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EML4551-2

Team 04: Danfoss IGV Monitoring System

Members: Travis J. Carter; Peter R. House; Brandon A. Klenck; Arnold M. Schaefer

FAMU-FSU College of Engineering 2525 Pottsdamer St. Tallahassee, FL. 32310

Abstract

Acknowledgement

We would like to thank Danfoss Turbocor and our project liaison, William Bilbow, for sponsoring this project. We also want to thank Dr. Shayne McConomy and Dr. Chiang Shih for guiding us through the design process, and Dr. Kunihiko Taira for his technical advice and guidance.

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Notation

CR	Customer Requirement
DIC	Digital Image Correlation
EC	Engineering Characteristic
HOQ	House of Quality
IGV	Inlet Guide Vane

Chapter One: EML 4551C

1.1 Project Scope

Our team has come up with the following project scope using the information from the initial sponsor meeting with Danfoss and the project background they provided (W. Bilbow, personal communication, September 22, 2017).

Description:

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Danfoss is currently redesigning and testing new inlet guide vanes (IGVs) to use in their TT series of compressors. The compressors use IGVs to manage inlet refrigerant mass flow and flow direction by changing the angle of the vanes. They are currently testing how the different IGV angles impact the mass flow rate and pressure ratio of the compressor; however, there are limitations to what Danfoss can analyze about the IGVs using their current equipment. Danfoss would like to have a better understanding of how the IGVs react in the flow of the refrigerant, and to have a more accurate reading of the current IGV angle. Therefore, the objective of this project is to design and build a system for real-time visual and position monitoring of the compressor inlet guide vanes.

Goals:

The three key goals to complete the objective of this project are as follows:

- Produce a system to reliably measure the angle of the IGV
- Provide detailed monitoring of low cycle failures
- Minimize impact on the fluid flow

Commented [AS2]: Removed monitoring of high cycle since it was considered a bonus and we will not be working on this part anymore

Deleted: and high cycle

Primary Market:

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The primary market for the testing equipment we are developing is the Danfoss Research and Development Testing Labs.

Assumptions:

- Monitoring and sensing equipment will need to be purchased by the group
- System will be used on the TT series of Danfoss compressors
- Manufacturing will take place through Danfoss facilities

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Stakeholders:

- Danfoss Research and Development Test Lab

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Deleted: <#>Danfoss Aero-Thermal Engineering Design Team

1.2 Customer Needs

The initial meeting with Danfoss provided a lot of useful information about the individual needs that their test lab has for this monitoring device. Using the information gained from this meeting and the needs outlined in the project description, our team came up with a list of customer statements given in table 1.

Our team then rewrote the customer statements as interpreted need statements. We wanted to remove some of the implied solutions to our project given in the statements so that we have a list of needs which outline what our final system needs to accomplish rather than how it should be accomplished. We also wanted to reword the negative customer statements into positive needs. The table below shows the customer statements and our team's interpreted need.

Table 1
List of Customer Statements and Interpreted Needs

#	CUSTOMER STATEMENTS	INTERPRETED NEED
1	We want a visual of the inlet to monitor guide vane, slip, impedance, flutter and vane loss	Visual monitor allows for qualitative analysis of inlet guide vanes
2	We need an angle reading of all of the Inlet Guide Vanes	The angles of all IGVs are determined
3	The camera needs to be in the center	The view of the vanes is from the center of the inlet
4	The device cannot break and have parts enter the compressor	System malfunction will not damage compressor
5	Compressor inlet flow should not be impacted	Allows for normal flow into the compressor
6	Device components like the camera and sensors need to be serviceable	Components can be replaced or serviced
7	To avoid interference with the rest of the compressor, don't use sonic or magnetic sensors	Allows for normal operation of the compressor's electronic subsystems
8	The vanes need to be illuminated to see them	The vanes are clearly visible

These new interpreted need statements will allow our group to focus on the main customer needs of the project without narrowing the possible solutions to those implied in the customer statements.

1.3 Functional Decomposition

Our team used the project scope and interpreted customer needs to come up with a list of functions that our system needs to accomplish in order meet the goals outlined in the project scope. The list of functions shown below acts as a guideline for our concept generation and selection which takes all the system requirements into account.

- Sense IGV Position
- Provide Power to Position Sensor
- Relay Position Signal to System
- Convert IGV Position Sensor Reading to IGV Percentage
- Send IGV Percentage to Indicator
- Indicate Percentage of IGV to User
- Provide Power to Indicator
- Capture Visual of IGVs
- Provide Power to Visual Sensor
- Relay Visual Signal to System
- Process IGV Visual Signal into a Video Feed
- Send Video Feed to Display
- Provide Power to Monitor
- Display Video of IGV to User
- Get Power from Source

Our team also created a graphical representation using the previously listed functions in order to create a better visualization of the system's main operating requirements. This diagram is included below.

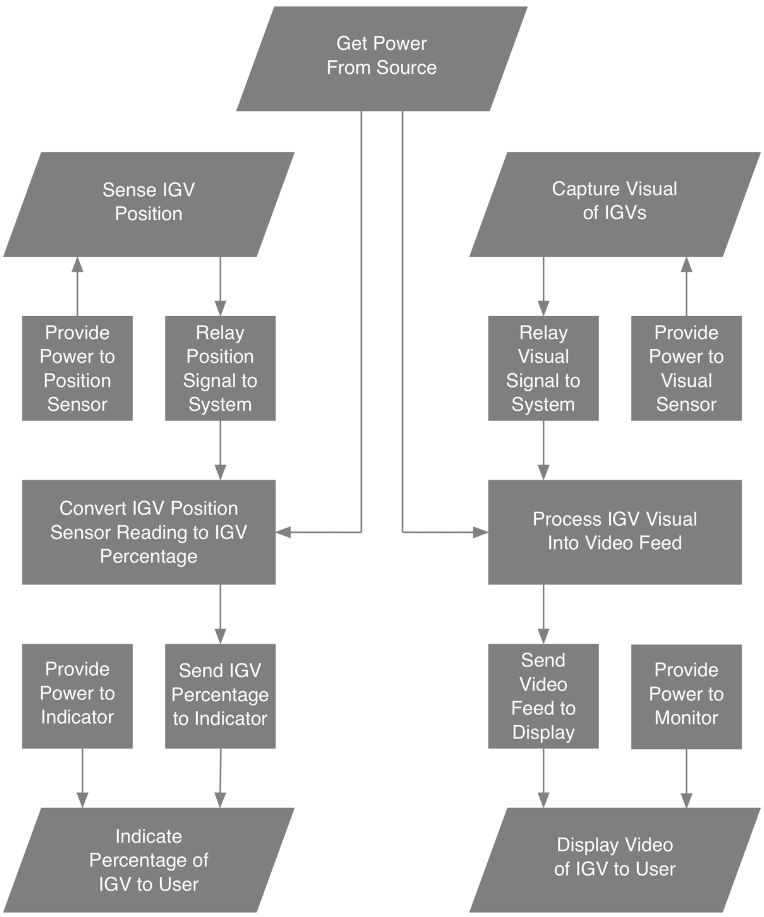


Figure 1. Flow diagram of all items in the functional decomposition.

1.4 Target Summary

In a meeting with the sponsor, our group constructed a list of required targets and their values that we need to accomplish for our project to be successful. The most important targets for our project are the impact on the fluid flow, and the monitoring rates for IGVs changes and failures. The impact on the fluid flow can be represented by the pressure drop across the system and by the induced swirl in the flow. For this project, there can be no induced swirl in the flow of refrigerant, and the overall pressure drop across the system should be less than 0.02 psi.

Our system needs to observe and detect low cycle IGV failures like latching or breaks due to constant forces in the flow, and high cycle failures due to vibrations in the system. To accurately measure these failures, a required measurement frequency is assigned to each. Low cycle failures like latching and breaks due to constant forces only require a sample frequency of 1Hz since the vanes move very slowly when turning and breaks only need to be indicated on a per second basis. Measuring high cycle failures requires a much higher sampling rate of 1kHz due to the high motor revolutions per minute and low natural frequencies of plastics which fall within the range of the motor frequency. A detailed list of targets is given in appendix B.

