University of Victoria
Engineering & Computer Science Co-op
Work Term Report
Term – Fall 2020

Design and Analysis of a High Speed Camera Mount

Vivitro Labs Inc.
Research and Development
Victoria, British Columbia, Canada

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Work Term 4
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December 22, 2020

In partial fulfillment of the academic requirements of this co-op term

Supervisor's Approval: To be completed by Co-op Employer

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I approve the release of this report to the University of Victoria for evaluation purposes only.

Signature: Ian Chen Position: Engineering Manager Date: 12/22/2020

Name (print): Ian Chen E-Mail: _ichen@vivitrolabs.com____________

For (Company Name)____Vivitro Labs. Inc. ____

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December 22, 2020

Dear Meeta Khurana,

I am writing to present you with my fourth work term report titled "Design and Analysis of a High Speed Camera Mount" as a partial requirement in completing my Mechanical Engineering degree at the University of Victoria.

The Research and Development team at Vivitro Labs Inc. contributes to the development of cardiovascular medical devices by designing and improving testing equipment. Currently, Vivitro is developing a new accelerated wear tester for prosthetic heart valve durability testing. Since high speed video is an integral part of durability testing, a camera mounting system capable of being transferred quickly and precisely between systems required designing. I got the opportunity to design, assemble and test this prototype along with several other projects like the camera lighting prototype. From this testing, it was determined that my design met or exceeded most of the project objectives, but required some modifications to improve the stiffness and stability of the assembly.

Throughout my work term placement, I was given the opportunity to multitask and collaborate with talented engineers to solve difficult challenges. I was able to greatly improve my oral communication skills in a technical setting and gain exposure to new styles of project management. My experience with Vivitro has become one that I will carry with me to future jobs. I genuinely looked forward to work every morning of the semester.

I would like to take this moment to thank Karim, Ian, Joe, Blake, and everyone at Vivitro for providing me with an amazing experience full of opportunities for growth and learning. The eagerness to teach was evident and I could not be more thankful.

Sincerely,

Nigel Swab

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Summary

Vivitro Labs Inc. contributes to the health and wellness of patients with cardiovascular disease by developing cardiovascular medical device testing equipment and providing testing services. The Research and Development team is responsible for creating and improving testing device designs. Since high-speed video is required for prosthetic heart valve durability testing, a camera mounting system design was needed for the new Accelerated Wear Tester (AWT) currently being developed at Vivitro.

Three concept designs were created with SolidWorks, reviewed by the Research and Development team, along with Testing team, and compared with a weighted objectives chart. The chosen design was then refined, finalized for prototype production, and manufactured.

The cost of production for a run of 10 units came in at around 108 USD below the target production cost of 500 USD. During testing, it was confirmed that this design provided a quick and easy way of transferring the camera between units while consistently retaining relative positioning to the prosthetic heart valves. However, testing showed that the design vibrated undesirably at operating frequencies above 20 Hz, well below the maximum expected operating frequency of the AWT.

As a result, two recommendations were given to improve the stability of the design. The first suggestion, shortening the rod length, happened to integrate well with the design changes being made on the fluid system in parallel. The second suggestion involved finding vibration isolating feet with a stiffness of approximately 12,500 N/m to reduce noise and decrease the instability of the AWT.

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1. Background

Medical devices can be vital to the treatment of patients with cardiovascular disease and any failure can have life-altering consequences. Vivitro Labs is dedicated to reducing the risk to patients by developing cardiovascular device testing equipment, offering laboratory testing, and providing consulting services. The Research and Development (R&D) team is responsible for the design and testing of new products, along with improving existing products.

1.1 Prosthetic Heart Valve Durability Testing

Durability testing is one of the most inherently expensive and time-consuming processes of heart valve development. Testing must adhere to ISO 5840, an internationally recognized standard for prosthetic heart valve verification and validation. According to this standard, testing must be "performed to demonstrate with reasonable assurance that rigid heart valve substitutes will remain functional for 400 million cycles and that flexible heart valve substitutes will remain functional for 200 million cycles." [1]. 95% or more of these cycles must also meet defined differential pressures consistent with normotensive conditions for 5% or more of the cycle's duration [1]. Accelerated Wear Testers (AWT's) reduce the time and cost of this test.

1.2 Vivitro's Durability Tester

Although Vivitro currently sells an AWT, the HiCycle, design limitations and advances in the market have led to declining sales. As a result, the R&D team has been largely focused on designing a new heart valve AWT (Figure 1) over the past year. The base configuration of the AWT comprises of six physical testing units, one high speed camera, a controller, and a data acquisition box. This base configuration can also be customized to include more controllers and testing units as requested.

