code. Five inputs are needed in order for the program to reach completion: (2) data files (one from each camera) obtained via LabVIEW of the marker coordinates during testing, (2) calibration cube data files of the calibration coordinates, which is used to reconstruct the 3D coordinates, and (1) data file containing the global coordinates of the calibration cube, which is also used to reconstruct the 3D coordinates. The first four files are obtained through LabVIEW, while the final global coordinate file must be user-input. Details of how each file is used will be described below.

The first step in the algorithm is opening and reading the text data files obtained through LabVIEW. The number of columns is dependent on the number of markers tracked and is irrelevant to the function of the system. Note that at the end of each file, there are three additional columns (the date, time, and pressure reading) that are separated from the data to be used later. This step is fairly straightforward. However, if any issues arose during the LabVIEW stage of the test, this first step will recognize it and output errors that must be corrected before analysis continues.

The algorithm inputs the information determined from the previous three MATLAB programs. The first is the rearranged 2D camera coordinates of the markers on the calibration cube from the two cameras.
used to capture the valve deformation. That information is the DLT coefficients calculated using the calibration cube and first MATLAB program. The second input is the rearranged 2D camera coordinates of the markers on the specimen. The second MATLAB program used was responsible for calculating each marker position on the valve. The third and final input is the 3D coordinates of the markers on the calibration cube. It is important to note that in order for the program to run successfully, at least six 3D marker coordinates must be input.

After the inputs go through the code, the program will output the 3D coordinates of each marker in all the frames, as well as the pressure-strain data. In addition, the program will generate plots, showing the movement of each marker on the valve.

### 2.3.2.2. Calculating the DLT Coefficient

The Direct Linear Transformation (DLT) method will be used in this design in order to analyze the heart valves. When using such an algorithm (as well as with any method) it is important to first calibrate the system to ensure accurate marker positioning on the specified plane. If the system was not calibrated, the data gathered could be inaccurate to the actual positioning of the valve and markers or inconsistent from trial to trial. Either outcome would produce an error-ridden analysis, which would be of no help to the improvement of heart valve design. Therefore, the first MATLAB algorithm used in the measurement system inputs the data from the calibration trial (using a pre-machined calibration cube), and calculates the DLT coefficients which will later be used in data analysis and reconstruction. It is important to notes that at least six (valid) calibration points are needed.

The matrix containing the global coordinates of the calibration frame will be input into the algorithm. In addition, a matrix containing the 2D coordinates of the calibration points seen via the camera as well as the points that are not visible in the camera (and are therefore not used to calculate the DLT coefficient) will be input into the program. Both of those data place the valve in a standard frame. Therefore, from trial to trial, it can be known that the data acquired is gathered from a calibrated, consistent frame. As previously mentioned, it is important to calibrate the system to ensure that the data collected is dependent solely on the valve deformation and not on an un-calibrated system.

After the data flows through the algorithm, the program will output 11 DLT coefficients as well as the average residuals (measure for fit of DLT), given in units of camera coordinates. That information will be later input into another MATLAB algorithm, to, once again, ensure calibration from trial to trial.

### 2.3.2.3. Markers

The next MATLAB algorithm that will be used to analyze the gathered data from the testing is responsible for keeping track of which marker is which, from one frame to the next—calculate the placement of each marker in relation to the marker next to it. Specifically, the program will calculate the position of the marker in RC (the coordinates of all the makers in one row) which has the nearest distance from M (the coordinates of the marker in the next row). Both RC and M are input into the program from LabVIEW.

After flowing through the program, the algorithm will output the position of the marker which has the nearest distance from the coordinates of the marker in the next row. Or in general terms, the program
will output the position of each marker in relation to the other markers. Not only is that important in the actual strain analysis and stress calculations, but it also keeps track of which marker is which from one frame to the next. Therefore, the data will remain clear and organized.

2.3.2.4. Reconstruction of 3D Coordinates

After the system is calibrated (with the DLT coefficients being calculated) and the marker positions are known, the data will be further analyzed in a third MATLAB program. This program is responsible for reconstructing the 3D coordinates (camera coordinates and the DLT coefficients for the two cameras) in order to observe the heart valve deformations.

The DLT coefficients will be input into the algorithm to ensure calibration. In addition, the camera coordinates of the maker points (gathered in the second MATLAB algorithm), will also be input. After the program reaches completion, the global coordinates, residuals, and cameras used will all be output. This program, as well as the previous two algorithms, is imperative for the heart valve analysis due to the foundational information it outputs. Alone, each of the programs tells the user very little about the behavior or the heart valve during the static and dynamic loading conditions. However, when input into the fourth and final MATLAB algorithm, the data gathered from the previous three programs will serve to aid in determining strain and calculating stress.

2.3.2.5. Inflation Testing with Marker Technique and DLT Method

This fourth MATLAB algorithm is the final step in the designed system, and is a post-processing data analysis. It takes all of the information gathered and relates it in order to determine strain and calculate stress. Specifically, the program performs a 3D reconstruction with the DLT method for each marker, as well as performs a stress-strain analysis for the inflation test.