1.5 Concept Generation

For the concept generation, we conducted background research on possible systems and components that could fulfill the requirements for this system. This research included defining the operating conditions, finding different ways to measure the angle of the IGVs, finding ways to capture a visual of the IGVs, and determining how our system processes all of these signals. Using this information, each member of our group presented and recorded detailed concepts for the system during multiple ideation meetings. Following these meetings, individual subsystems in the concepts were extracted and sorted into the relevant categories. The following table outlines each of the subsystems and the related concepts, and the following sections go into further details all of the concepts.

Table 2
List of Subsystems and Related Concepts

SUBSYSTEM	#	CONCEPT DESCRIPTION
Low Cycle Monitoring Subsystem	1	Camera in pipe elbow to monitor IGVs from center
	2	Fiber optic camera in central body to see from center of pipe
	3	Multiple cameras on pipe side used to construct a composite image
	4	Mirror on central body with external camera to see from center of pipe
High Cycle Monitoring Subsystem	1	High speed camera to see and analyze flutter frequency
	2	Accelerometer on IGV to measure the flutter frequency
	3	Laser vibrometer to measure the flutter frequency
	4	Linear potentiometer with high pass filter to monitor flutter frequency
	5	Digital Image Correlation
Angle Monitoring Subsystem	1	Accelerometer to measure position based on change in gravity
	2	April tags used with a camera to calculate angle based on aspect ratio
	3	Light sensitive paper to easily see and approximate angle of each IGV
	4	Linear potentiometer with low pass filter to monitor distance change
	5	Digital Image Correlation
IGV Lighting Subsystem	1	Individual lights in pipe close to the IGV to light IGVs
	2	Ring light around camera to evenly light IGVs
	3	Clear pipe which allows ambient light in the room to enter pipe

Low Cycle Monitoring Subsystem Overview

The low cycle monitoring system is in charge of monitoring and detecting problems with the IGV that occur over a span of time lasting longer than a second. Its main function is to determine if all the vanes are present in the system, or if some of the vanes have broken during testing. It will also monitor for geometrical interference between vanes when the vanes rotate. This interference is most likely to occur in the center of the inlet where the tips of the IGV could interfere causing a failure of the IGV system.

Low Cycle Monitoring Subsystem Concept 1

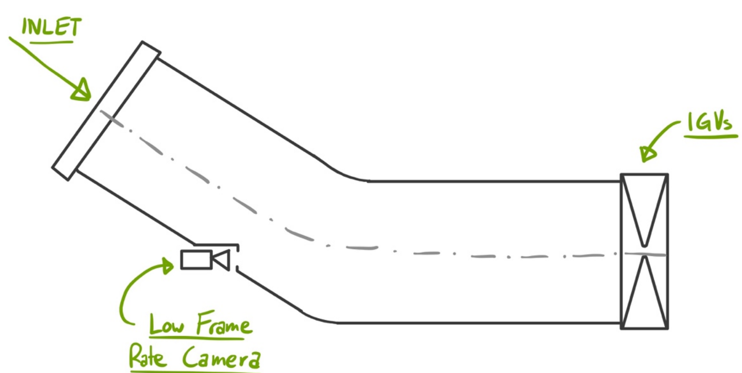


Figure 2. Low cycle monitoring concept utilizing a camera in a pipe elbow.

A low frame rate camera is positioned in the side of a pipe elbow to monitor the IGVs. Placing the camera inside a pipe elbow provides a central view of the IGVs without large disturbances to the inlet refrigerant flow.

Low Cycle Monitoring Subsystem Concept 2

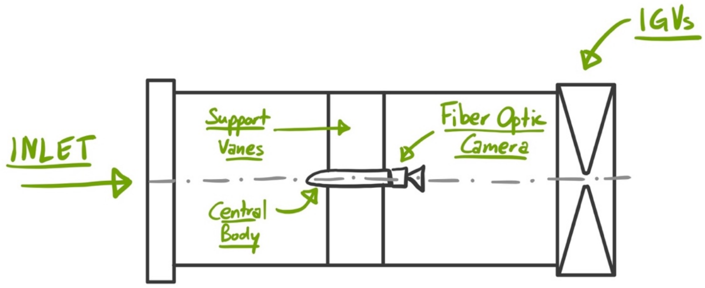


Figure 3. Low cycle monitoring concept utilizing a fiber optic camera in a central body.

Here, a central body acts as a housing for a fiber optic camera. The position of the camera allows the user to see the IGVs from the center of the pipe, and the streamlined design of the central body and support vanes minimizes the impact on the fluid flow.

Low Cycle Monitoring Subsystem Concept 3

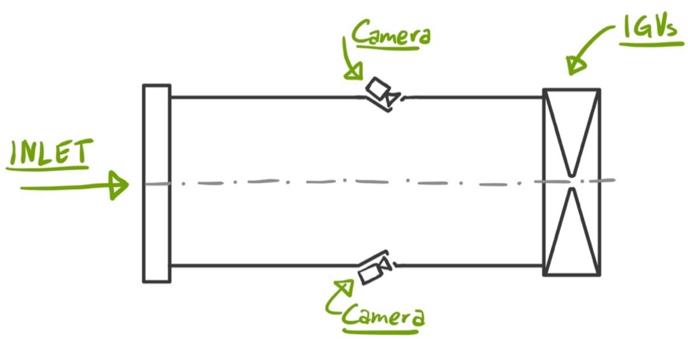


Figure 4. Low cycle monitoring concept utilizing cameras to make a composite image.

Multiple cameras at different locations in the pipe create a composite image of the IGVs whose view appears from the center of the pipe. This concept will also minimize the impact on the flow since no elements are located in the center of the pipe.

Low Cycle Monitoring Subsystem Concept 4

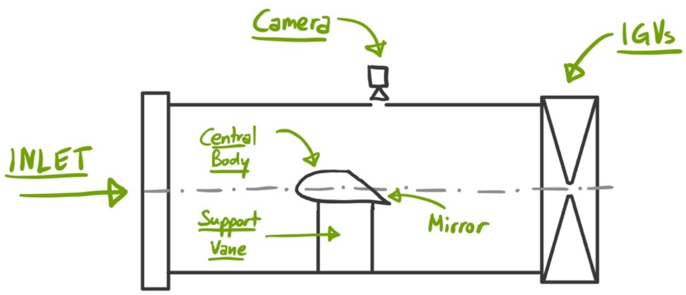


Figure 5. Low cycle monitoring concept utilizing a mirror and external camera.

In the final concept for low cycle monitoring, a central body with a mirror attached at 45 degrees to the inlet provides a clear image to a camera positioned at the side of the pipe. The flow properties are very similar to the previous concept involving the fiber optic camera in the central body, however, the implementation of the camera is less expensive since the size of the camera is less important. Since the flow into the compressor inlet is in the gaseous state, visibility on the mirror shouldn't be a large concern.

High Cycle Monitoring Subsystem Overview

The high cycle monitoring system will be used to analyze high frequency flutter of the vanes in the system. Therefore, the sampling rate of the system needs to sample at double the frequency of flutter. The system should capture the vibrations in the IGV before a failure occurs so that the information can be used in further design iterations.

High Cycle Monitoring Subsystem Concept 1

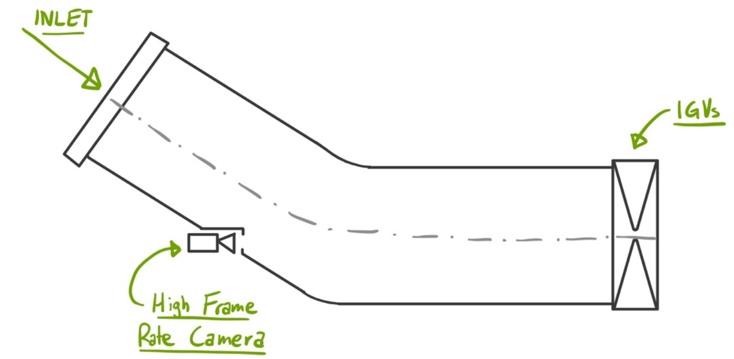


Figure 6. High cycle monitoring concept utilizing a high framerate camera.