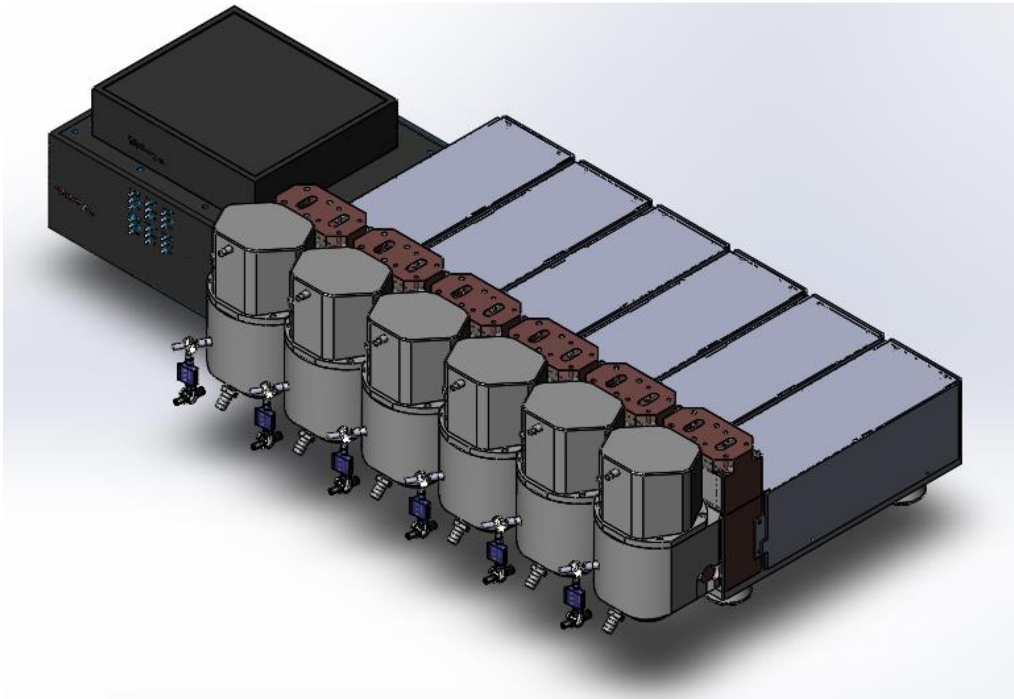


Figure 1: Preliminary AWT Base Configuration.

The new AWT provides customers the ability to accelerate durability testing and run valves at 300-2100 beat-per-minute (BPM), or 5-35 Hz. While it is capable of higher speeds, cycle frequency is often limited by the heart valve prosthetic; leaflet kinematics must be consistent with physiological operating conditions to properly fatigue the valve and identify failure modes and risks.

2. A Need for a High Speed Camera Mount

A high speed camera is used for several steps in durability testing, as outlined in Figure 2. First, high speed video is used to record the kinematics of the valve operating during more physiologically accurate conditions (such as those provided by the Vivitro Pulse Duplicator). This footage acts as a baseline for tuning the AWT and visually observing the effects of wear.

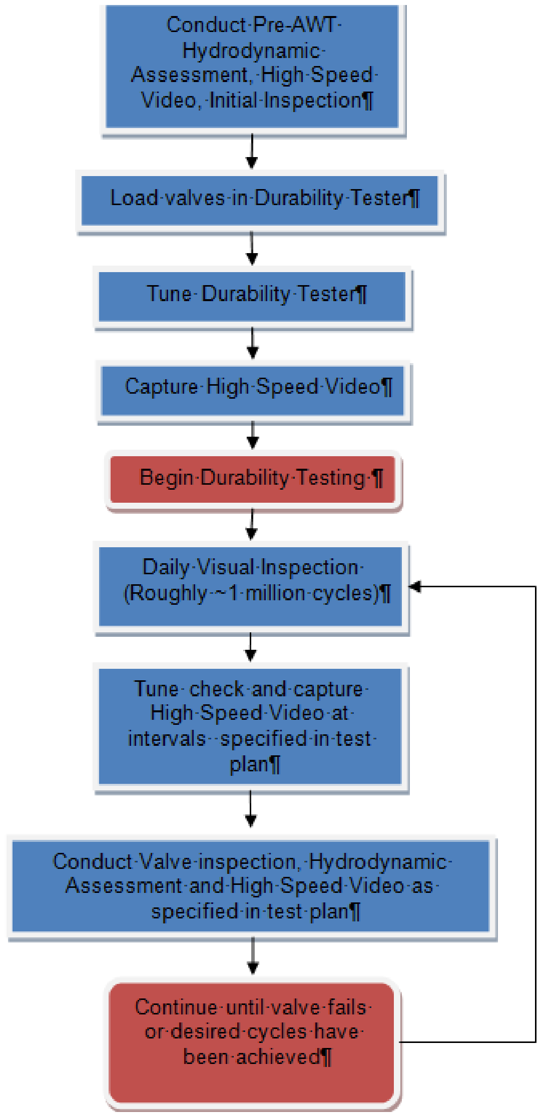


Figure 2: Outline of durability testing procedure [2].

Currently, all video recording done on the HiCycle uses a separate tripod, cart, or custom jig. As a result, capturing high speed video is a time-consuming and often frustrating process. To avoid having to go through the process of setting up a camera, expensive stroboscopes are often used for tuning and visual inspection in place of high speed video whenever video is not required to be captured. However, this requires specific lighting conditions and is much more difficult than using high speed video.

2.1 Purpose

To design a camera mount system that integrates with the new AWT architecture and remains stable under the oscillating forces caused by the system when in operation.

2.2 Aims

The camera mount must:

- Take less than one minute to remove and install between units
- Have enough vertical adjustability to account for varying valve dimensions
- Locate the camera relative to the valve consistently between units
- Be sufficiently stiff to retain camera position relative to the valve during AWT operation
- Cost less than 500 USD to produce at scale

2.3 Constraints and Considerations

The timeline of the AWT's release is very tight with little room for delays, and as such, development time is a large constraint in the design and development of the camera mounting. The new AWT is focused on maximizing valve visibility, therefore, all solutions must be designed with consideration for their impact on valve visibility. Additionally, durability testing is often done with a saline solution that is highly corrosive. Since spills are common during testing and setup, materials and fasteners must be resistant to corrosion. Lastly, since the majority of parts surrounding the valve are acrylic, any solution must consider the potential for scratching the AWT.

