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Corrosion Detection in Enclosed Environments using Remote Systems

By

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Table of Contents

List of Tables

List of Figures

Abstract

Infrastructure throughout the United States is ageing and the need for its preservation is in a greater demand than ever. In order to maintain and monitor the infrastructure, routine inspection for corrosion is a necessity. A new inspection platform is needed in order to reduce inspection time and increase corrosion data collection. Currently, corrosion detection can be performed via many different technologies, such as thermography, ultrasonic, radiography, magnetic, and visual inspection. Each technology has different benefits and drawbacks with none being best suited for examining corrosion under all potential conditions. This thesis analyzes a process of detecting corrosion in difficult-to-reach areas. The research was then paired with a remote device to be used to detect corrosion in enclosed environments for the University Student Design and Applied Solutions Competition.

I. Introduction

Corrosion is an electrochemical process that causes the oxidation of metal in the presence of water. Corrosion can be viewed as the spontaneous reaction that turns a metal back into its original ore.[1] Rust is a chemical reaction between water, oxygen, and iron causing the iron, a main component in steel, to undergo changes. In some cases this can be beneficial in protecting the metal and in other cases this process may continue to occur thereby degrading the material. Due to the abundance of oxygen and water in the environment, the process of oxidation occurs frequently.

This natural phenomenon brings about multiple problems throughout the world. Heavily corroded structures weaken and could jeopardize its safety. Degraded structures could also lead to high maintenance costs. Routine inspection of metal structures is needed to ensure structural strength and reliability. Currently, inspection for corrosion or pre-corrosion is mostly performed visually.[2] For improved inspection, detection devices allow for more thorough inspections as well as increased data collection. Corrosion detectors can enhance the knowledge of a corroded area by providing accurate length and depth measurements. Some devices, such as eddy current and ultrasonic devices, have abilities to detect corrosion and defects beneath the surface. These devices are used when coatings have been applied onto metal surfaces. One such corrosion defect is the pin hole, invisible to the human eye, that can allow water and oxygen into get to the underlying metal and corrode the structure. Devices such as, but not limited, to eddy current and ultrasonic help inspectors locate areas of corrosion below-the-surface. Image processing techniques can also be used to better analyze photos of corrosion for documentation of future action. Documentation is very important when detecting corrosion to learn more about the rate of corrosion which can lead to estimates of the life-times of coatings and structures.

The inaugural University Student Design and Applied Solutions Competition focuses on addressing the problem of detecting corrosion in enclosed environments. The competition is hosted by NACE International, the worldwide corrosion authority, and funded by the United States Department of Defense. The Department of Defense is involved because of the huge demand for the inspection of corrosion on its weapons systems and massive infrastructure all over the world in harsh environments. For this competition, NACE international created a structure that represented a mixture of box girders on bridges, highly structured areas similar to ones on ships, small spaces such as fuel tanks or aircraft fuselage areas, and pipelines.[2] The posed challenge is to design a system that can detect and locate the presence of corrosion or pre-corrosion conditions in the structure. A list of all the different types of corrosion and pre-corrosion defects possibly located in the mock structure was given to each team along with practice samples. Each team was given the freedom to come up with their own idea on how to solve the problem. On April, 19th 2016 the teams met in Houston, Texas to present their ideas for corrosion detection in enclosed environments.

One of the main goals of the competition is to create awareness of the issues associated to strengthen and expand the corrosion industry. Students benefit from the competition by;[2]

- Gaining practical experience
- Enhancing project management skills
- Understanding the impact of corrosion and methods of its detection
- Increasing exposure to corrosion-related industries such as NACE international and the Department of Defense
- Gaining insight into the structures that require corrosion control and prevention

Our group arrived at a design solution involving the use of drone technology applied to problems associated with corrosion detection. Drone technology is not new, however new applications for drones have recently expanded significantly. This thesis discusses the usage of manually piloted quadcopters to detect corrosion. A list of limitations to the solution and future areas of study relating to this problem are also discussed.

II. Literature Review

The competition called for the detection of red rust, cracking, damaged coating, coating holidays, scratches, scribe creep, % RH, and standing water.[2] In inspecting, teams are given the freedom to come up with any solution to solve the problem. The only limitations are the students need to remotely control the system from 15 feet away and that the evaluation of the structure needs to be nondestructive.