The algorithm inputs the information determined from the previous three MATLAB programs. The first is the rearranged 2D camera coordinates of the markers on the calibration cube from the two cameras used to capture the valve deformation. That information is the DLT coefficients calculated using the calibration cube and first MATLAB program. The second input is the rearranged 2D camera coordinates of the markers on the specimen. The second MATLAB program used was responsible for calculating each marker position on the valve. The third and final input is the 3D coordinates of the markers on the calibration cube. It is important to note that in order for the program to run successfully, at least six 3D marker coordinates must be input.

After the inputs go through the code, the program will output the 3D coordinates of each marker in all the frames, as well as the pressure-strain data. In addition, the program will generate plots, showing the movement of each marker on the valve.

2.3.3. LabVIEW Programming

2.3.3.1. Image Acquisition

LabVIEW was used to build three programs; one to acquire the images and create a video file, another to analyze that video, and a third to ensure that the markers from both cameras were in the same order. The entire first program resides within a two-framed sequence structure, the first of which is used to
acquire the video, and the second is used to review the video before using the second program to analyze it. The first part begins by using the ‘IMAQ Init’ and ‘IMAQ Create’ VI’s to initialize the creation of the video file. The ‘IMAQ Init’ VI creates an ‘IMAQ Session’ data type. It also allows the image type to be set. The ‘IMAQ Create’ VI creates a temporary memory location for the image to be operated on, and allows the image type to be set. For this project the image type was set at Grayscale (U8) meaning that each pixel has 8 unsigned bits per pixel. The VI ‘IMAQ AVI Create’ is used to set other parameters for the AVI file creation. The frames per second are set at 30, while the max data size and quality are user-controllable from the front panel. A True Boolean constant is wired to the ‘Has Data’ terminal of the ‘IMAQ AVI Create’ VI so that time and pressure data can be added to the image using the ‘IMAQ AVI Write Frame’ VI (which will later be used for analysis). The user also designates the file path to save the AVI file to, and the ‘IMAQ AVI Create’ VI outputs an AVI refnum as a reference to the AVI file created. This procedure is done in parallel for both cameras, but the output errors are merged and split at this point so that if there is an error with either video files both parallel processes know it and can handle it. A while loop containing the code to write the images to the file is wired to stop if either the error or button labeled as “Stop Recording” outputs a true Boolean value. This is done by wiring both the “Stop Recording” button and the error status into a ‘Not Or’ operator, which outputs to a ‘Continue if True’ Loop Condition. The image and data is added to each frame using the ‘IMAQ AVI write frame’ VI. The ‘Get Date/Time’ function is used to produce separate abbreviated date and time stamp strings which are concatenated into a single string and fed into the ‘Data’ terminal in the ‘IMAQ AVI write frame’ VI. The code uses a DAQmx Read VI to acquire real-time pressure transducer information which is added to the inputted data. The transducer voltage read from the DAQ will be operated on according to an equation that takes into account calibration values (user-inputted) to calculate the pressure in mmHg. The while loop continues to acquire images from the cameras and write them to the AVI file until there is an error or the ‘Stop Recording’ button is pressed on the front panel.

At this point the errors are merged and split again for reasons explained before. The merged error is sent through a shift register, which stores the error information and is read on the next iteration of the while loop. Once the while loop has been stopped, the ‘IMAQ Close’ and ‘IMAQ AVI Close’ VI’s are used to close the ‘IMAQ Session’ and the AVI file. The ‘IMAQ Dispose’ VI destroys the ‘new image’ data sent out from the ‘IMAQ Create’ VI that was operated on by the other programs, releasing the information from memory. After this is all done, the last part of the program lets the user review the AVI file. The user is able to select which frame to review using a sliding scale. The range on the scale is changed using a property node with a ‘Write’ terminal for the ‘Maximum’ property. The input to this comes from the ‘IMAQ Get AVI Info’ VI which received the refnum from the ‘IMAQ AVI Open’ VI and outputs the number of frames in the file. The ‘IMAQ AVI Open’ VI has the path of the saved AVI file as an input and outputs the refnum for the file. The ‘IMAQ Create’ VI creates a temporary memory location for the image, which is sent to the ‘IMAQ AVI Read Frame’ VI. This VI also receives the refnum from the ‘IMAQ AVI Open’ VI and the user-controllable scale selects the frame to examine which is wired to the ‘Frame Number’ terminal. The reading VI outputs the image of the frame, which is displayed on the front panel. The string data is unflattened using the ‘Unflatten From String’ function and is displayed along with the frame image. The displayed image and data is updated every five milliseconds by using a case structure and a surrounding while loop. The case structure executes the previously described code to display the
image and data if the ‘Frame and Data to Examine’ scale was different from the previous iteration of the while loop. That is, the ‘True’ case contains the code, while the ‘False’ case contains simply a ‘Wait (ms)’ function. If the User changes the value on the scale during an iteration of the while loop, then the value will be stored in the shift register and be different from the previous iteration and the ‘Not Equal?’ operator outputs a true Boolean value to the Case Selector. A separate stop button is wired to the Stop if True Loop Condition for this while loop for when the user wants to stop reviewing the file. When the while loop is stopped, it outputs the AVI refnum and IMAQ image data to the ‘IMAQ AVI Close’ and ‘IMAQ Dispose’ VI’s, respectively. This is the end of the first program. At this point the AVI file has been created and reviewed, and now the second program can analyze the file.