A higher frame rate camera is used to measure both low cycle and high cycle events. This configuration allows for the placement of the high frame rate camera in many of the positions outlined in the previous concepts for low cycle monitoring.

High Cycle Monitoring Subsystem Concept 2

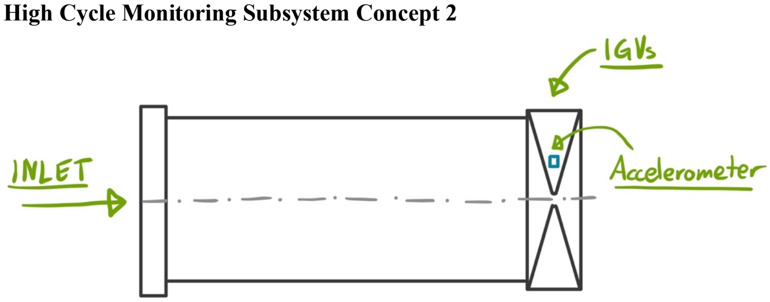


Figure 7. High cycle monitoring concept utilizing an accelerometer.

An accelerometer placed onto or into the IGV provides another method of determining high cycle vibrations. The accelerometer sends voltages to the computer or microcontroller in use which are converted to a frequency of vibration for the IGV.

High Cycle Monitoring Subsystem Concept 3

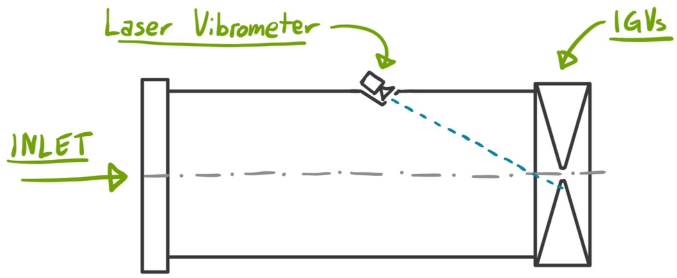


Figure 8. High cycle monitoring concept utilizing a laser vibrometer.

A similar solution uses a laser vibrometer to measure the change in distance of the vane due to vibration. The placement of the vibrometer is near the outside of the pipe to avoid impacting the flow of the refrigerant.

High Cycle Monitoring Subsystem Concept 4

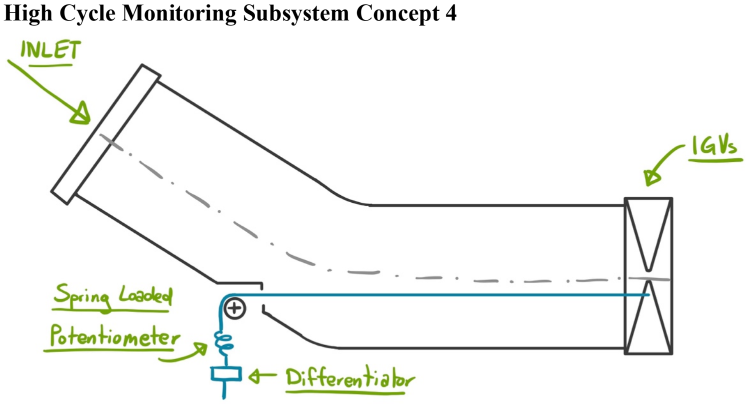


Figure 9. High cycle monitoring concept utilizing a potentiometer with a differentiator.

The cheapest solution is to use a spring loaded linear potentiometer. This potentiometer would connect directly to the vane and only monitor high frequency changes through the differentiator which gives the vibrations of the IGV.

High Cycle Monitoring Subsystem Concept 5

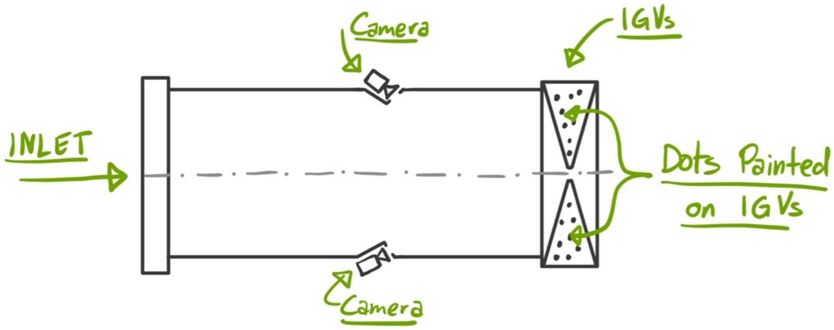


Figure 10. High cycle monitoring concept utilizing digital image correlation.

The final subsystem concept is to use a dot pattern painted onto the IGVs and then use two cameras to analyze the vanes using digital image correlation. The accuracy of this concept is highly dependent on the resolution of the camera and the frame rate would need to be high enough to see any vibrations.

Angle Monitoring Subsystem Overview

The angle monitoring subsystem will be used to determine any major differences in the angles of the IGV, and will be used to see if the stepper motor reading is correct. A large difference in the angle of a few of the IGVs could indicate that some of the blades are interlocked due to geometrical interference, or that one of the IGVs has failed completely.

Angle Monitoring Subsystem Concept 1

Figure 11. Angle monitoring concept utilizing a gyroscope.

For the first concept, a gyroscope is used to determine the angle of the IGV. The implementation of the gyroscope is similar to the accelerometer where it sends voltages to a computer or microcontroller, which will use those voltages to calculate a change in the angle of the IGV.

Angle Monitoring Subsystem Concept 2

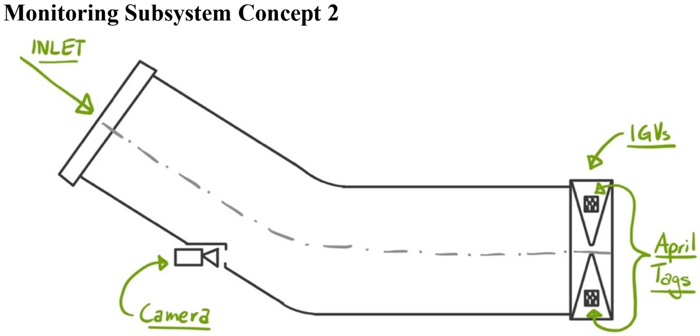


Figure 12. Angle monitoring concept utilizing a camera and April tags.

This system calculates the angles using a camera system and a series of April tags placed on each one of the IGVs. The system uses the camera feed as an input and determines what angle each IGV is at based on the aspect ratio of each of the April tags (which look like QR codes).

Angle Monitoring Subsystem Concept 3

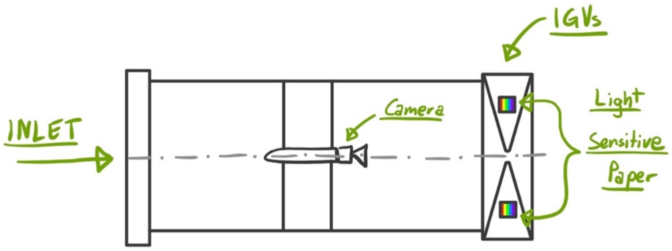


Figure 13. Angle monitoring concept utilizing a camera and light sensitive paper.

Light sensitive paper on each IGV will display a certain color on the spectrum representing one angle based on where the light originates from. This concept doesn't directly calculate each angle; however, angle discrepancies can be identified if one IGV color is significantly different than the others.

Angle Monitoring Subsystem Concept 4

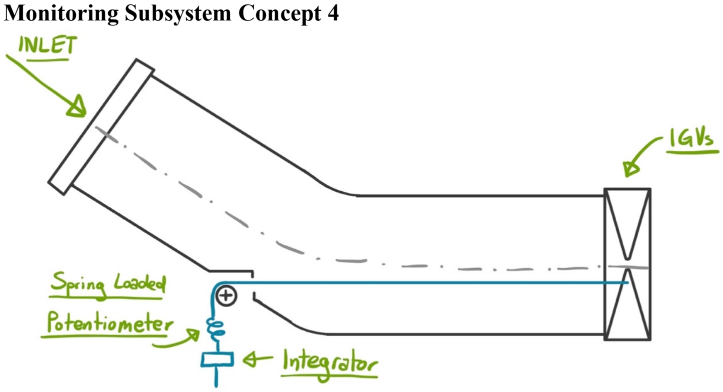


Figure 14. Angle monitoring concept utilizing a potentiometer and an integrator.