3. Preliminary Design and Analysis

Before beginning detailed design, it is important to brainstorm concepts and evaluate them objectively. This process should also include input from potential users whenever possible. Vivitro has the advantage of having direct access to their future users since their testing engineers and lab technicians use Vivitro equipment daily.

3.1 Preliminary Design Concepts

Several preliminary designs and approaches were taken before settling on three rough designs for review and discussion with the R&D and Testing teams. Two solutions rely on a clamped rod while one solution employs a linear stage. Each design was made with the intention of gaining feedback before working on a more detailed design.

3.1.1 Concept 1: Front Pillow Blocks with Quick-Release

The first concept, shown in Figure 3, utilizes two pillow blocks with a split that act as C-clamps to hold a rod 30° off of the longitudinal axis of the AWT to retain visibility. Vertical adjustments can be made by loosening the bolts on the pillow blocks and raising or lowering the height of rod.

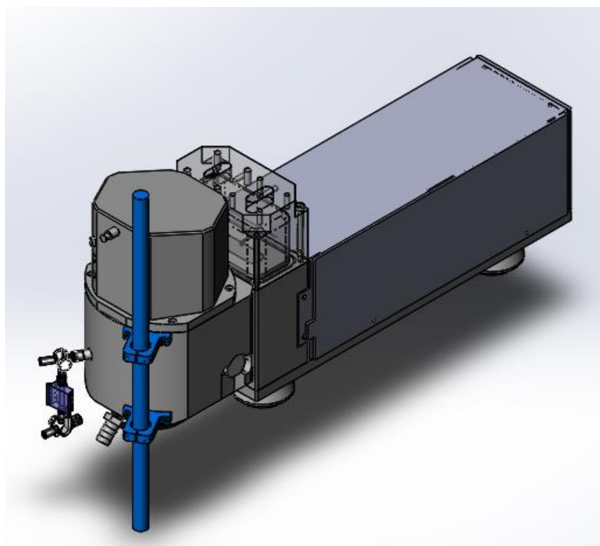


Figure 3: Concept 1 mock up.

For this concept, every testing unit would be fitted with a rod and pillow blocks. The camera would then be transferred between systems using a camera mounting system like the Kondor Blue Mini Quick Release (see Figure 4).

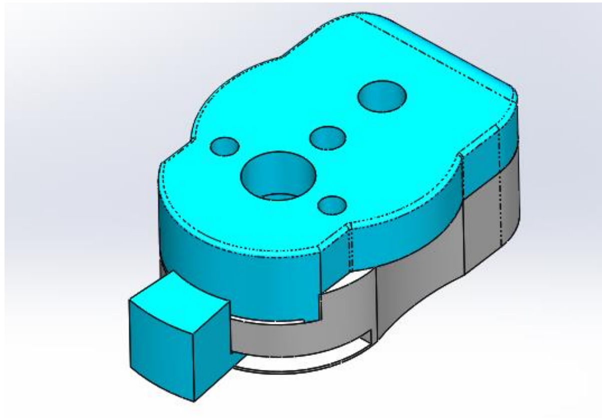


Figure 4: Model of the Kondor Blue Mini Quick Release.

3.1.2 Concept 2: Air Chamber Flange Mount

The next concept developed focused on transferring the camera and the mount as a single unit to provide repeatable camera framing. The rod and camera bracket (highlighted in blue on Figure 5) are removed together by loosening a flanged bracket that resides on the air chamber. This flanged bracket can be fastened with a hex key or a quick-release cam lever.

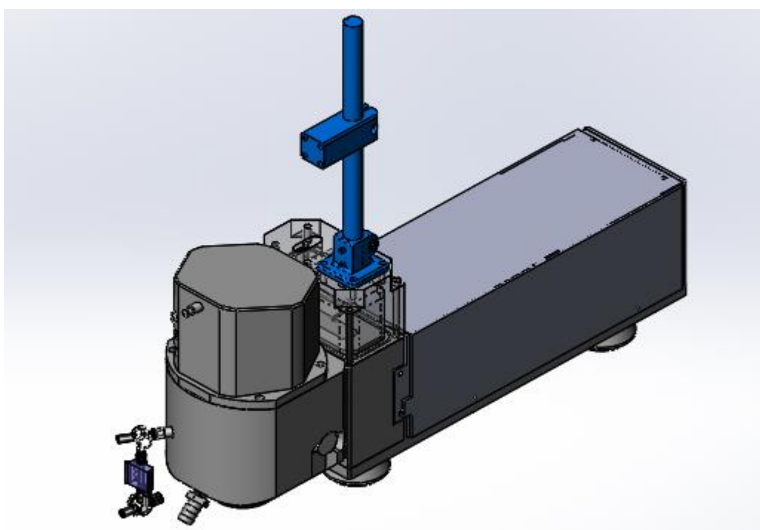


Figure 5: Concept 2 mock up. The lateral offset is used to allow for testing of different brackets.

Underneath each flanged bracket, the air chambers have a slot that guides the flats on the base of the rod to consistently locate the camera rotationally. The top camera bracket acts as a clamp on the rod to allow for vertical adjustments. This option is relatively unobtrusive as units without the camera only retain the flanged bracket.

3.3 Concept 3: Linear Actuator

The last concept uses a linear stage to move the camera between units with high precision. Figure 6 shows a mock up of a linear stage that spans the distance of 6 testing units, along with a camera bracket similar to concept 2.