### 2.3.3.1. Image Analysis

The second program is used for computing the coordinates of the markers placed on the heart valve leaflets for each frame. It analyzes one AVI file at a time, and starts by opening the AVI file created previously by the first LabVIEW program. First, ‘IMAQ Create’ creates a temporary memory location for the image, and ‘IMAQ AVI Open’ opens the desired file, the path of which is selected by the user (and should be the path used to save the file using the first LabVIEW program). The entire rest of the program is contained in a Flat Sequence Structure within a while loop. After the last frame is executed it outputs a True Boolean constant to the while loop’s conditional terminal, ending the program, so the program stops automatically once all analysis has been completed. The first frame in the main sequence structure is used to ensure the program is operating within the desired bounding rectangle and has detected the right number of markers, and that no artifacts or other objects are being recognized as markers. The coding of the first frame operates within a while loop which ends when the button labeled ‘Start’ is pushed, indicating that the user is satisfied with the current marker readings and is ready for the program to begin analysis. Within the while loop is a two-framed sequence structure. The first frame in this sequence structure first acquires the frame of the AVI file using the ‘IMAQ AVI Read Frame’ to be used to adjust the marker detection settings. The user can switch between frames by adjusting the ‘Frame Number’ slide control. The resulting image can have a threshold applied if the user desires. A case structure with a ‘Raw/Threshold’ switch wired to the case selector contains the code to apply a threshold. If the user selects raw, the data is not operated on and simply output to the other side, but if the user selects threshold, the ‘IMAQ Threshold’ VI operates on the image. The threshold should be applied if the user desires optimal contrast between the darker and lighter areas of the frame by replacing pixels of certain darkness with purely white pixels which will not be read by the marker counter. The user selects the minimum pixel value (i.e. the darkest pixel shade) that will be operated on using a scale, and the maximum is set at 255 (white). These values are bundled and input into the ‘Range’ terminal of the ‘IMAQ Threshold’ VI. A constant of ‘255’ is wired to the ‘Replace Value’ terminal, meaning that any pixel with a value that falls within the set range will be replaced by a white pixel.

A central part of this program is the ‘IMAQ Count Objects’ VI. It not only counts how many markers there are based on desired settings, it also outputs information about those objects, such as their center XY coordinates, areas, and bounding box coordinates. A cluster of four values is wired to the ‘Search Rect’ terminal, which designates the coordinates for the sides of the rectangle to be searched. It is controlled from the front panel and the values represent the Y coordinates for the top and bottom sides,
as well as the X coordinates for the left and right sides. A rather large cluster of settings is wired to the ‘Settings’ terminal. This cluster contains the settings for what kind of objects it is looking for, the threshold for the pixel value, the minimum and maximum size of the particle (in pixels) and other settings. The markers are black so ‘Dark Objects’ is selected, and a set value of ‘80’ is used for the threshold. The minimum and maximum size of the markers can be adjusted based on what size range of markers used. If this range can be minimized, then this will further reduce the chances of the object counter falsely recognizing extra markers. The object counter overlays the searching rectangle onto the image, which is output to the ‘CAMERA 1’ display on the front panel. A for loop is used to process each element of the 1D array of clusters that the counter outputs. Each cluster contains information about each ‘object’, including information about the bounding box that immediately surrounds the edges of the object. Within the for loop is a ‘IMAQ Overlay Rectangle’ VI which overlays a rectangle around each marker according to the coordinates provided by the cluster. These coordinates can be changed by the user by using the ‘Left’, ‘Right’, ‘Top’, and ‘Bottom’ controls on the front panel. The ‘Number of Objects’ terminal is wired to a numeric indicator which displays the value on the front panel. If the thresholds and other settings are appropriate and all goes well, the right objects have been identified as markers and the correct number of markers is displayed. At this point the user may choose to start the second part of the program by clicking ‘Start’.