Potentiometers can also calculate angles of the IGV by using an integrator instead of a differentiator when reading the voltages. The integrator acts as a output voltage smoother and only relays large changes in distance to the microcontroller, as opposed to the small changed relayed by the differentiator. The system used this voltage change and determines the angle of the IGV.

Angle Monitoring Subsystem Concept 5

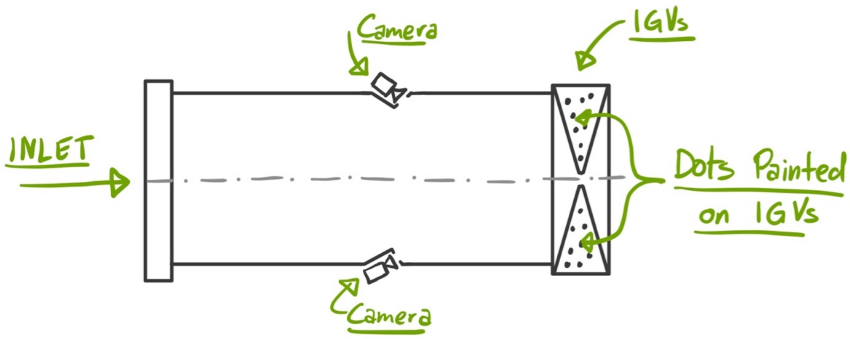


Figure 15. High cycle monitoring concept utilizing digital image correlation.

The final subsystem concept is to use the same DIC system as the high cycle concepts, but to calibrate it to calculate angle instead of vibrations.

IGV Lighting Subsystem Overview

The IGV lighting subsystem must provide enough light in the pipe for the cameras to clearly see the IGVs. Therefore, the system needs to light the IGVs so that the monitoring system provides a clear overview of the status of the blades.

IGV Lighting Subsystem Concept 1

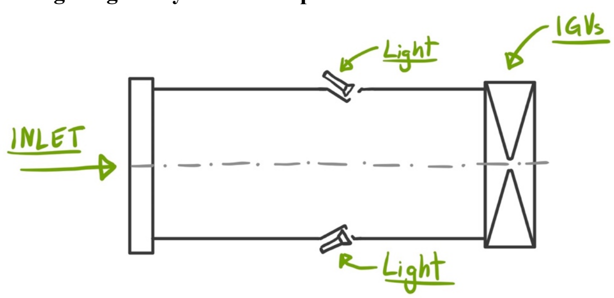


Figure 16. Lighting concept utilizing individual lights in pipe.

Individual lights illuminate the IGVs from multiple angles resulting in a clear and even view of the vanes for the camera monitoring systems. Similar to the cameras in the composite imaging concept, the position of the lights does not impact the flow of refrigerant into the compressor.

IGV Lighting Subsystem Concept 2

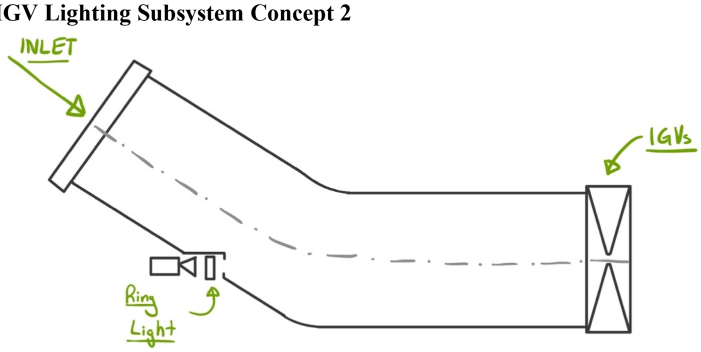


Figure 17. Lighting concept utilizing a ring light around the camera.

A light ring positioned around the lens of the camera provides lighting to the IGVs which is directly from the view of the camera without adding additional lighting components in the center of the pipe, minimizing the flow impact.

IGV Lighting Subsystem Concept 3

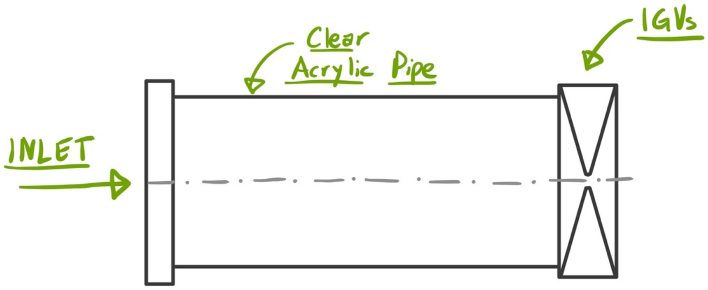


Figure 18. Lighting concept utilizing clear acrylic pipe.

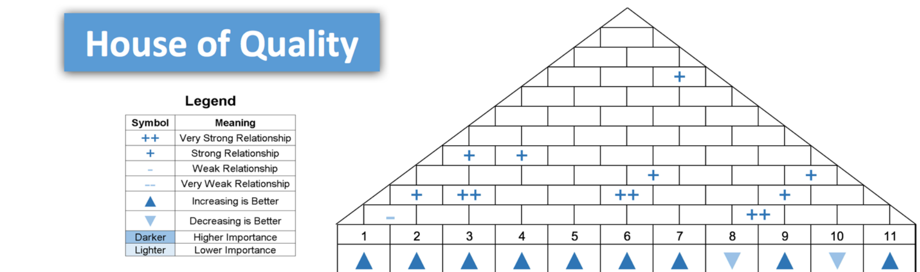
Finally, a clear pipe would negate any additional lighting in the system as ambient light from multiple directions in the test lab evenly illuminates each of the IGVs. This also provides a separate monitoring mode for test lab operators to check on the status of the vanes.

1.6 Concept Selection

Concept Selection Procedure

Our group utilized a house of quality and a decision matrix in order to select the final design for this project. We used the house of quality to determine the engineering characteristics that are required to complete this project and their weight factors determining which engineering characteristics deserve a larger emphasis. Then we made decision matrixes for each of the subsystems using the previously determined engineering characteristics. These decision matrixes will give us a good idea of all of the strengths and weaknesses of the subsystems and will eliminate some of the worst concepts. Finally, we will use the best subsystems from each decision matrix and combine them to get the final concept for the project.

Below is our group's house of quality (Figure 19) outlining the customer requirements, engineering characteristics and their weight factors.



Row Number	Relative Weight	Weight / Importance	Customer Requirements \ Engineering Characteristics	1 Image Clarity	2 Camera Frame Rate	3 Angle Measurement Accuracy	4 Angle Measurement Refresh Rate	5 Vibration Sensing Accuracy	6 Vibration Sensing Refresh Rate	7 System Stability	8 System Length	9 Ease of Integration	10 Pressure Drop across System	11 Pipe Illumination
1	14.7	5.0	Qualitative analysis of IGV's low cycle failure	9	3	1	1			9	3	1	1	9
2	5.9	2.0	Qualitative analysis of IGV's high cycle failure	3	3	1	1	9	9	9	3	1	1	3
3	8.8	3.0	The angle reading is accurate	3	3	9	9			9	3	1	1	3
4	11.8	4.0	The view is of the center			3	1	1		3				
5	14.7	5.0	Malfunction will not damage compressor							9			1	
6	11.8	4.0	Allows for normal flow into the compressor							3	3	1	9	
7	8.8	3.0	Components can be replaced or serviced							1	1	3		
8	14.7	5.0	The vanes are clearly visable	9	3	1	1			9	3			9
9	8.8	3.0	Ease of use by test lab								9	9		
			Technical Importance: Absolute	309	132	150	126	65	53	609	256	147	150	309
			Technical Importance: Relative	13.4	5.7	6.5	5.5	2.8	2.3	26.4	11.1	6.4	6.5	13.4

Figure 19 House of Quality for Concept Selection.