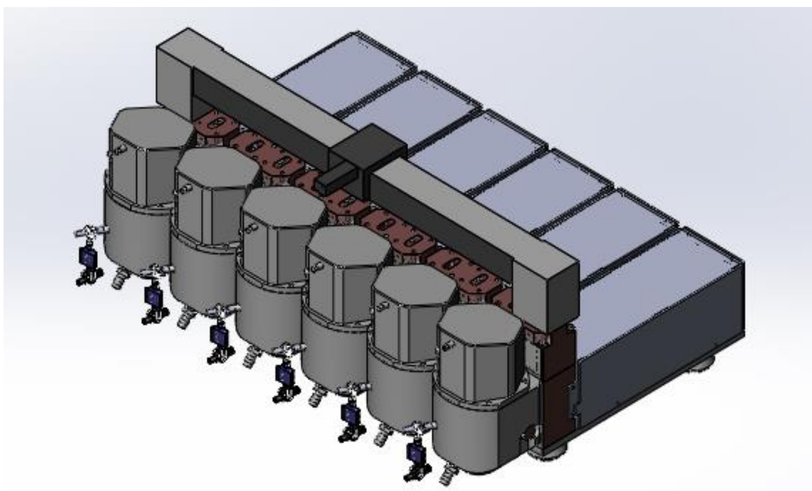


Figure 6: Concept 3 mock up.

This option provides the most precise, consistent, and user-friendly experience. However, this option is also significantly more expensive and would require both electrical and software integration into the existing control system.

3.2 Preliminary Design Evaluation and Comparison

Before evaluating and comparing designs, concept 3 (linear stage) was ruled out due to its complexity, lack of compatibility with the Pulse Duplicator, and cost. While its operation may provide an ideal experience for users, the development and integration of a linear actuator does not provide enough benefit to users to justify extending project timelines and increasing the cost to customers.

The weighted objectives chart primarily employs evaluation criteria that are relevant to the project objectives. However, additional criteria related to Vivitro's AWT design approach, like visibility and aesthetics, were added along with the company's design philosophy of modularity. This can be seen in Table 1, where compatibility with the Pulse Duplicator is considered in the weighted objectives chart.

Table 1: High speed camera mounting weighted objectives chart.

		Concept 1: Pillow Blocks			Concept 2: Air Chamber Flange		
Criteria	**Weight**	**Score**	**Weighted Score**	**Justification**	**Score**	**Weighted Score**	**Justification**
Cost	20%	80	16.00	5 custom parts: - 4, 3-axis milled parts. - 1 simple lathe part.	95	19.00	2 off the shelf and 3 custom parts: - 2, 3-axis milled parts. - 1 simple lathe part.
Transfer Time	25%	90	22.50	Estimated 30 seconds with quick release.	85	21.25	Estimated 45 seconds with a hex key.
Ease of Setup	15%	20	3.00	Every unit requires individual setup.	90	13.50	Only one unit requires setup.
Repeatability	20%	30	6.00	Duplicating setup between units will be difficult.	85	17.00	Easy repeatability, but tolerance stack-up could introduce error.
Stiffness & Stability	10%	60	6.00	Stable mounting, but there is a long moment arm between the mounting and camera.	70	7.00	Small moment arm between the base and camera, but cantilever beam mounting is less than ideal.
Visibility & Aesthetics	8%	10	0.75	The need for permanent mounting on the front of each unit reduces valve visibility.	80	6.00	Mounting is discreet, but remaining brackets contrast the acrylic build.
Pulse Duplicator Compatibility	3%	80	2.00	Only small modifications to the pillow block design is required.	65	1.63	Moderate tweaks, including new flanged brackets and a longer rod are required.
Total		**385**	**56.25**		**570**	**85.38**	

As can be seen, Concept 2: Air Chamber Flange is the clear winner. The largest advantage concept 2 holds over the concept 1 is its repeatability. In addition to making it easier for users to compare videos between units, being able to consistently frame the valve in the center of the shot when transferring the camera between units will significantly reduce the time required take advantage of high speed video when tuning the AWT. Concept 2 also had a distinct advantage in visibility and aesthetics.

4. Design and Frequency Analysis

Moving forward with Concept 2, detail design is needed to flesh out the concept and refine it into a prototype. This also means that considerations like natural frequencies should be evaluated given that the AWT will be vibrating at 10-35 Hz.

4.1 Detailed Design

The camera setup currently in use on the Pulse Duplicator uses a 20 mm rod with an acetyl camera bracket. With this in mind one 20 mm rod and an off-the-shelf flanged bracket from J.W. Winco were ordered so that the AWT prototype would be ready to test with high speed camera. It was noted that the bracket for an 18 mm rod would be significantly smaller, so a second implementation of concept 2 was implemented. This size difference is can be seen in Figure 8.

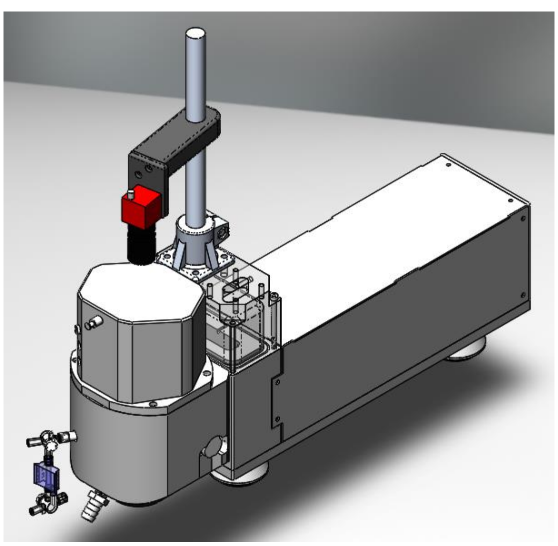


Figure 7; Concept 2 modified to utilize existing parts.

