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EML4551-2

Team 04: Danfoss IGV Monitoring System

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Abstract

Disclaimer

Acknowledgement

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Notation

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:

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 and high cycle failures
- Minimize impact on the fluid flow

Primary Market:

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

Stakeholders:

- Danfoss Research and Development Test Lab
- 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.

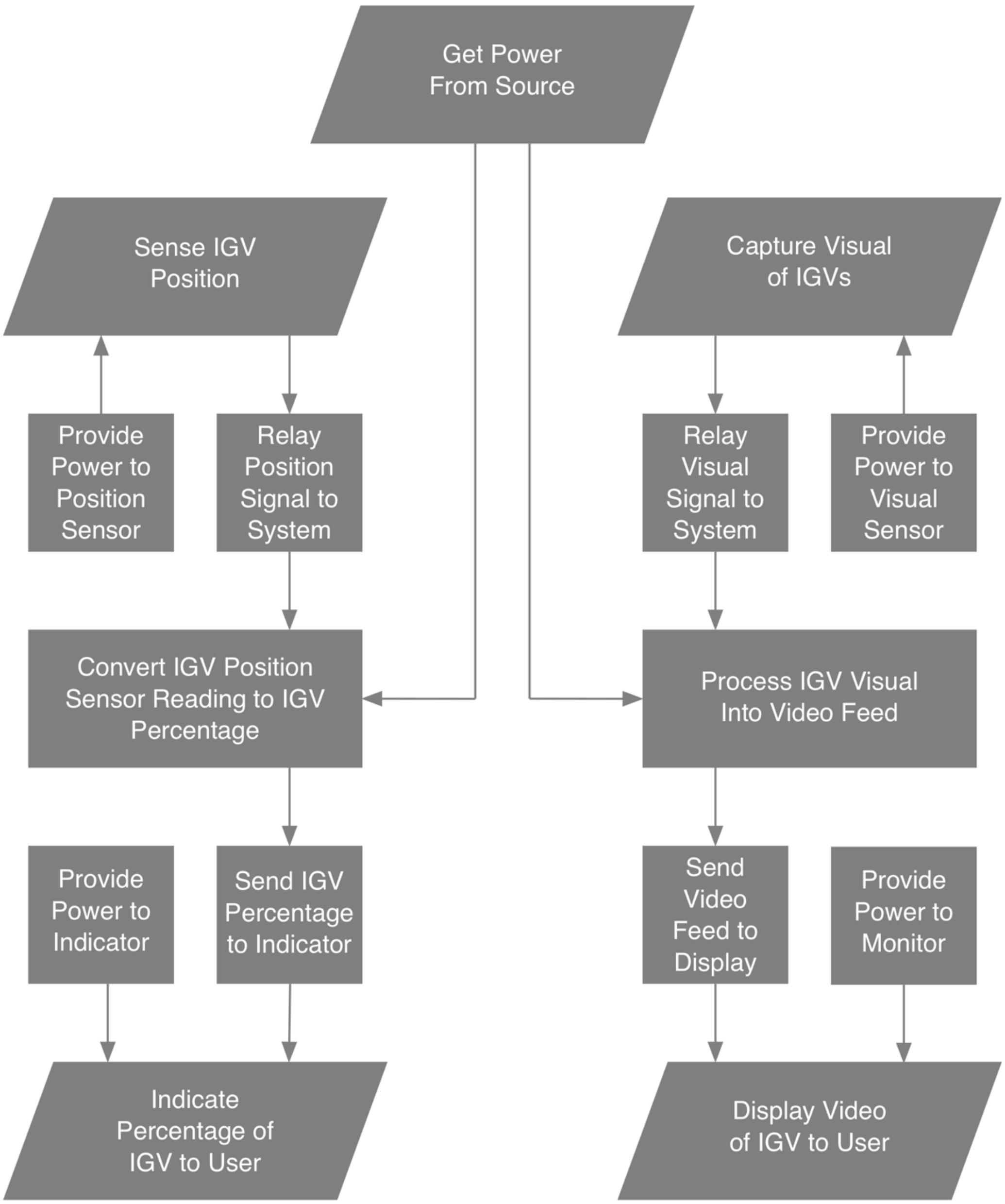

Figure 1. Flow diagram of all items in the functional decomposition.