We started our house of quality with the list of customer requirements (CRs) that were previously determined in the customer needs section. With these requirements, we determined the proper engineering characteristics (ECs) that this project needs to meet in order to fulfill the needs of the customer. This includes two ECs for each of the monitoring subsystems (low cycle, angle, high cycle) determining the measurement quality and sampling rate, and also includes various other parameters to measure how well the system integrates into the Danfoss testing environments and how much the system will impact the flow. With these ECs determined, we filled out the center of the house of quality with factors determining the relation between the ECs and CRs based on how strong that relation is. With this information, we could determine the weight factors. The top EC for this project is system stability. This is very important because it represents the overall integrity of the monitoring tool which is required to keep the compressor loop from failing but is also required to keep all of the cameras and sensors in our monitoring system stable. Without a stable system, camera views could be blurry and sensor reading may not be accurate. The second most important ECs are Pipe Illumination and Image Clarity. These represent the main goal of the project which is to have a clear view of the compressor inlet to monitor low cycle failures. Achieving this alone would make our project successful. The lowest ranked ECs are those for vibration sensing. This is because the vibration sensing component of our design is not a firm requirement but rather an addition to the system that Danfoss characterized as extra credit. Therefore, our group will not make large design changes or select concepts that impact the integrity of the other monitoring subsystems to accommodate this function.

Decision Matrix: Low Cycle Monitoring Subsystem

With the engineering characteristics determined, the decision matrices can be made. The first decision matrix is for the low cycle monitoring system (Table 3) and compares the concepts that our group generated in the previous section.

Table 3

Decision Matrix for Low Cycle Monitoring Subsystems

		Camera in Elbow		Camera & Central Body Mirror		Camera in Central Body		Composite Imaging	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	8	107.1	6	80.4	7	93.8	8	107.1
Camera Frame Rate	5.7	8	45.9	8	45.9	7	40.2	8	45.9
Angle Measurement Accuracy	6.5	0	0.0	0	0.0	0	0.0	0	0.0
Angle Measurement Refresh Rate	5.5	0	0.0	0	0.0	0	0.0	0	0.0
Vibration Sensing Accuracy	2.8	0	0.0	0	0.0	0	0.0	0	0.0
Vibration Sensing Refresh Rate	2.3	0	0.0	0	0.0	0	0.0	0	0.0
System Stability	26.4	8	211.2	5	132.0	6	158.4	8	211.2
System Length	11.1	2	22.2	8	88.8	8	88.8	6	66.6
Ease of Integration	6.4	3	19.1	8	51.0	7	44.6	5	31.9
Pressure Drop across System	6.5	8	52.0	7	45.5	7	45.5	9	58.5
Pipe Illumination	13.4	4	53.6	3	40.2	7	93.8	3	40.2
			511.2		483.8		565.1		561.5

The main focus of this comparison is around the image clarity and framerate offered by each subsystem. Since individual cameras have not been selected yet, the rating for this matrix represents how limited we are in selecting from a large range of cameras and how the shape and design of the subsystem will impact overall performance.

For image clarity, composite imaging and camera in an elbow score highest because they allow for a wide range of cameras that can be used since the placement of the cameras will be external of the pipe. For the camera in a central body, the score is slightly worse because the range of cameras is limited to small form factor and fiber optic cameras. Therefore, the image clarity would be less than the other options for a camera costing the same. The camera pointing at a central body with a mirror scores the worst because this subsystem requires keeping the camera and the mirror clean. If these cannot be regularly cleaned and maintained, then image clarity will be severely impacted.

We used a similar approach for the camera frame rate analysis. All of the subsystems where the cameras can be placed outside the pipe score the same, but the camera in the central body scores slightly worse because the range of cameras available for use in our price range cannot achieve the same performance as those that could be used externally. All subsystems received scores of zero for the angle and vibration sensing systems because none of them can achieve these ECs. For the rest of the subsystem analyses we will give ratings to systems that can perform multiple functions to reward those that can serve more of our needs.

The scores in system stability have a more significant range in this matrix. Both subsystems with central bodies score lower due to the vibrations that could occur with the support vanes (similar phenomenon to what the IGVs experience) while the pipe elbow and composite imaging score higher because they do not have large components inside the system. The rest of the EC scores are filled out based on how long the system is, how easy it would be to implement it into the current testing refrigerant loop, and how much the flow inside the pipe would be impacted.

Given these scores, the pipe in an elbow concept is eliminated because its length and shape make it hard to implement into the current test loop. We also eliminated the camera looking at a central body because of the risk that the image would not be clear enough and that a mirror held in place by just one or two support vanes would not be stable enough to have usable data from the camera feed. Composite imaging and camera in a central body stay and will be further discussed later in the section.

Decision Matrix: Angle Monitoring Subsystem

The next decision matrix (Table 4) compares all of the concepts generated for the angle monitoring subsystem.

Table 4
Decision Matrix for Angle Monitoring Subsystems

		Potentiometer with Integrator		Iridescent Measurement		Camera with April Tags		Gyroscope/ Gyrometer		Digital Image Correlation	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	0	0.0	7	93.8	6	80.4	0	0.0	6	80.4
Camera Frame Rate	5.7	0	0.0	7	40.2	7	40.2	0	0.0	7	40.2
Angle Measurement Accuracy	6.5	4	26.0	3	19.5	9	58.5	6	39.0	9	58.5
Angle Measurement Refresh Rate	5.5	8	43.9	7	38.4	7	38.4	8	43.9	7	38.4
Vibration Sensing Accuracy	2.8	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Vibration Sensing Refresh Rate	2.3	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
System Stability	26.4	1	26.4	7	184.8	8	211.2	1	26.4	8	211.2
System Length	11.1	7	77.7	6	66.6	6	66.6	7	77.7	6	66.6
Ease of Integration	6.4	1	6.4	5	31.9	4	25.5	1	6.4	4	25.5
Pressure Drop across System	6.5	3	19.5	4	26.0	7	45.5	2	13.0	7	45.5
Pipe Illumination	13.4	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
			199.9		501.1		566.3		206.4		566.3

For the angle monitoring subsystems, some concepts received scores for the image clarity and camera frame rate sections. Even though none of these subsystems are specifically designed for these functions, we reward these concepts with scored in these sections to indicate that they could serve multiple functions. However, no subsystem received a score for the vibration sensing since none are capable of providing a usable measurement.

For angle measurement accuracy, the camera with April tags and composite imaging score the highest since they use a camera view which would not have as much noise introduced into the measurement signal. This is not the same for the potentiometer since there could be flow tugging on the string which could make the measurement useless. For the iridescent measurements, the color spectrum range would not be clear enough to have a great accuracy in the measurement.

For the angle measurement refresh rate, the potentiometer and the gyroscope score the highest since the sampling rate is done of an analog voltage so the rate can be determined by the microprocessor used. The others score slightly lower due to the dependence on the refresh rate of the camera. However, all of the subsystems have high scores because they easily meet the required sampling rate for angle measurements.

For system stability, the potentiometer and gyroscope subsystems score very low because they have strings or wires attaching to the vanes which could break off and impact performance. In the case of the gyroscope, computer components would need to be placed on the vanes themselves. This is similar for system integration. The need to attach things to the IGVs will make these concepts very hard to integrate into the testing environment and workflow while the other systems would be much easier to use.

For the pressure drop across the system, the potentiometer subsystem scores lower because it requires 7 waterproof potentiometers inside the pipe whose placement along the outer pipe edge will cause the flow inside the system to be impacted. For the iridescent paper and gyroscope concepts, a very thick sticker or computer chip will be placed on the IGV which will impact their overall performance and lead to a pressure drop. The April tags and DIC concepts score highest because the required image can be painted on the IGVs and will result in minimal flow impact.

Based on this matrix, the potentiometer concept is eliminated based on how hard it would be to integrate into the testing setup and how unstable it will make the system. The gyroscope is eliminated because it requires a computer component on every IGV and because of the instability it introduces. Finally, the iridescent concept is eliminated because it requires a thick sticker on each IGV and because of the low accuracy in the measurement of the angle. Camera with April tags and DIC will stay and be further discussed later in the section.