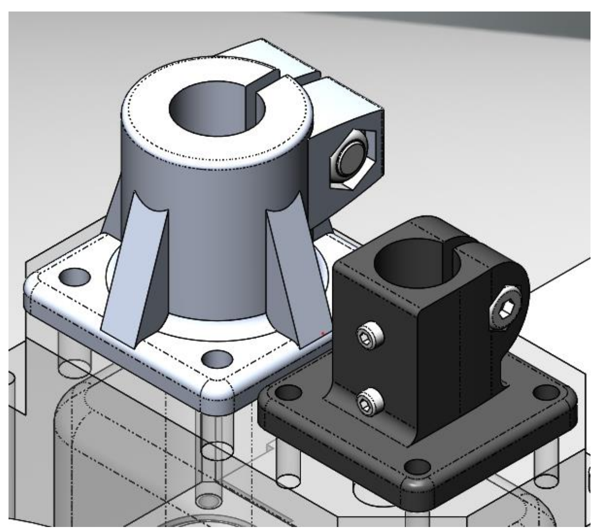


Figure 8: The size difference between the 20mm flanged bracket (left), and the 18mm (right).

After consulting with testing engineers, it was determined a more precise way of controlling the height of the camera would be preferable. This was in comparison to the Pulse Duplicator and preliminary camera bracket designs. As a result, the Novoflex CASTEL-MINI II focusing rack (shown in Figure 9 and Figure 10) was specified and integrated into the design to provide precise and easy vertical adjustments of up to 110 mm. Each rod was oversized for the prototype to allow for additional testing and compatibility with the Pulse Duplicator.

Figure 9: Novoflex CASTEL-Mini II focusing rack [3]

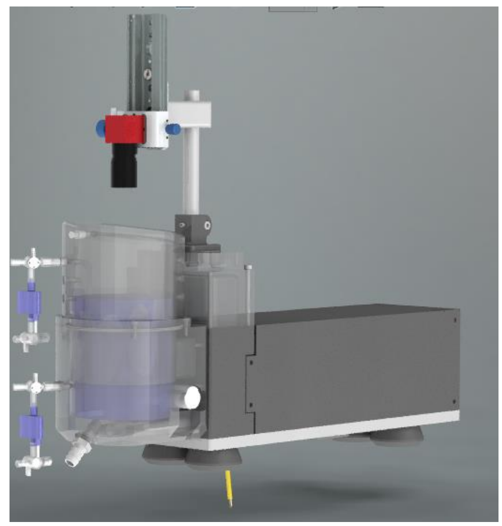


Figure 10: Integrated Novoflex focusing rack model.

4.2 Natural Frequency Analysis

Since the camera mount is subject to oscillating base excitation, the natural frequency of the system should be calculated to ensure that it is sufficiently higher than the operating frequencies of the AWT.

The camera mounting assembly can first be simplified into a point-mass system with the rod acting as a spring. Since the primary concern for system compliance is the long rod, camera mounting components such as the focusing rack and the bracket are assumed to be rigid. The stiffness of the rod, acting as a cantilever beam, can be calculated using equation 1 [4].

$$k_{rod} = \frac{3*E*I}{L^3} \tag{1}$$

The stiffness of the rod is k_{rod}, the Young's Modulus of 6061-T6 aluminium is E, the second moment of area about the neutral axis is I, and the length between the camera bracket and the flanged bracket is L. Substituting in the values of the camera mounting system:

$$k_{rod} = \frac{48 * 69\ GPa * 5153\ mm^4}{(145\ mm)^3} = 3.55 * 10^5 \frac{N}{m}$$

The natural frequency can then be determined using equation 2 [5] where ω_n is the natural frequency in radians, and m is the mass of the camera and half of the rod in kilograms.

$$\omega_n = \sqrt{\frac{k_{rod}}{m}} \tag{2}$$

This evaluates to:

$$\omega_n = \sqrt{\frac{3.55 * 10^5 N/m}{0.65\ kg}} = 739 \frac{rad}{s} = 117\ Hz$$

This calculation neglects the mass along the length of the rod, along with all joint compliance and structural damping. To investigate these effects, a frequency simulation was setup in SolidWorks using an equivalent system to simplify computational demands on the computer. To simplify the assembly, the camera bracket was modified and its material was changed to reflect equivalent mass and mass distribution of the designed camera bracket, focusing rack, camera, and lens. Figure 11 shows the results of this simulation where the first natural frequency was found to be 119 Hz with a peak amplitude of 0.9-2.3 mm depending on the camera's location.

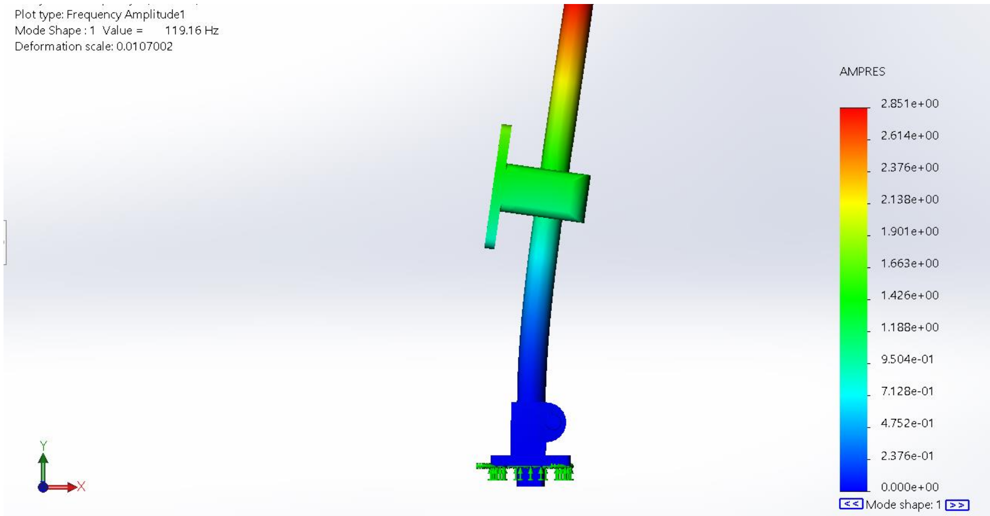


Figure 11: Frequency analysis of prototype design in SolidWorks.