In the second frame of the main sequence structure a memory location for the ‘Final Image’ is simply created using the ‘IMAQ Create’ VI. The remaining code lies within a For Loop which executes for each frame. The user specifies how many frames to analyze, starting with the frame number chosen with the ‘Frame Number’ control. The iteration count is acquired from the iteration terminal and is wired to the ‘Frame Number’ terminal of the ‘IMAQ AVI Read Frame’ VI so that for each iteration of the loop a different frame is analyzed. Similar coding to what was used previously is used to apply a threshold to the frame if desired. To ensure that no markers are lost or gained, and that they are written to the spreadsheet file in the same order for each frame, the center coordinates from the first analyzed frame are compared to the center coordinates in the next frame. This continues, with the center coordinates from the third frame being compared with those in the second frame and so on. The Cluster output by the Object Counter is unbundled to extract the ‘Object Center’ data which is further unbundled in to the ‘X’ and ‘Y’ coordinates. This happens within a for loop which runs ‘Number of Objects’ times, i.e. for each marker. Within that for loop there is another nested for loop. In the outer for loop the cluster from the previous frame is unpacked to expose the coordinates, which are fed into the nested for loop. In the inner for loop, the data from the current frame is compared to the data from the previous frame. This is done with a pair of ‘In Range and Coerce’ operators, which return a T or F value depending on whether the input is within set parameters. The inputs in this case are the X and Y coordinates from the current frame, and the upper and lower limits are determined by the coordinates from the previous frame. A parameter called ‘Flexibility’, set by the user, indicates how much to add and subtract from the previous frame’s coordinates, effectively determining how big of a square the program should accept the marker’s center within. If both the X and Y coordinates are within the limits and it isn’t the last object of the current frame, the for loop’s conditional terminal is triggered and the coordinates are output to both the auto-indexing terminals on the outer for loop (which is collecting data to be written to the spreadsheet file) and are bundled into the current frame’s cluster. This cluster is then auto-
indexed out of the inner for loop and sent back to the next iteration of the outer for loop through a shift register, to be used as the ‘previous frame’ cluster for the next iteration. If, however, the inner for loop reaches it’s final marker to check and still didn’t it up with the markers from the previous frame, a ‘-1’ constant is instead sent to the data to be written to the spreadsheet file (to indicate the marker it could not be found, as a placeholder), and the coordinates from the previous frame are instead bundled to be used again in the next iteration, in case the marker re-appears in the same area due to a change of lighting or some other factors. Note that since it is not searching for markers that didn’t exist in the previous frame, it will never write data for additional markers, but it is possible to lose a marker because of the lack of contrast, or perhaps if the marker center moved out of the range determined by the ‘Flexibility’ parameter. In that case the parameter should be increased, but this comes with the risk that a different marker that happened to move into the space will be mistaken for the original marker.

A 1D Array of strings is written to the spreadsheet file for each frame analyzed. The array includes X and Y center coordinate values for each marker, the frame number, and the data previously added to the image using the first program (pressure and time/date stamp). The data is extracted from the frame using the ‘IMAQ AVI Read Frame’ VI and unflattened and unbundled using the ‘Unflatten From String’ and ‘Unbundle’ operators. All of these values are converted into strings using the ‘Number to Fractional String’ operator which converts them into fractional-notation, floating-point strings.

The third program, deemed the ‘Corresponding Markers’ VI, ensures that the markers are in the same order for both cameras. Since each camera has a slightly different perspective, one of them may have chosen a certain marker as the first marker, and the other may have chosen a different one. For this reason the spreadsheet file for one of them needs to be reorganized. In this program the order in the first array is kept constant to be used as a reference, and reorders the columns in the second array so that the first column in both arrays are data from the same physical marker, and so on. To do this, the program first splits the arrays in half, width-wise (to separate into X and Y portions) and goes through a few For-loops to index them. Before entering the For-loops, each array is indexed to output only the top row, as this will be used as the guideline for determining which marker corresponds to which. Then, a relative ‘min/max’ position for each marker is determined. This is done by taking the min/max of the first rows and then seeing how far along the range between the min and the max it is. This is used as the comparison tool, since the min/maxes of each coordinate frame will be different, but the relative distances of the markers from the boundaries should be similar. The user inputs a ‘percent give’ that indicates how lenient the program is when determining whether two markers match up. It compares both the X and Y coordinates, and both ‘relative positions’ for each must match in order to be accepted. When accepted, the for loop indexes the entire column from the original arrays (the column corresponding to the index of the tested marker in the row), and compiles them outside the for loop. This way they are put in proper order. One thing to note is that the ‘percent give’ input by the user will need to be fine-tuned, and depend on how close the markers are relative to the total size of the bounding area. Similarly to the second program, this program writes a ‘-1’ if the corresponding marker can not be found. This program will only work assuming that the two cameras are even in level and twist, because if the markers are not similarly spaced from the edges in both cameras, it will not recognize them as the same. The program
only uses data from the first frame because it is assumed that the analysis LabVIEW program properly kept the data for each point in their respective columns using the technique described above.

This analysis program must be run individually for each file from the two cameras, as well as for the calibration cube files, and will create one spreadsheet file for each. Then the ‘corresponding markers’ program must be run to reorder the file from the second camera (for both the marker video and calibration cube video). Each of these files will be then be used together in the MATLAB programs to reconstruct the 3D coordinates of the system, and to do further analysis of the data. Below are screenshots of the front panel and block diagrams of the three VI’s. There is some code that was not explained and that is because it is for debugging purposes. The block diagrams are broken up into several screenshots because they are larger than the size of the screen.