Decision Matrix: IGV Lighting Subsystem

The third decision matrix (Table 5) compares all of the concepts generated for the IGV lighting subsystem.

Table 5
Decision Matrix for IGV Lighting Subsystems

		Lighting Around Pipe		Camera Ring Light		Clear Acrylic Pipe	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	0	0.0	0	0.0	0	0.0
Camera Frame Rate	5.7	0	0.0	0	0.0	0	0.0
Angle Measurement Accuracy	6.5	0	0.0	0	0.0	0	0.0
Angle Measurement Refresh Rate	5.5	0	0.0	0	0.0	0	0.0
Vibration Sensing Accuracy	2.8	0	0.0	0	0.0	0	0.0
Vibration Sensing Refresh Rate	2.3	0	0.0	0	0.0	0	0.0
System Stability	26.4	7	184.8	7	184.8	6	158.4
System Length	11.1	7	77.7	7	77.7	5	55.5
Ease of Integration	6.4	7	44.6	7	44.6	9	57.4
Pressure Drop across System	6.5	7	45.5	6	39.0	10	65.1
Pipe Illumination	13.4	7	93.8	7	93.8	4	53.6
			446.4		439.9		389.9

All IGV lighting subsystems received scores of 0 for the first 6 engineering characteristics because they cannot serve those functions. All of the concepts for this subsystem have acceptable system stabilities but the clear acrylic pipe scores slightly lower because it uses a different material which may introduce problems if the material properties of the pipe network don't all match. For system length, the clear acrylic pipe scores lower again. This is because it requires a longer pipe section to allow for more of the ambient light to enter the pipe while the other concept could just be implemented into a thin ring attached between the compressor inlet and the inlet pipe.

For ease of integration and pressure drop, the acrylic pipe scores the highest because it is just a straight section of pipe that doesn't require any computer hardware or electronics to function, while the other concepts need power to work and will have components placed inside or along the edge of the pipe.

The acrylic section of pipe scores the lowest for pipe illumination because of how dependent it is on the lighting in the room. In addition, it is possible that the lights in the room have a frequency that could impact our sensing equipment and could result in a stroboscopic effect. We can control and remove this risk with our own dedicated lights.

Given this decision matrix, the clear acrylic pipe concept is eliminated because of the high dependence on the ambient light in the room and how a different material may introduce instability into the system. The ring light around the pipe and the lighting around the pipe concepts will stay and will be further discussed later in the section.

Decision Matrix: High Cycle Monitoring Subsystem

The final decision matrix (Table 6) compares the high cycle monitoring subsystems.

Table 6

Decision Matrix for High Cycle Monitoring Subsystems

		Potentiometer w/ Differentiator		Accelerometer on IGV		High Frame Rate Camera		Laser Vibrometer		Digital Image Correlation	
Option	Weight Factor	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating
Image Clarity	13.4	0	0.0	0	0.0	6	80.4	0	0.0	6	80.4
Camera Frame Rate	5.7	0	0.0	0	0.0	7	40.2	0	0.0	7	40.2
Angle Measurement Accuracy	6.5	2	13.0	2	13.0	0	0.0	3	19.5	9	58.5
Angle Measurement Refresh Rate	5.5	3	16.5	4	21.9	0	0.0	9	49.4	7	38.4
Vibration Sensing Accuracy	2.8	2	5.6	4	11.2	3	8.4	8	22.4	6	16.8
Vibration Sensing Refresh Rate	2.3	8	18.4	8	18.4	5	11.5	8	18.4	5	11.5
System Stability	26.4	1	26.4	2	52.8	8	211.2	8	211.2	8	211.2
System Length	11.1	7	77.7	7	77.7	6	66.6	6	66.6	6	66.6
Ease of Integration	6.4	1	6.4	1	6.4	7	44.6	5	31.9	4	25.5
Pressure Drop across System	6.5	3	19.5	2	13.0	7	45.5	8	52.0	7	45.5
Pipe Illumination	13.4	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
			183.4		214.4		508.4		471.4		594.6

Again, some of the subsystems received scores for the first four engineering characteristics to reward those concepts for serving multiple functions.

When looking at the vibration sensing accuracy, the laser vibrometer scores the highest due to the laser it uses. The accuracies of the high frame rate camera and digital image correlation are highly dependent on the camera used. The cameras would need to be very high resolution in order to detect very small changes in motion of the vane. For the potentiometer, the accuracy will be impacted because the strings attached to the IGV will move based on the flow in the pipe. The accelerometer also has a low accuracy score because the computer chip placed on the vane will likely impact the vibrations enough so that the measurement doesn't represent the true vibration that the vane is undergoing.

For the vibration sensing refresh rate, the potentiometer, accelerometer and laser vibrometer all score the highest because they output a voltage which can be read to get the data.

The high framerate camera and DIC concept's refresh rates are dependent on the refresh rate of the camera which will be lower than that of the voltages.

For system stability, the accelerometer and potentiometer score low for the same reasons as previously discussed where components need to be attached to each vane. For system length, all concepts that require a camera view have a lower score since the cameras need to be far away enough to get a full view of the IGVs while the potentiometer and accelerometers can be placed right next to the IGVs.

The potentiometer and accelerometer received lower scores for ease of integration and pressure drop for the same reasons as previously discussed where components need to be placed on the IGVs. The DIC received a lower integration score because it requires dots to be painted on the IGVs and the laser vibrometer received a low integration score because it needs to be calibrated onto the vane tip.

Because of how hard it is to integrate into the system, both the potentiometer and accelerometer concepts are eliminated. While the high frame rate camera has a pretty high score, it is also eliminated because of its low performance in the vibration measurement. The DIC and laser vibrometer concepts stay and will be further discussed.

Final Concept Selection

From the previous matrices, only a few concepts remain, outlined in table 7 below.

Table 7
Remaining Concepts from Each Subsystem

Low Cycle Monitoring	Angle Monitoring Subsystem	IGV Lighting Subsystem	High Cycle Monitoring
Camera in Central Body	Camera With April Tags	Camera With Ring Light	Laser Vibrometer
Composite Imaging	Digital Image Correlation	Lighting Arround Pipe	Digital Image Correlation

These remaining concepts need to be combined in a way that best meets the needs of the customer and provides an easy to use comprehensive monitoring system. For the low cycle monitoring subsystem, the camera in the central body is the better solution. This is because Danfoss specified that they want a view directly from the center of the inlet. While this could be achieved with composite imaging, the processing would be much more intensive and the hardware would be harder to calibrate. In addition, composite imaging requires the use of multiple cameras which would increase the cost of our system by a factor of two. While the central body might impact the flow more than the composite imaging, Danfoss has a lot of experience with designing central bodies since some of their higher end compressors use them in the IGV assembly. This is expertise that we could leverage in our design.

For similar reasons, the camera with April tags is the more desirable subsystem for angle measurement. Since Danfoss only requires an angle accuracy range of ±10%, the larger cost of the DIC system with multiple cameras would provide no real benefit over the much cheaper solution using the camera in the central body. Both of these concepts require thin stickers or paint on the IGVs so there is no real difference in the flow impact or ease of integration between the two subsystems.

Given that our range of possible cameras is already somewhat restricted to match the size specifications of our central body, requiring a ring light to be a part of the camera assembly would further limit our options. For this reason, specifying a separate lighting system with lights placed around the pipe gives us more options to provide the best lighting of the IGVs. Therefore, it is the concept that we select for this subsystem. If we do find a suitable camera with a ring light, then we can still remove this separate component but for the purposes of this project, it is better to plan for a separate subsystem then to have to make one last minute.

Since Danfoss has told us that the high cycle measurement subsystem is more of an extra credit component than a requirement, our group decided that it would be better to have a system that is more modular in measuring vibrations as opposed to a system that is deeply integrated into the rest of the project. That way it can be easily added or removed depending on if the presence of IGV vibrations is detected. For this reason, the laser vibrometer is chosen for the high cycle monitoring subsystem. Not only does this subsystem better fit the needs of our sponsor, but it is also cheaper than a DIC system which requires two cameras, and has much better performance than the DIC solution.

The final concept selection that we will move forward with is given below in table 8.