5. Prototype Testing and Results

After finalizing the prototype design, all components were ordered, manufactured, and assembled in parallel with the AWT fluid chamber. This alpha prototype can be seen in Figure 12 and Figure 13. Of note, the original design did not account for the angle of refraction due to the slope on the fluid chamber. As a temporary solution for this, a washer was added between the mounting plate and the top bolt hole on the focusing rack.

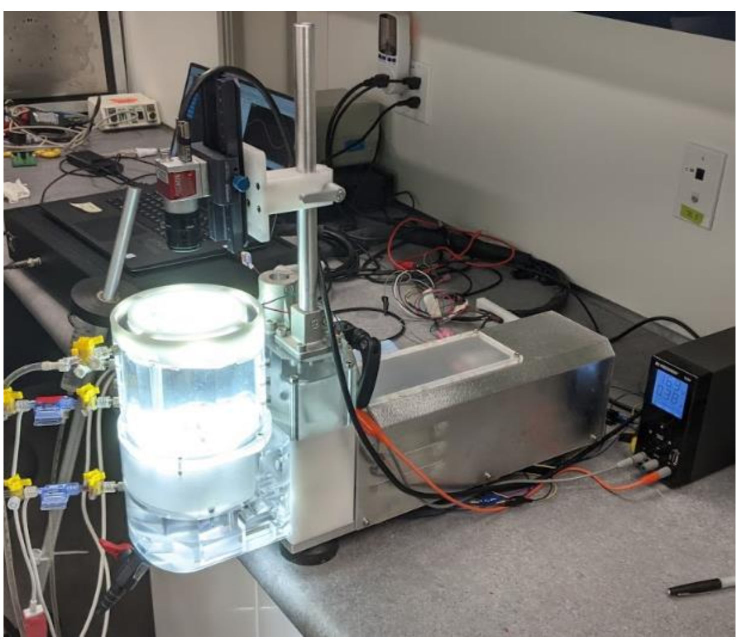


Figure 12: AWT alpha prototype: isometric view.

Figure 13: AWT alpha prototype: front view.

It was also found that all of the quick-release mechanisms, be it cam levers, finger knobs, or handles, made tightening and loosening the flanged clamp more difficult than using a hex key. With an assembled and functional prototype, testing could then be conducted to evaluate how well the design meets the project objectives.

5.1 Transfer Time

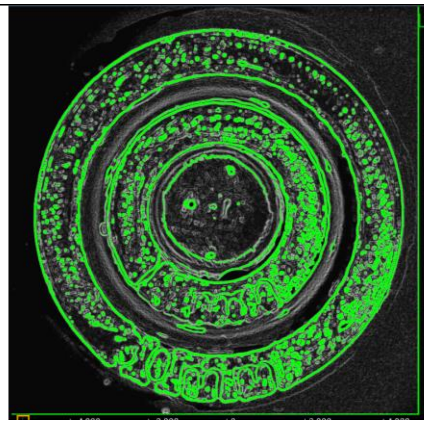
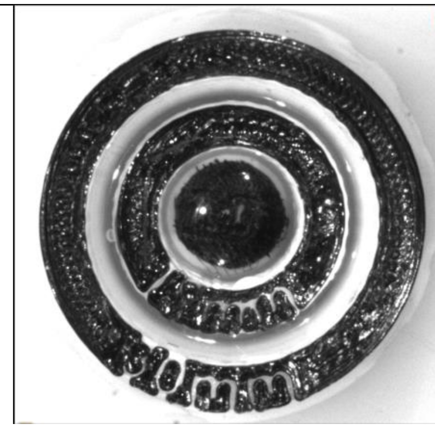
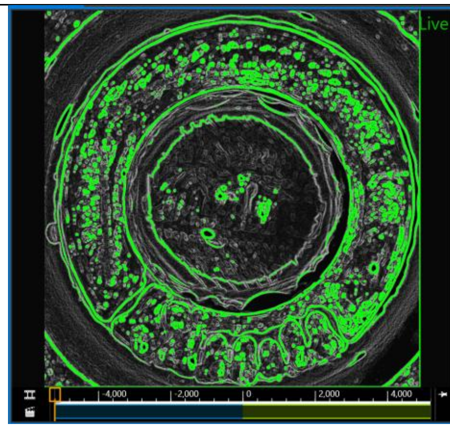
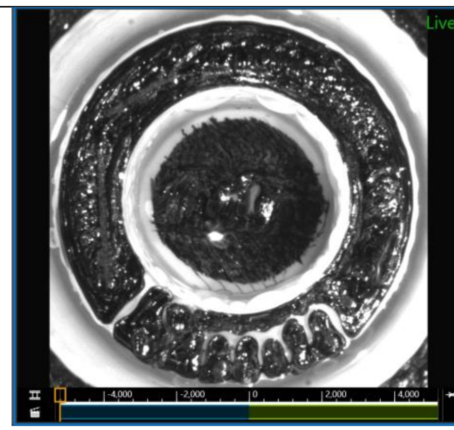
To simulate transferring the camera between testing units, a timer was used to track how long it took to remove the camera from the AWT, set it down on the bench, and reinstall it onto the same unit, and center the camera frame on the valve. After five tests, it was found to take an average of 42 seconds, well below the goal of one minute. The majority of this time is spent loosening and tightening the bolt with a hex key, so there is some room for improvement if a more suitable fastening method is found. It is also worth noting that the 20 mm rod's bracket was significantly more difficult to sufficiently tighten, requiring an unreasonable amount of force to stabilize the rod and camera.