**Figure 3: Front Panel for Acquisition Program**

![Front Panel for Acquisition Program](image_url)
Figures 4-3: Block Diagram for Acquisition Program
A System to Quantify 3D Spatial Deformation of Heart Valve Leaflets

Figure 4: Front Panel for Analysis Program

Figures 5-8: Block Diagram for Analysis Program
A System to Quantify 3D Spatial Deformation of Heart Valve Leaflets

Team 8: 25
Figure 9: Front Panel for Corresponding Program
Figures 10-11: Block Diagram for Corresponding Program
3. **Realistic Constraints**

With any measurement system, there is some level of constraint in the accuracy and precision of the data gathered and results calculated. Since this measurement system was developed to test heart valves *in vitro*, the goal was for the system to yield results as close to *in vivo* testing conditions as possible. However, *in vivo* conditions include many more advanced aspects than the *in vitro* system designed. For example, the measurement system developed includes a single bioprosthetic heart valve only, mounted to a rigid polycarbonate plate via suturing. However, when implanted into a patient, the valve is secured to biological tissue in the heart which is a very different and less rigid material. Additionally, other tissues and mechanisms, such as the aortic root (aortic valves), chordae (mitral valves), cardiac muscle, and the heart as a whole, all act in unison with the valve during a normal rhythm. Such conditions are not included in the design, and therefore, cannot be taken into consideration during testing. However, the goal of the system is to measure the deformation of valve leaflets, not the valve in relation to the heart as a whole. Therefore, for all intents and purposes, the system will accurately measure the desired objective—the deformational behavior of the heart valve leaflets—which should ideally behaves similarly under both the developed *in vitro* conditions and typical *in vivo* conditions.

Realistically, acquiring data with this system during valve testing holds the most constraints. Firstly, the way in which the valves are mounted into the device—via suturing—will inevitably result in slight leakage of both the saline solution and pressure, whereas when the valve is implanted into the patient, the surrounding tissue typically creates a seal at said suture points. However, since the apparatus does not include surrounding tissue to help create a tight seal, the mounting plates were designed and constructed in a precise manner in order to reduce such an outcome of leakage.

Along the same lines, leakage is possible at other areas of the device. Since the system was designed to house replaceable mounting plates (in order to account for the different valve geometries and sizes), as well as with a removable lid to gain access into the housing apparatus, areas where both saline and pressure can leak are created. However, in order to account for such constraints, tight seals were designed. Not only do the pieces have a tight fit together, but additional rubber sheets were added between the polycarbonate to create an even tighter seal. Other areas where leakage could occur are at the holes created to house the hand pump to create pressure, borescopes, and the pump used during dynamic loading. To account for those constraints, precise drilling and rubber seals were added. Since each test is over a short period of time (of only a couple of seconds), the steps taken to reduce leaking were shown to be successful.

Error has also been associated with the graphite marker technique used. About 60-90 markers will be super-glued to a leaflet area comparable to the size of a human thumbnail. Imaging of the markers in such a small area requires meticulous care in the digitalization process. If the placement of the centroid of a marker is off by even a single pixel, error will occur in the strain data, and consequently, the stress data and 3D reconstruction. Picture clarity issues are also expected. For example, as the leaflets...
deform, they may go out of focus from the cameras, which will lead to LabView imaging error, causing errors in the analysis that follows.

Time has also been proven to be a realistic constraint during the development of the apparatus. Specifically, the testing of different heart valve geometries and sizes is limited to the mounting plates constructed. The system was developed for the most common valves (per the client’s recommendation). However, there are a large number of valves that are not accounted for. The limitation is due to the fact that specific mounting plates need to be developed for each specific valve geometry and size. If one wanted to construct mounting plates for every type of valve on the market, a great deal of time would have to be devoted to doing such. However, one of the advantages of this design, is that the mounting post can house virtually any mounting plate designed for the system. So although plates for only the most common valve geometries and sizes were developed, if a future engineer desires to analyze other valves, he/she is able to use the device by simply constructing a mounting plate for the said valve.

4. Safety Issues

Although this system has very few safety concerns, the user must still take caution while operating the device. Contamination to both the user and tissue sample increases when improper precautions are taken. Injury could also occur with inappropriate use.

One area of caution is related to the actual bioprosthetic heart valve that is to be tested. With any biological tissue, precaution should be used while handling the tissue. It is recommended for gloves to be worn to avoid contamination of and reduce bacterial, viral, or toxic transfer to and/from both the valve and the user. Additionally, one should avoid contact with eyes, nose, mouth, and other orifices as well as open skin areas once the tissue sample and/or saline solution are handled. Also regarding the handling of the bioprosthetic heart valves, while suturing the valve to the mounting plates, one should be sure to take their time so as to not puncture the skin and/or glove with the sharp needle. Such punctures increase the chance of contamination to/from both the user as well as the sample, making them more receptive to bacteria and/or toxins.

Assembling the system is another area where proper precautions should be taken. When securing both the mounting plates and lid onto the system, it is important for the user to secure the wing nuts onto the bolts slowly and precisely. Although uncommon, the user could pinch their glove and/or skin in the wing nut, which could create areas of contamination and injury. In addition, if the wing nut is not aligned onto the bolt correctly, there is the potential to damage/strip the bolt, forcing the part to be replaced.

While running the system, one should take precaution when dealing with the physical apparatus and computer hardware. It is important for the user to be aware that the system is filled with a saline solution. Since salt ions conduct electrons, the solution will conduct electrical currents easily. Therefore, since the system utilizes both the saline solution as well as electrical equipment (i.e., CCD cameras, light bulbs, power cords, transducers, etc.), there is always the risk of electrical shock if used
incorrectly. Not only could electric shock injure the user, but it could also cause shortages and damage to the apparatus. In addition, improper use of the electrical equipment could cause sparks, which consequently could result in damage not limited to melting, burning, and fire. Therefore, it is important for the user to constantly check and ensure that all wires and devices are encased and positioned properly to avoid such an outcome.