Table 8
Final Concepts Selected

Low Cycle	Angle Monitoring	IGV Lighting	High Cycle
Camera in Central Body	Camera With April Tags	Lighting Arround Pipe	Laser Vibrometer

1.7 Spring Project Plan

Now that the design has been selected, our team has created a plan for the next semester to design, prototype and build the final product for Danfoss. The timeline for our plan is included in our Gantt Chart in figure 20. The critical path of our project is shown by the boxes in dark blue.

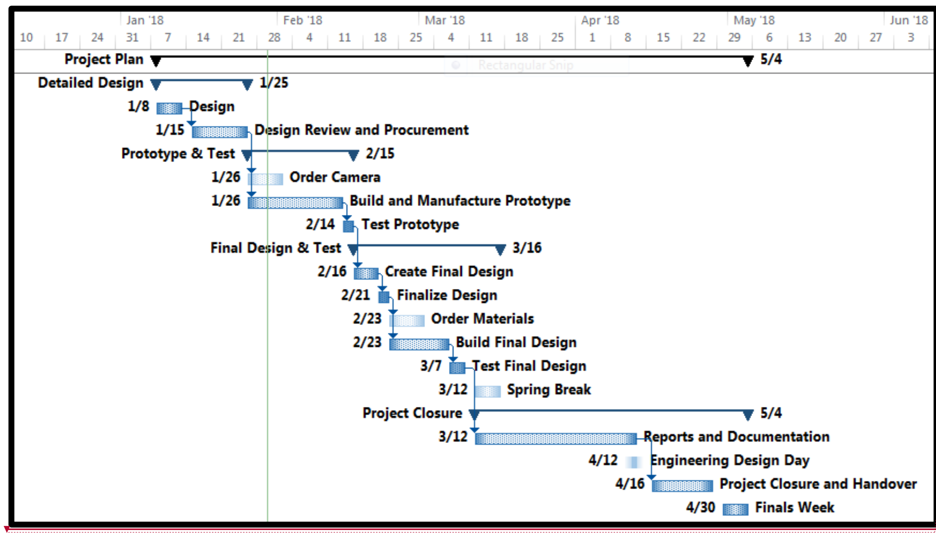


Figure 20 Spring Project Plan Gantt Chart.

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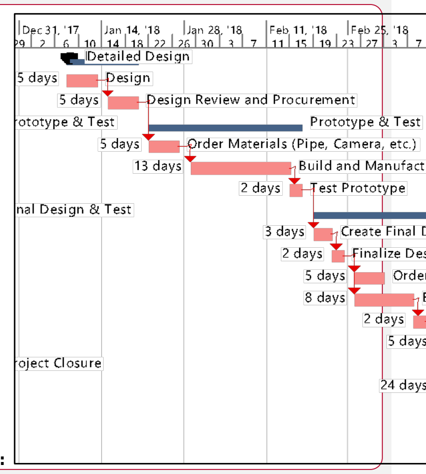

This timeline includes the dates for spring break, engineering design day, and finals week. These gauge how the project is progressing in relation to major dates in the semester. The final product must be completed by engineering design day so we can present it to the sponsors and instructors. In order to meet this deadline, we plan on completing the design process in late January so that we can order parts and build the prototype by the middle of February. After building and testing the prototype, our team will do a redesign to address any issues discovered in the original prototypes. We plan on having this completed by the start of spring break.

The time between spring break and senior design day will be spent on final tweaks to the product and documentation. This also act as our buffer time if any of our other tasks take longer than expected. After engineering design day, we will complete the project and hand it over to our sponsor.

Our main bottleneck in this project will be testing our prototype due to the Danfoss test lab which is currently under construction. As a result, testing time is limited. Additional bottlenecks include the time to manufacture parts at Danfoss and other processes that we will need to go through in assembling our prototype (like brazing the brass components). Since the camera has already been purchased and has arrived, procurement is no longer a bottleneck.

Details about the project budget and individual task assignments can be seen in the One Page Project Manager (OPPM). This is included in appendix C..

Appendices

Appendix A: Code of Conduct

Mission Statement

Team 4 is dedicated to ensuring a positive work environment that supports professionalism, integrity, respect, and trust. Every member of this team will contribute a full effort to the creation and maintenance of such an environment to bring out the best in all of us as well as this project.

Roles

Each team member is assigned one of the following roles based on their previous experiences and skill set and is responsible for completing the following actions. All team members must contribute to the project in the following ways:

- Must work on their certain tasks for the project
- Must work toward the project goals and its success
- Deliver any commitments on time
- Work as an effective team member with team spirit

Arnold M. Schaefer - Team Leader

Manages team as a whole; develops a plan and timeline for the project; delegates tasks among group members according to their skill sets; finalizes all documents and provides input on other positions where needed. The team leader is responsible for promoting synergy and increased teamwork. If a problem arises, the team leader will act in the best interest of the project.

The team leader keeps the communication flowing, both between team members and the sponsor. The team leader takes the lead in organizing, planning, and setting up all of the meetings. The team leader will also be responsible for editing the evidence manual and keeping it up to date. The team leader is responsible for the overall project plans and progress.

Brandon A. Klenck - Lead Mechanical Engineer

Takes charge of the mechanical design aspects of the project. Lead ME is responsible for knowing the details for the design, and presenting the options for each aspect to the team for the decision process. Keeps all design documentation for record and is responsible for gathering all reports and maintains product quality and safety. In addition, the lead ME is responsible for keeping a record of all correspondence in group meetings.

Peter R. House – Lead Efficiency Engineer

Takes charge of the efficiency of the project design. Will work in conjunction with the Lead ME to identify problem areas and to work on smaller improvements and iterations leading to a more streamlined final product.

Will also work to identify problematic areas in the rest of the team to try and implement solutions to increase the team's overall workflow. Will finally be responsible for aggregating documentation and working on final presentations.

Travis J. Carter – Operations Officer

Manages the orders and budget and maintains a record of all credits and debits to the project account. Any product of expenditure requests must be presented to the advisor, whom is then responsible for reviewing and the analysis of equivalent/alternative solutions. They then relay the information to the team and if the request is granted, order the selection. A record of all these analyses and budget adjustment must be kept.

Additionally, the Operations Officer will build and maintain the team website to ensure that all relevant information is posted and up to date and maintain the group's one page project manager.

Team Role Matrix

Team Member:	Team Leader	Lead ME	Lead Efficiency Engineer	Operations Officer
Travis Carter				X
Brandon Klenck		X		
Peter House			X	
Arnold Schaefer	X			

Communication

All remote team communication will occur in two main places, GroupMe and email. GroupMe will be used for casual conversations and planning while email will be used for more official purposes such as document preparation, review and submission. Therefore, all team members must have access to a working email account, access to GroupMe and regularly check all accounts to keep up with group progress. All files transferred via email to Danfoss or the instructors should have the rest of the team members carbon copied, while files emailed between team members should only have the rest of the team members carbon copied if their input is needed.

The team will also conduct weekly meetings on Tuesdays and Thursday from 12:30PM to 2:00PM to discuss all progress and further actions. Team members must all be present for this meeting. 24 hour notices should be given if a member cannot make the meeting in time. Repeated absences will not be tolerated. All members of the team must also attend all meetings with the sponsor. 24 hour notices should be given if a member cannot make the meeting in time. Repeated absences will not be tolerated.

All team members must be present for presentation practice sessions in the week leading up to the due date. Practice times will be decided a week in advance at the weekly team meeting.

Team Dynamics

All team members will work with a team dynamic allowing the others to make comments and suggestions without fear of embarrassment or ridicule. If any team member finds their given task too difficult or they face a roadblock, they should inform the rest of the team members and ask for help so that the tasks can be completed with the quality and timeliness expected of our team. If any team member feels that they are not being respected or taken seriously, they should address the issue with the team so that a resolution can be found. Everything is done for the benefit of all members and no individual member should suffer an unequal burden.

Ethics

Team members are required to be familiar with the NSPE Engineering Code of Ethics as they are responsible for their obligations to the public, the client, the employer, and the profession. There will be stringent following of the NSPE Engineering Code of Ethics.