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
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
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

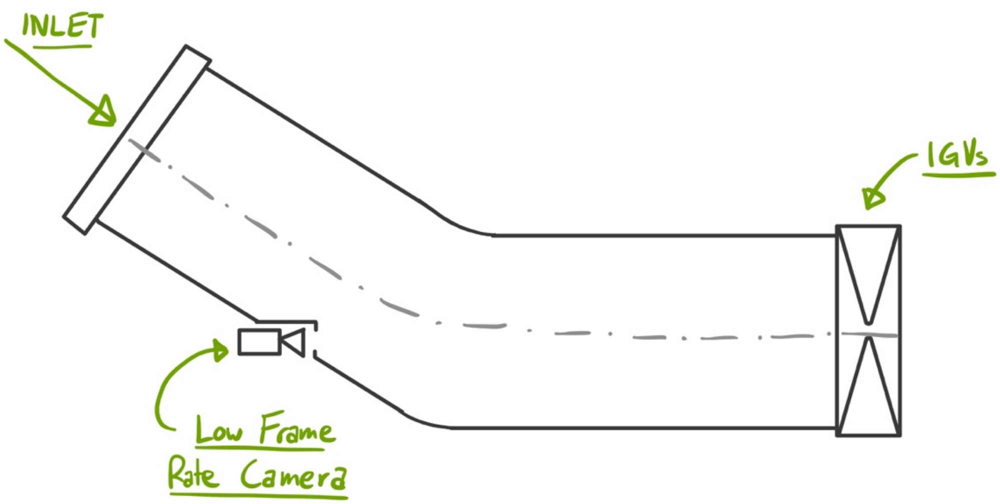

Figure 2. Low cycle monitoring concept utilizing a camera in a pipe elbow.

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

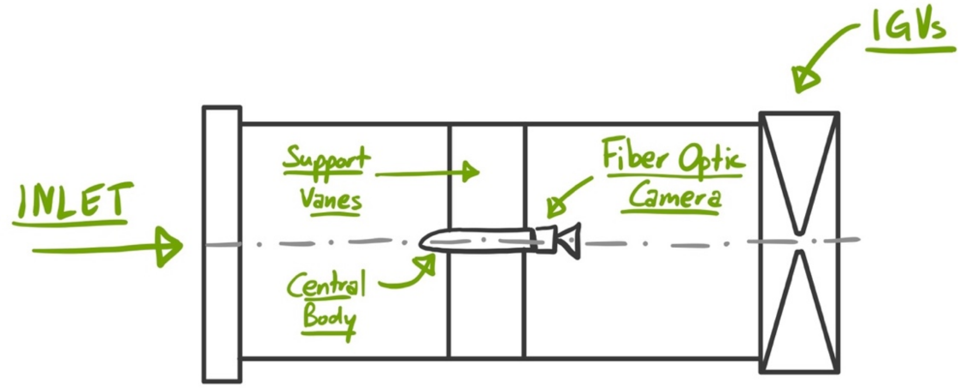

Figure 3. Low cycle monitoring concept utilizing a fiber optic camera in a central body.

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

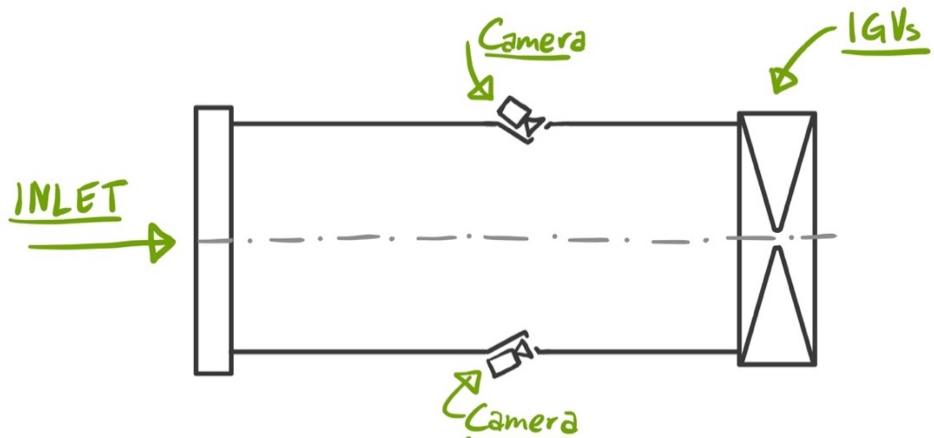

Figure 4. Low cycle monitoring concept utilizing cameras to make a composite image.