Finally, the apparatus should always be lifted from the bottom and not the sides or top ledge to avoid cracks, breaks, or dropping the system.

5. Impact of Engineering Solutions

Many studies have been conducted that show that the regions of tearing of bovine heart valves (BHV) correlate to the regions of high tensile and bending stresses acting on the leaflets during leaflet opening and closing. Stress concentrations within the cusp have been shown to both directly accelerate tissue structural fatigue damage and/or initiate calcification, both of which ultimately lead to failure. Although the details remain unclear, it is widely accepted that a valve design that results in lower stress concentrations on the leaflets will likely yield improved performance in long-term applications. The developed system allows for behavioral, mathematical, and visual examination of heart valves and the stresses and strains acting upon the leaflets. Such information will surely aid with the development of better functioning and longer-lasting valves.

The measurement device developed will have a major impact on both Biomedical Engineering as well as Health Care in general. Prosthetic heart valves are becoming increasingly more in demand with the rise in cardiovascular disease. However, with each valve design remains major flaws and mechanical issues, which all lead to failure. Many times, the patient receiving the prosthetic valve will outlive their replacement, and will need to undergo another procedure to a.) remove the failed valve and b.) to replace it with a new, functioning one. Also, with prosthetic heart valves, many patients feel a decrease in their quality of life due to their inability to live life as they previously may have. They will be required to be on medications for the rest of their life, and oftentimes, patients’ activity decreases. With that in mind, research about prosthetic heart valves is a very competitive field. Any design improvement will lead to the advancement of prosthetic heart valves, not only making the field of biomedical engineering stronger and more successful, but improving the quality of life for many patients.

The measurement device developed allows for prosthetic valve testing in an in vitro environment versus testing after implantation in an in vivo environment. Not only does that enable more testing to be done, it is easier and requires less due to the fact that there is no longer a patient involved. With more testing, more flaws can be determined, leading to further advancement in heart valve design. In addition, the more one knows about the mechanical behavior, the closer the design can become to an original valve, leading to better performance.
6. **Lifelong Learning**

Through the development process, our design team has gained extensive knowledge about heart valves and how they function. Knowing that information has led to the development of a successful measurement system. It is very important to be able to connect the background knowledge about the tested material to the testing device in order to obtain accurate and productive results.

In addition, our team has gain knowledge about testing mechanisms including dynamic loading, closed-loop systems, heart valve mounting, pressure transducers, borescopes, and DLT algorithms. Exposure to design, manufacturing, and coding is very important, and has made our team stronger and more knowledgeable engineers.

Also, when our team enters the industry, experience working in a team is a very useful thing, and can be the making point in a career. Engineers need to be able to work with others and successfully get their ideas across to other people in order to be productive. There is no use for an engineer that cannot work with other people nor relay their ideas. Therefore, the entire team experience is an important tool that our team can take from this project.

7. **Budget and Timeline**

7.1. **Budget**

For this design project, the Biomedical Engineering Department at the University of Connecticut allotted a $1,000.00 budget for this design. However, since the system will be utilized by one of Dr. Sun’s graduate assistants for research purposes, Dr. Sun wanted the system to be developed without monetary constraints, and therefore, allotted the team with the funds necessary (within reason) to complete the design. Features such as the two borescopes put the team well out of the BME department’s budget, and could not have been purchased without the additional funds provided by Dr. Sun. The final budget for the apparatus is outlined in Table 1.

<table>
<thead>
<tr>
<th>eStreet Plastics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QTY</strong></td>
</tr>
<tr>
<td>12&quot; x 48&quot; Clear Polycarbonate Lexan Sheet 3/8&quot; Thick</td>
</tr>
<tr>
<td>9&quot; x 18&quot; Clear Polycarbonate Lexan Sheet 1/2&quot; Thick</td>
</tr>
<tr>
<td>3&quot; OD x 2 3/4&quot; ID x 23 7/8&quot; Long Clear</td>
</tr>
</tbody>
</table>

Table 1. Final Budget
As can be observed, most of the budget went into purchasing the borescopes and borescope adaptors. However, in order to see success with the system, those features were imperative. It should also be
noted that the borescopes are removable from the system, and therefore, can be used in future projects and testing.

### 7.2. Timeline

Over winter break we will be focusing on finishing research for our individual focuses, which are outlined in section 8. It is our goal to start getting hands on experience with testing as soon as we get back. This means that the physical apparatus will be assembled in the first two weeks, while the LabVIEW and MATLAB programming is tested and altered using markers on paper, or other deformable objects. During the third week we will be trying our first static testing. We are expecting a lot of problems and errors to arise, as this is a learning experience, so the third week will be devoted to debugging the programs and making any necessary alterations to the apparatus. The fourth week will follow the same process, but with dynamic loading conditions. The rest of the semester will be devoted to testing different valves and modifying various aspects of the system as seen fit. A more detailed timeline can be found below in figure 17.