5.2 Vertical Adjustability

Before finalizing the prototype design, it was determined that the amount of vertical adjustability only needed to account for the variation of same kind of valve sizes. For example, aortic valves range in diameter from 19-30 mm while mitral valves are much larger at up to 55 mm or more. However, since most customers specialize in one valve type, appropriate lenses will be specified for each use case.

To confirm that the focus rack provides adequate vertical adjustability, a test marker was designed and printed to confirm that the camera can frame the valve's diameter with at least equal depth of field. As can be seen in Table 2, the current design provides sufficient range for aortic valves.

Table 2: Vertical adjustability testing results.

Details	AIS Focusing Tool Overlay	Camera Screenshot
• 640 x 640 frame. • 240 mm between bottom of lens and base of marker.		
• 640 x 640 frame. • 140 mm between bottom of lens and base of marker.		

5.3 Camera Location Repeatability

Testing of repeatability was run in parallel with the transfer time testing. In each of the five trials, no modifications to the mounting or recording software were needed. Figure 14 and Figure 15 show the alignment of a tissue aortic valve in the camera frame before and after removing and re-installing the camera mounting. The red marker remained on the same pixels for all tests.

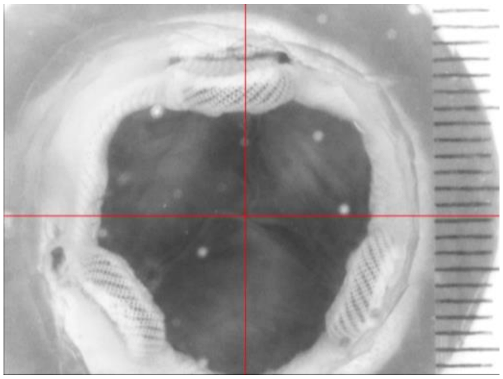


Figure 14: Valve alignment prior to camera re-installment.

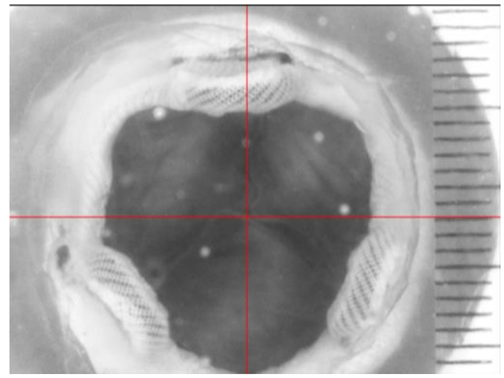


Figure 15: Valve alignment post camera re-installment.

Since there is only one prototype unit, the potential for tolerance stack-up between components could not be tested, however, the maximum offset due to this was calculated to be 1 mm, or 0.05% of a small aortic valve's diameter. Therefore, it was determined that tolerance stack-up is not a large concern, especially relative to the tolerances on the valve holders.

5.4 Mounting Stiffness and Stability

To test the stiffness of the camera mounting system, the AWT was tuned to operating conditions for operational frequencies between 10 and 35 Hz, incrementing by 5 Hz each step. Since the AWT's natural frequency was found to be 22Hz, this frequency was also tested. Both the 18 mm and 20 mm rod configurations were tested, along with the Pulse Duplicator's camera bracket on the 18 mm rod to isolate any effect the camera rack introduces.

It is worth noting that a ruler was placed beside the valve to measure the movement between the camera and valve, as seen in Figure 14 and Figure 15. However, even when significant vibrations were visible, the amplitude remained under 1 mm. Without the equipment to quantitatively measure the relative movement of the camera, qualitative observations were made and summarized in Table 3.

Table 3: Camera mount stability testing results.

Excitation Frequency (Hz)	Standard 18 mm Configuration	18mm Rod with Pulse Duplicator Bracket	20 mm Rod with Pulse Duplicator Bracket
10	Stable	Stable	Stable
15	Fairly stable	Fairly stable	Fairly stable
20	Somewhat stable	Somewhat stable	Somewhat stable
22	Small vibration noticeable	Small vibration noticeable	Somewhat stable
25	Vibration noticeable	Vibration noticeable	Small vibration noticeable
30	Significant vibration noticeable	Significant vibration noticeable	Vibration Visible
35	Significant vibration noticeable	Significant vibration noticeable	Significant vibration noticeable

As can be seen, all configurations fail to provide adequate stability throughout the expected operational range of the AWT. With increasing frequency, both rod diameters became more susceptible to vibrations, though this effect was more pronounced on the 18 mm rod. However, the focusing rack was not found to reduce the stability of the camera mounting system.

5.5 Cost

Included in the quote for prototype parts was a quote for varying quantities to gage production costs at volume. Table 4 breaks down the cost of each component for a low-volume run of 10 camera mounts. As can be seen, this design falls well under the limit of 500 USD.

Table 4: Cost breakdown for 10 camera mounting systems.