Dress Code

Team meetings will all be held in casual attire. Meetings with the sponsor will be held in business casual attire (i.e. pants & button down shirts). Team presentations will be held in formal attire (i.e. suits). Color coordination will be decided on a case by case basis at team meetings.

Weekly and Biweekly Tasks

Team members will participate in all meetings with the sponsor, adviser, and instructor. During said times ideas, project progress, budget, conflicts, timelines and due dates will be discussed. In addition, tasks will be delegated to team members during these meetings. Repeat absences or incomplete tasks will not be tolerated.

Decision Making

It is conducted by consensus and the majority of the team members. Should ethical or moral reasons be cited for dissenting reason, then the ethics or morals shall be evaluated as a group and the majority will decide on the plan of action. At least 3 team members must participate in the vote. In the case that the vote ends up in a tie, the advisor to the team will be given a vote. Individuals with conflicts of interests should not participate in decision-making processes but do not need to announce said conflict. It is up to everyone to act ethically and for the interest of the group and the goal of the project. Achieving the goal of the project will be the top priority for each group member. Below are the steps to be followed for each decision-making process:

- Problem Definition – Define the problem and understand it. Discuss among the group.
- Tentative Solutions – Brainstorm possible solution. Discuss among most plausible group.

- Data/History Gathering and Analyses – Gather data required for implementing tentative solution. Re-evaluate tentative solution for plausibility and effectiveness.
- Design – Design the tentative solution product and construct it. Re-evaluate for plausibility and effectiveness.
- Test and Simulation/Observation – Test design for tentative solution and gather data. Re-evaluate the testing phase and determine its level of success. Decide if design can be improved and if time/budget allows for it.

Conflict Resolution

In the event of discord amongst team members the following steps shall be employed:

- Communication of points of interest from both parties which may include demonstration of active listening by both parties though paraphrasing or other tools.
- Administration of a vote, if needed, favoring majority rule.
- Team leader intervention.
- Instructor will facilitate the resolution of conflicts.

Work Schedule Prioritization

The team will attempt to organize tasks and meetings in a way that time spent working during the weekend is minimized. In addition, federal, university and religious holidays will be observed and no work will be required of any team member during that time.

Individual Work Schedules

In addition to the weekly team meetings and sponsor meetings, each team member is required to commit to at least 15 working hours per week, and more if needed. This working time can be completed by working on individually assigned tasks or working with others in the team.

Amendment Procedure

In the case that a change is required to be made to this document, the following amendment process will be followed. Any team member can present an amendment in a written email or text message to the group. Following the proposal, each team member must vote on the issue before a decision is made. One vote will be given to each team member with the option to vote for the amendment, vote against the amendment, or to voluntarily abstain from the vote. To pass, the proposal must receive at least 3 votes for the amendment. If the vote is 3 to 1 for the amendment, the change will be made effective one week after the decision is made. A unanimous vote for the proposal will leads to immediate effective implementation. A new code of conduct will then be written and re-signed by all members.

Statement of Understanding

By signing this document, the following members of team 4 agree to all of the above and agree to abide by the code of conduct set forth by the group.

Peter R. House:

Sign: ______________________ Date: 10/5/17

Travis J. Carter:

Sign: ______________________ Date: 10/5/17

Brandon A. Klenck:

Sign: ______________________ Date: 10/05/17

Arnold M. Schaefer:

Sign: ______________________ Date: 10/5/17

Amendments

10/5/17

- Changed team meetings from Thursdays after senior design lectures to Tuesdays and Thursdays from 12:30PM to 2:00PM
- Added team leader responsibility of maintaining the evidence manual
- Added operations officer responsibility of maintaining the one page project manager

Appendix B: Target Catalogue

Below is a table outlining all of the individual targets that are required for the project.

Table 9
List of Required Targets and Their Values

TARGET	VALUE
Minimum Camera View Resolution	720 x 720 pixels
Minimum Sample Rate for Measuring Vane Low Cycle Failure	1 Hz
Minimum Sample Rate for Measuring Vane High Cycle Failure	1 kHz
Minimum Refresh Rate for Measuring Vane Latching Failure	1 Hz
Minimum Angle Sensor Accuracy (in terms of percent open)	± 10%
Minimum Sample Rate for Measuring Angle	1 Hz
Required Source of Power	US Outlet AC at 110V
Allowable Flow Impact	No Detectible Swirl
Maximum Allowable Pressure Drop Across Device	0.02 psi
Internal Pipe Illumination	1000 lux
Minimum Video Display Resolution	720 x 720 pixels
Minimum Video Display Refresh Rate	60 Hz
Required Inner Pipe Diameter	80 mm
Maximum Monitoring System Length	0.5 m
Minimum Angle Display Refresh Rate	1 Hz
Maximum Refrigerant Pressure	110 psi (absolute)
Minimum Refrigerant Pressure	10 psi (absolute)
Maximum Refrigerant Temperature	80° F
Minimum Refrigerant Temperature	-10° F
Maximum Refrigerant Mass Flow	2.5 kg/s
Minimum Refrigerant Mass Flow	0 kg/s

Appendix C: One Page Project Manager

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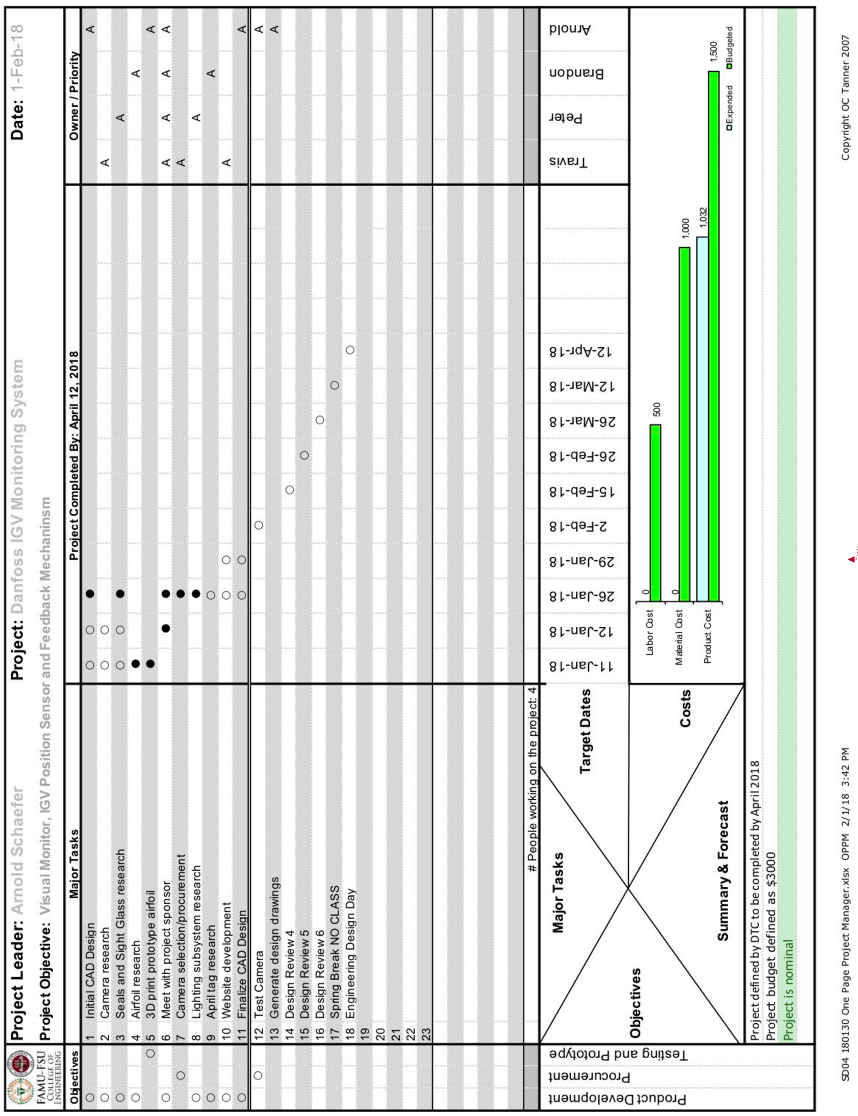

References

There are no sources in the current document.