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

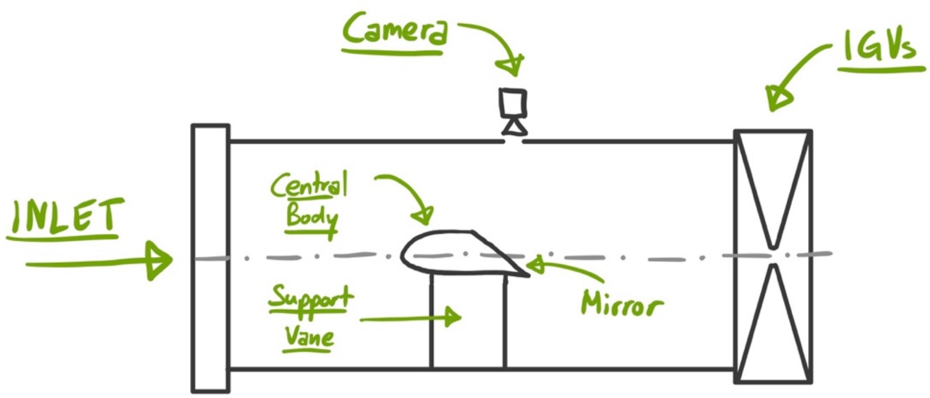

Figure 5. Low cycle monitoring concept utilizing a mirror and external camera.

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

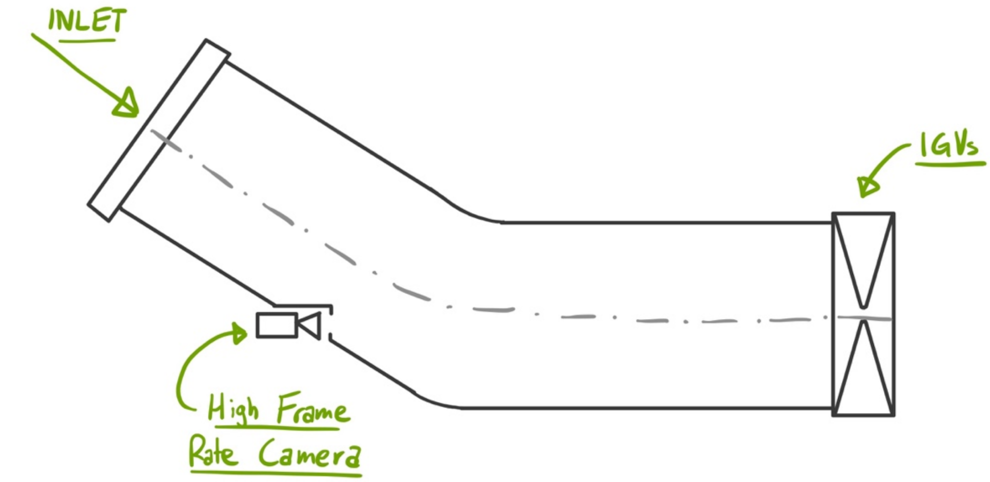

Figure 6. High cycle monitoring concept utilizing a high framerate camera.

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

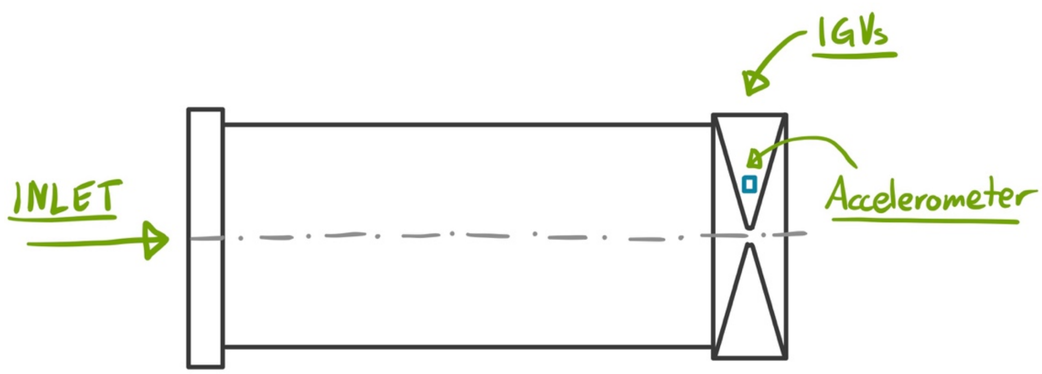

Figure 7. High cycle monitoring concept utilizing an accelerometer.