Part	**Cost (USD)**
Novoflex CASTEL-Mini II Focusing Rack	$ 200.00
GN 162-B18-2-BL - Flanged Bracket	$ 17.56
AWT – High Speed Camera Mounting Plate	$ 35.35
AWT – High Speed Camera Mount Adapter	$ 75.09
AWT – Camera Mounting Rod – 18mm	$ 64.62
Total	**$ 392.61**

6. Recommendations

Moving forward, several small changes should be made to the camera mounting system. First, locating slots and flats can be reduced from ½ an inch to 1/8 of an inch to improve aesthetics. The final design should also be centered on the air chamber and the camera mounting plate should be modified to reflect this. However, there are two major changes that should be made to improve camera stability.

6.1 Mounting Rod Modifications

First, the length of the rod should be decreased as much as possible. Fortunately, this aligns well with modifications being made to the fluid chamber as a result of AWT waveform testing on the current prototype. The new architecture, shown in Figure 16, increases the height of the air chamber and flanged bracket while also lowering the valve. The combined effect of these changes results in a very small moment arm between the flanged bracket and the camera bracket.

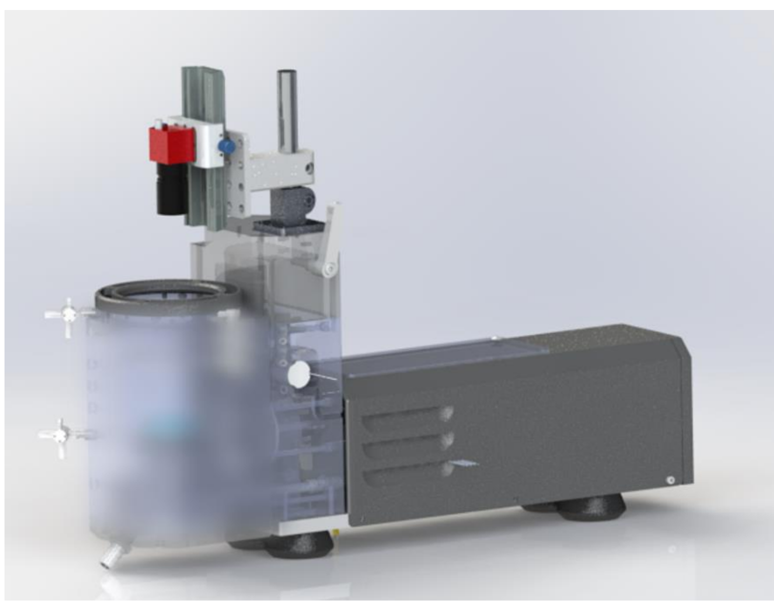


Figure 16: New AWT beta prototype with modified camera mounting. Image blurred to retain design confidentiality.

6.2 Vibration Isolating Feet

The feet currently being used on the AWT were not designed to isolate vibrations, thus causing the entire system to vibrate significantly. In addition to disturbing the video stability, this generates undesirable noise. However, many products exist that are designed to isolate vibrations from oscillating machines. Since the AWT operates between 10 and 35 Hz, a median excitation frequency of 22.5 Hz will be used to calculate the required spring rate of each mount. For 80% isolation, the natural frequency of the system should follow equation (3)[6] where f_n is the natural frequency of the system and f_d is the excitation frequency.

$$fn = \frac{f_d}{2.45} = \frac{22.5\ Hz}{2.45} = 9.18\ Hz \tag{3}$$

Equation (2) can then be rearranged to calculate the spring rate of each mount using ¼ of the mass of the system per mount since the feet act as springs in parallel.

$$k_{foot} = \omega_n^2 * \frac{m_{sys}}{4} = \left(57.7 \frac{rad}{s}\right)^2 * \left(15 \frac{kg}{4}\right) = 12{,}476\ N/m$$

7. Conclusions

Since high speed videography is an important part of heart valve durability testing, a camera mounting system design was needed to integrate with the new AWT currently in development at Vivitro Labs. Three preliminary designs were created with SolidWorks before being reviewed with Vivitro's R&D and Testing teams. After being evaluated using a weighted objectives chart, the design concept that took advantage of a flanged bracket on each unit to move the camera, along with a mounting rod, was further refined by adding a small focusing rack to control the height of the camera. An alternate mounting bracket was also added to allow R&D to test different diameter rods and utilize an existing camera bracket. Before parts were ordered, a frequency analysis was conducted to ensure the natural frequency of the camera mount was sufficiently higher than the operational range of the AWT.

During the quotation process, it was found that the camera mounting system would cost about 392 USD to manufacture in North America for a production run of 10 units. This is well below the limit of 500 USD, meeting the cost of production criteria. Once the camera mounting system and AWT prototypes were manufactured and assembled, testing could begin. It was found that transferring cameras between units takes approximately 42 seconds with very precise locating relative to the prosthetic heart valve. However, it was found that the design was not sufficiently stiff, exhibiting noticeable movement relative to the heart valve with increasing operational frequency.

Given this, two recommendations were given to improve the stability of the design. First, shortening the mounting rod to reduce the length of the effective cantilever beam was recommended to increase the stiffness of the system. This change integrated well with the updates being made in to the AWT fluid architecture in parallel. The second recommendation targeted the system's tendency to oscillate during operation. By installing new feet with a calculated stiffness of around 12,500 N/m, the median operating frequency can be isolated by up to 80%, improving the stability of the camera mounting system and reducing the noise of the AWT. Together, these modifications should produce a camera mount that meets all requirements and provides users with a pleasant experience.

8. References

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