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purchase parts</strong></td>
<td></td>
</tr>
<tr>
<td>Assemble fluid chamber walls</td>
<td>1 hr</td>
</tr>
<tr>
<td>Attach connection A</td>
<td>10 mins</td>
</tr>
<tr>
<td>Attach connection B</td>
<td>10 mins</td>
</tr>
<tr>
<td>Attach connection C</td>
<td>10 mins</td>
</tr>
<tr>
<td>Attach mounting post</td>
<td>10 mins</td>
</tr>
<tr>
<td>Create lid system</td>
<td>20 mins</td>
</tr>
<tr>
<td>Assemble mounting plate</td>
<td>1 hr?</td>
</tr>
<tr>
<td>Insert borescope holes</td>
<td>10 mins</td>
</tr>
<tr>
<td>Place marks on valve leaflet</td>
<td>30 mins</td>
</tr>
<tr>
<td>Suture valve to mounting plate</td>
<td>10 mins</td>
</tr>
<tr>
<td>Attach mounting plate to mounting post</td>
<td>5 mins</td>
</tr>
<tr>
<td>Calibrate system</td>
<td>20 mins</td>
</tr>
<tr>
<td>Finish understanding programs</td>
<td>2 hrs</td>
</tr>
<tr>
<td>Modify aesthetics</td>
<td>1 hr</td>
</tr>
<tr>
<td>Modify data to be input/equations</td>
<td>1 hr</td>
</tr>
<tr>
<td>Test tracking system with calibration cube</td>
<td>2 hrs</td>
</tr>
<tr>
<td>Test paper with many markers and modify program if needed</td>
<td>3 hrs</td>
</tr>
<tr>
<td>Test with flexible tissue</td>
<td>3 hrs</td>
</tr>
<tr>
<td>Debugging/modifying</td>
<td>5 hrs?</td>
</tr>
<tr>
<td>Analyze MATLAB programs</td>
<td>4 hrs</td>
</tr>
<tr>
<td>Understand the DLT coefficients and how they relate to the measuring of the heart valve</td>
<td>1 hr</td>
</tr>
<tr>
<td>Gather an array of DLT coefficients in order to get a consistent calibration</td>
<td>1 hr</td>
</tr>
<tr>
<td>Work on the coding of the second algorithm in order to apply it to the marker system that is decided for the project</td>
<td>3 hrs</td>
</tr>
</tbody>
</table>
Need to change the code to take into account many more markers (up to 90) than what the code was previously written for (15)

Need to ensure that the code will be successful even when the markers are not laid in a uniform pattern
Work with the third program (reconstruction)
   Make sure that it properly inputs the information from the first two algorithms that were previously altered

Make sure that the program reads the heart valve deformations properly, accounting for 3D movements
Make sure that the fourth algorithm works properly after changing the other three algorithms
   Proper and consistent stress-strain data

Analyze the expected behavior
(Optional—if time allows): Develop an Abaqus program that uses the calculated data from the fourth algorithm to show the behavior of the tested valve

8. **Team Member Contributions to the Project**

8.1. **Group Collaboration**
During the research and development phases of the strain measurement system, the majority of the aspects were comprised of team collaboration. Therefore, the final design of the system including its function and specifications was developed as a team. However, the production of the design was divided into three sections—physical apparatus, LabVIEW programming, and MatLab programming—in order to work to implement our design more efficiently. Each member took lead of one of the three sections.

8.2. **Michael Hahn**
Michael was the lead regarding the physical apparatus. He was responsible for all aspects of the physical system including size, mounting, and versatility (i.e., removable lid, interchangeable mounting plates, etc.). The final design including all of its features was approved by Michael. Along the same lines, the materials selected to build the system, as well as the techniques used to construct it were all Michael’s responsibility. In addition, the design of the mounting plates was also Mike’s responsibility. Michael worked extensively in the Machine Shop, designing and building the apparatus.

Once testing began, Michael was also responsible for finding solutions to problems that arose. When saline and pressure leakage occurred at specific areas in the system, Michael researched and implemented the rubber layer between removable parts.

8.3. **Elizabeth Morgan**
Elizabeth’s efforts were focused on the MatLab aspect of the design. She was responsible for understanding every line of code provided to the group in order to fit our design to the code as well as fit the code to the design; she had to make decisions about what areas should be changed versus what
areas the design should be changed to. For example, the MatLab algorithm opens and reads data files formatted in a specific way, with three non-coordinate files at the end of the data set (i.e., the time, date, and pressure reading). The algorithm is written to disregard the last three columns in the initial analysis stages. Therefore, Elizabeth made the format known and opened discussion about whether LabVIEW should format to MatLab or MatLab be changed to the LabVIEW format.

In addition, Elizabeth opened communication with Avizio engineers, beginning work on a 3D finite element model of the tested valves. Although that aspect of the project was not seen to the end, the work that was initiated regarding Avizio surely helps future engineers using the system to implement the modeling feature.

Finally, Elizabeth was the lead regarding all required technical documents. She wrote a detailed preliminarily skeleton of each document, sending to the other group members instructions on what is required for each section. Elizabeth was also responsible for the final editing of reports, presentations, and manuals.

8.4. Oskar Perskaas

Oskar was responsible for the LabVIEW aspect of the design, including fitting the algorithm to the system as well as making sure it was compatible with both the physical apparatus and MatLab program.