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

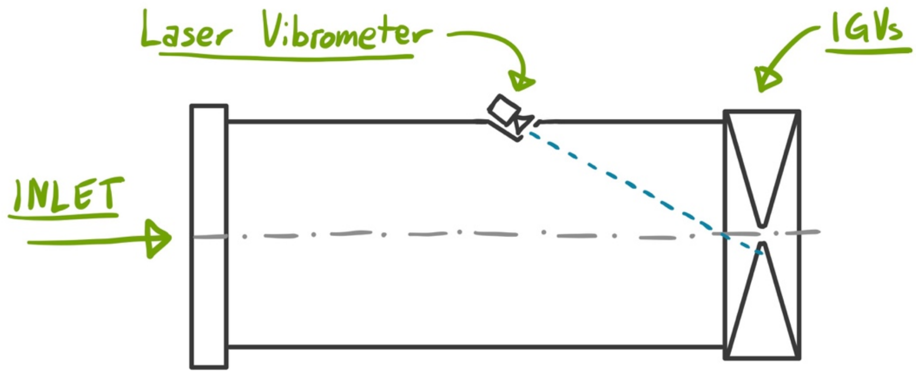

Figure 8. High cycle monitoring concept utilizing a laser vibrometer.

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

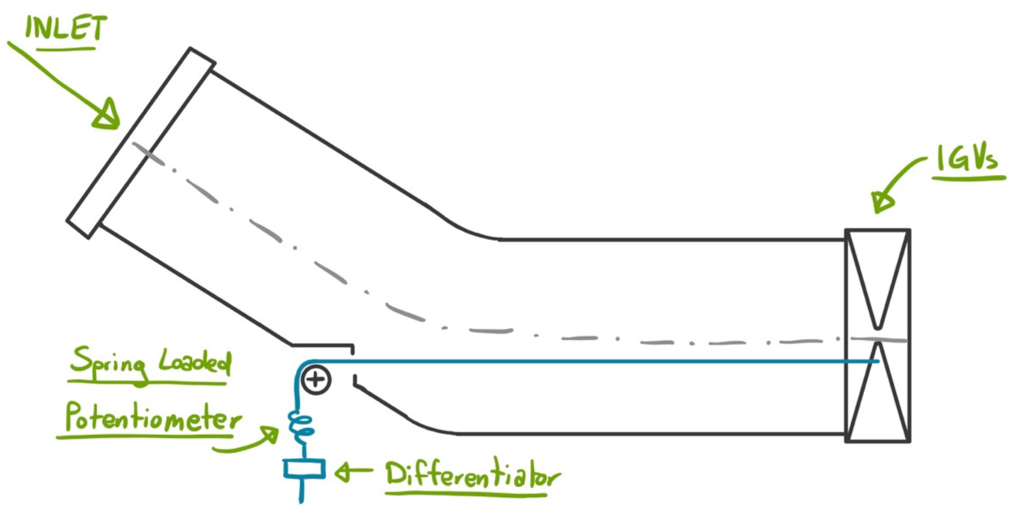

Figure 9. High cycle monitoring concept utilizing a potentiometer with a differentiator.

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.

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

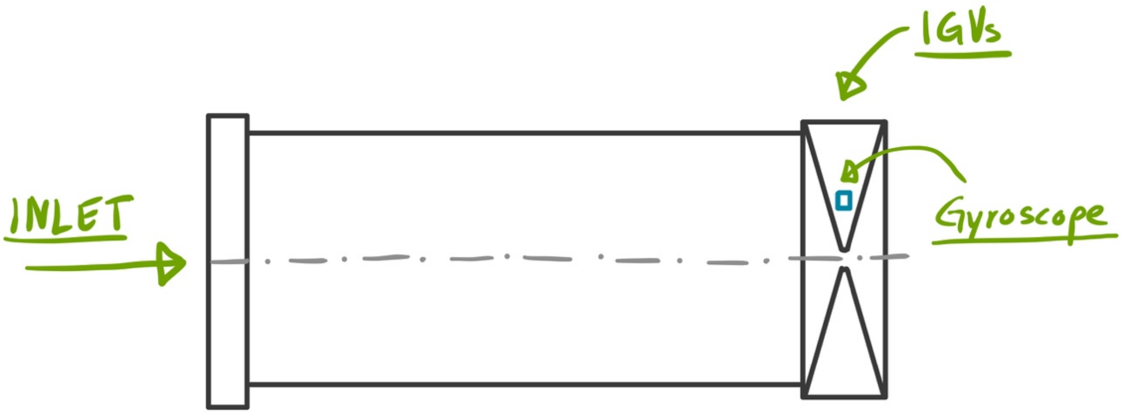

Figure 10. Angle monitoring concept utilizing a gyroscope.

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

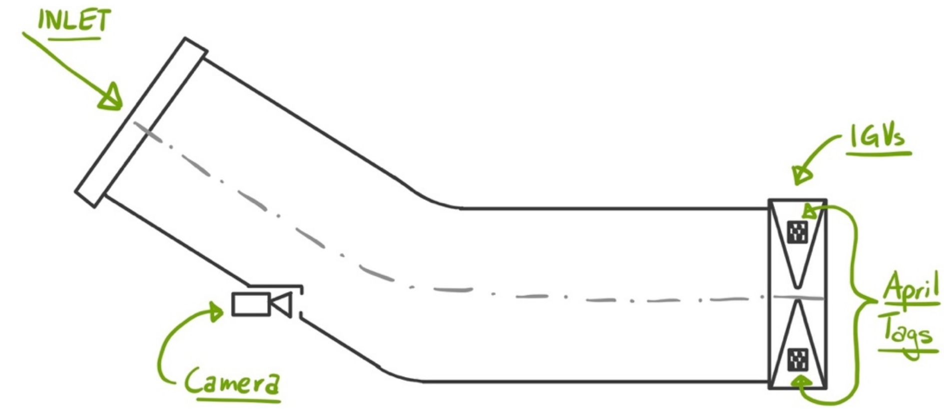

Figure 11. Angle monitoring concept utilizing a camera and April tags.

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

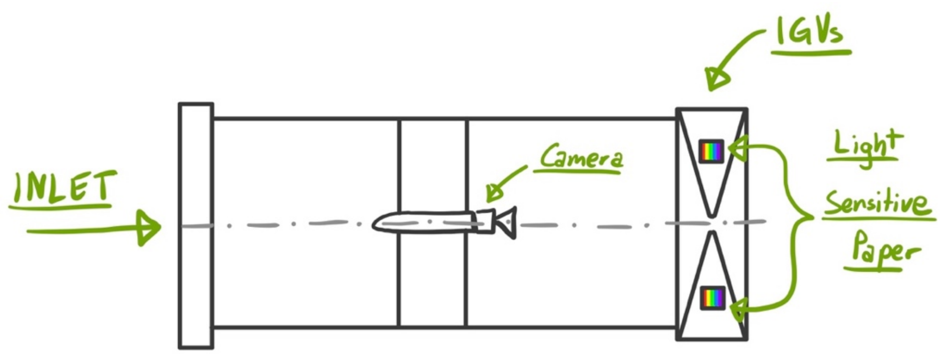

Figure 12. Angle monitoring concept utilizing a camera and light sensitive paper.

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

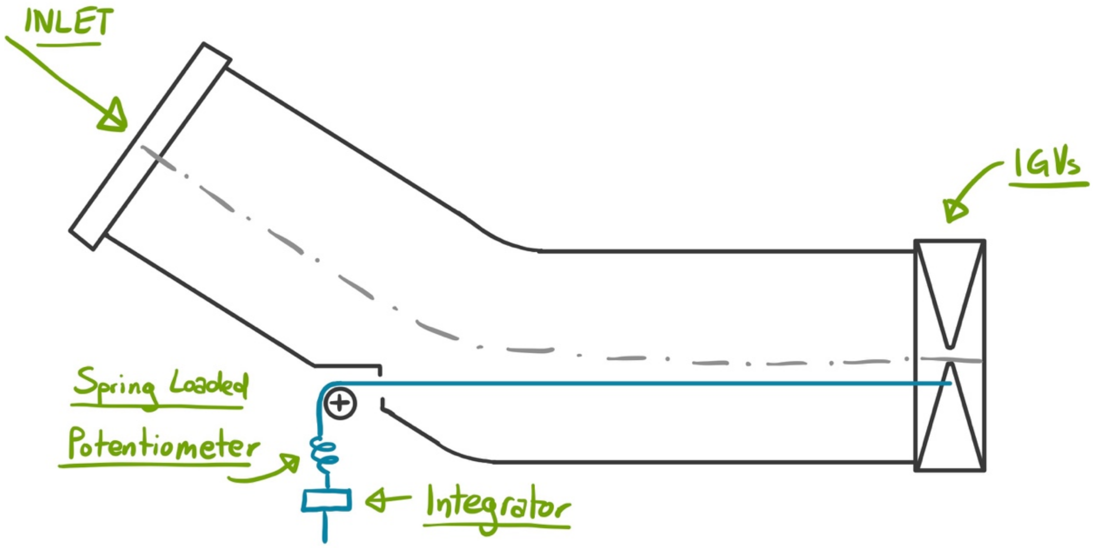

Figure 13. Angle monitoring concept utilizing a potentiometer and an integrator.