Oskar was responsible for coding the LabVIEW programs and ensuring their seamless integration into the project. He worked to understand new subVIs that were used for image acquisition and analysis. His time was spent analyzing previously written programs and learning to understand them so he was able to modify them so they were tailored for the needs of the project. After modifying the programs he ensured that they worked for the purposes of the project including successful tracking of all the markers with proper calibration.

Oskar was also responsible for the two borescopes, including ideal mounting and proper function and connection with the LabVIEW VIs.

9. Conclusion

In conclusion, a functioning strain measurement system was designed and developed with the purpose of analyzing the mechanical behavior of bioprosthetic heart valve leaflets. Artificial heart valves save thousands of lives every year, and therefore, the design of such devices is important to understand and perfect. However, relatively little knowledge and information about the effects of strain and stress on bioprosthetic heart valve leaflets is known. Given the commonality and severity of valve failure, op top of the number of people who rely on heart valve replacements, creating a system that can ultimately lead to optimal valve design is crucial. The goal of the design presented was to develop such a system to test such valves under variable loading conditions. The final design developed includes a single apparatus that can be used to test both static and dynamic loading conditions. During such loading, two CCD cameras are used to track the graphite markers superglued to the valve leaflets as they deform under pressure. The cameras are connected to a LabVIEW VI that tracks and creates a 2D coordinate
table for each marker for each camera. Using a DLT algorithm in MatLab, the tables are then converted into 3D coordinates for use to measure strain and calculate stress at points all along the leaflets. Using that process, a tester is now able to evaluate different heart valves.

Although the system is functioning, it can still use a great deal of developing and perfecting. However, such improvements are easily obtainable and compatible with the system.

10. Acknowledgements

Our team would like to acknowledge several people who have been continual help and support to our project. Firstly, Dr. Wei Sun, our client and sponsor, has been our guidance and lead on the project. His input has helped with both the design and development of the strain measurement system. Additionally, Kewei Li, a graduate student at the University of Connecticut working in Dr. Sun’s Biomechanics lab, has been an exceptional and imperative resource throughout the entire process. Not only has his knowledge about the subject been a great asset, but the LabView and MATLAB code that he supplied to the team became the backbone to the design.

Our team would also like to thank Pete and Serge in the machine shop for their advice, recommendations, and huge help during the construction process. In addition, we would like to thank Mike Marsh, Ph.D., the Applications Engineering in the VSG-Visualization Sciences Group at Avizo for his help regarding the 3D visualization of the heart valve leaflets.

Dr. Enderle and Emily Jacobs both also deserve acknowledgements for the opportunity to design such a project, as well as their continual advice and support throughout the entire process.

And finally, thank you Jen Desrosiers, the Program Assistant II/Office Manager and Kerri Wenzler, the Administrative Specialist in the BME office for dealing with the constant purchase orders and deliveries.

11. References


12. Appendix

12.1. Updated Specifications

12.1.1. Operational Specifications:
The strain measurement system should consist of a fluid chamber that houses a bioprosthetic heart valve, an optical strain measurement system to capture 3D leaflet cusp deformations under a variety of hydrostatic loading conditions, and a pressure transducer that simultaneously measures the transvalvular pressure. The apparatus should allow for at least the most common heart valve sizes to be tested. The system should be computer-controlled with automatic data visualization and analysis. 3D motion of the leaflets should also be numerically reconstructed. The accuracy of the strain measurement should be determined and validated.

12.1.2. Technical Specifications:

Physical:
Type of Material: Transparent plastic or glass fluid chamber

Mechanical:
Fluid Chamber Size: 4 x 4 x 8 inches (L x W x H)
Fluid Chamber Weight: 2 pounds (lbs)
Mounting Post Size: 1.5 x 3 inches (D x H)
Mounting Plate Sizes: TBD

Environmental:
Operating Temperature: 20-25 ºC (room temperature)

Software:
User Interfaces: LabVIEW control panel
Programs: LabVIEW and Matlab
Features: -Automatic data visualization and analysis.
-3D motion of the leaflets numerically reconstructed.

Hardware:
Devices: Computer, monitor, 3 high-resolution cameras, rigid borescope (2.7 mm diameter x 175 mm length)

Computer Requirements:
Operating System: Windows 7/Vista/XP
Processor: Pentium 4
Memory: 512 MB of RAM

Maintenance:
Cleaning Method: TBD
### 12.2. Purchase Requisitions and Price Quotes

**PURCHASE ORDER REQUISITION - UCONN BME SENIOR DESIGN LAB**

*Instructions: Students are to fill out boxed areas with white background*

*Each Vendor will require a different purchase requisition*

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<td>Oskar Perskaas</td>
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Biomedical Engineering  
U-2247, 260 Glenbrook Road  
Storrs, CT 06269-2247 |
| Attn       | Oskar Perskaas |
| Project Name | Quantifying spatial deformation of heart valves |

**ONLY ONE COMPANY PER REQUISITION**

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**Vendor**: TAP Plastics

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**Phone**: 

**Contact Name**: 

**Shipping**: $14.23  

**Total**: $86.55