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.

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

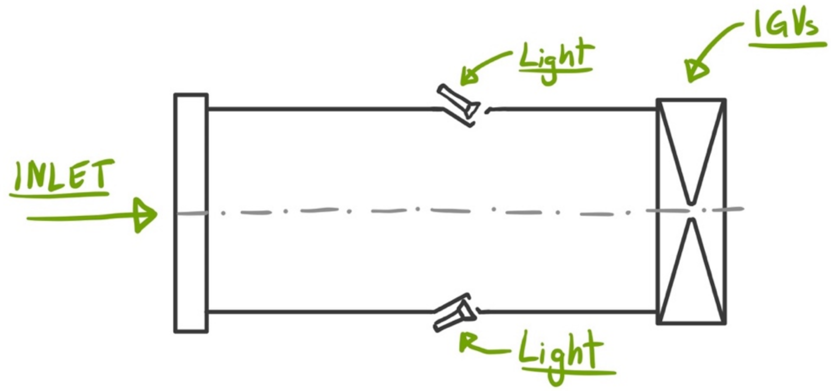

Figure 14. Lighting concept utilizing individual lights in pipe.

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

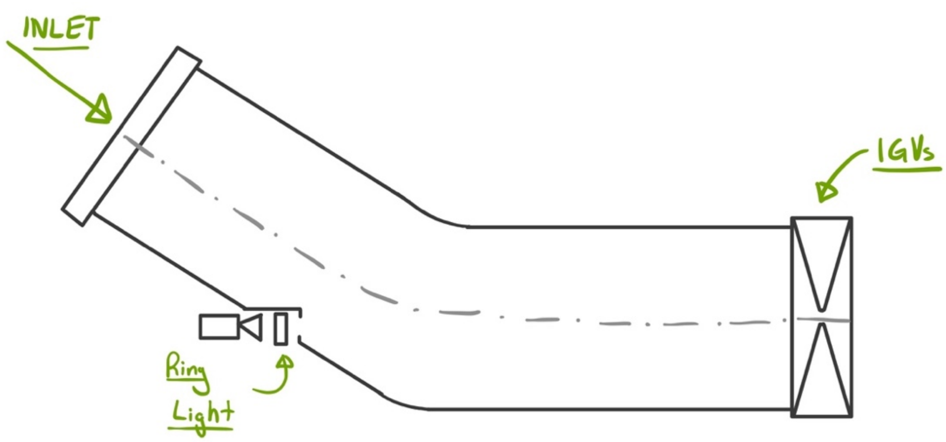

Figure 15. Lighting concept utilizing a ring light around the camera.

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

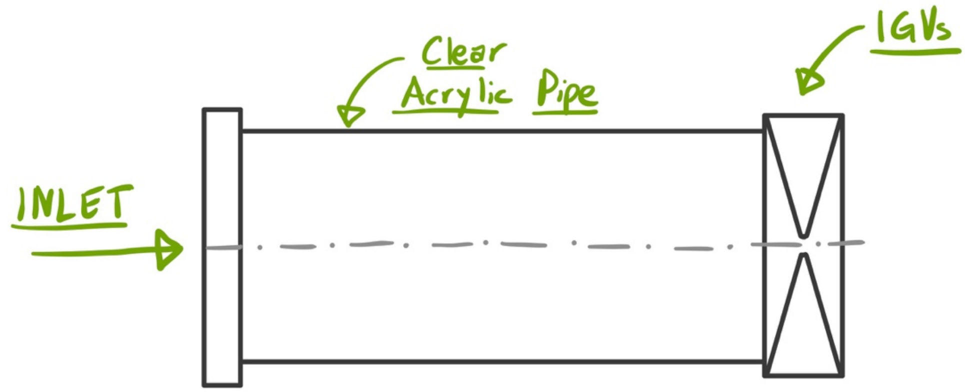

Figure 16. Lighting concept utilizing clear acrylic pipe.

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

Placeholder for Concept Selection

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 3
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

References

There are no sources in the current document.