II. A. Corrosion

Firstly, an understanding of the corrosion mechanisms that will be detected in the competition is needed. Corrosion is the degradation of a material by its environment.[3] This process is environmentally assisted due to the fact that the reactions are assisted or aggravated in the presence of an aqueous environment. Corrosion is an electrochemical process that involves multiple half-cell reactions and is not a direct reaction between metal and its environment. An oxidation half-cell reaction is one that has electrons as products. A reduction half-cell reaction is one that has electrons as reactants. From corrosion there is a loss of metal due to the oxidation and the loss of electrons on the anodic site. Examples of these reactions are represented in the three equations below;

Equation 1. $Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$

Equation 2. $Al(s) \rightarrow Al^{3+}(aq) + 3e^-$

Equation 3. $2Cu(s) + H_2O(l) \rightarrow Cu_2O(s) + 2H^+(aq) + 2e^-$

From the creation of electrons, cathode reactions then occur and there exist a reduction in the given species.[3] For acidic solutions the hydrogen ions are reduced as shown in the equation below:

Equation 4. $2H^+(aq) + 2e^- \rightarrow H_2(g)$

For neutral and basic solution there is a reduction in oxygen as shown in the equation below:[3]

Equation 5. $O_2 (g) + 2H_2O + 4e^- \rightarrow 4OH^-(aq)$

Rusting occurs due to the corrosion of iron and carbon steel.[3] There are many different forms of rust based on the environment it was created in. Red rust occurs due to highly corrosive environments where there exists high oxygen and water exposure.[4] Red rust environments usually include a salt which enhances the oxidation reaction. Yellow rust occurs when there is very high moisture content; usually occurring where standing water exists or existed. Brown rust occurs when there is high oxygen and low moisture. Black rust occurs when there is limited oxygen. Although there are four different types of rust, in most instances more than one form of rust is present.

Rust is a hydrated ferric oxide that is produced from the products of the cathodic and anodic corrosion reactions.[3] The following two equations show the creation solid ferrous hydroxide and its conversion into a hydrated ferric oxide.

Equation 6. $Fe^{2+} (aq) + 2OH^-(aq) \rightarrow Fe(OH)_2(s)$

Equation 7. $Fe(OH)_2(s) + (x-1) H_2O(l) \rightarrow Fe_2O_3*xH_2O(s) + 2H^+(aq) + 2e^-$

Cracking, damages, holidays, and scratches in the coating can lead to forms of corrosion such as scribe creep, pitting, and rust. Relative humidity and the presence of standing water increase the chance of corrosion to occur. The average humidity worldwide is 75% and the corrosion of metal occurs with greater frequency in environments where the relative humidity is above 55%.[5]

II. B. Corrosion Detection Techniques

From a basic understanding of the types of corrosion that need to be detected, the next task required researching corrosion detection techniques. The five most used and developed technologies are visual inspection, electromagnetic eddy current, acoustic ultrasonic, radiography, and thermography.[6]

Visual inspection can detect corrosion on the surface of the part. This can be preformed with the help of optical devices such as flashlights, mirrors, magnifying aids, borescopes, fiberscopes, and video imaging systems. Quantitative data is received and determining extent of the corrosion is up to the discretion of the inspector. Visual inspection is a very reliable technique as long as the inspector is well experienced in the field of corrosion.[6] Visual inspection is usually paired with ultrasonic and eddy current techniques for further analysis. Video and image processing can then be applied to identify measure and classify defects.

Electromagnetic eddy current devices induce eddy currents on and below the surface which generate magnetic fields opposite of the original magnetic field. [6] Impedance is created that can be easily measured and compared with other locations. Eddy current devices are sensitive to changes in conductivity, geometry, and defects. These devices are usually battery powered probes with coils. A main limitation of using eddy current devices is that the area to be detected needs to be accessible to the eddy current probe.

Acoustic ultrasonic devices create high frequency sound waves and detect variations in the reflection of the waves over the surface.[6] Differences in the reflection of the waves suggest flaws in the part. A disadvantage of ultrasonic is that water or some other medium is needed between the transducer and the surface.

Radiography devices produce radiation in the form of x-rays or gamma rays.[6] The absorption of the radiation is then measured and flaws which affect absorption can be detected. Radiation hazards and the complexity of the equipment are disadvantages for the use of this form of detection.

Thermographic devices can detect anything that affects the thermal properties of the part.[6] Infrared detectors and IR cameras detect thermal changes; however the resolution is limited.

III. Concept Design

Table I, below, show the judging criteria for the competition.

Table I. Judging Criteria for the USDASC[2]

Defect Type	Increasing Difficulty in Detection Measurement Accuracy →		
	Minimum	Better	Ideal
Corrosion/Cracking	• Is any red rust present • Appearance/ photo of corrosion	• Approximate fractional area of red rust present • Pit diameter of 3mm (~1/8") • Pit depth of 3mm (~1/8")	• Pit diameter <1mm (<3/64") • Pit depth <1mm (<3/64")
Coating Damage	• Missing damaged coating (area %) • Appearance/photo of damage	• Coating Holidays >6mm (1/4") diameter • Scratches > 50mm (2") long in coating	• Coating Holidays <3mm (~1/8") diameter • Scribe creep and corrosion in scratches
Water/Moisture	• % RH • Any standing water	• Standing water in tight space/crevice with 6mm (1/4") gap	• Standing water in tight space with 1mm gap

Summarizing the judging criteria, the solution will need the following capabilities;

1.) Detect and image red rust

2.) Measure surfaces- lengths and % area coverage

3.) Measure depths

4.) Locate water

5.) Measure %RH

In understanding the judging criteria, a list of different types of devices with capabilities of fulfilling the requirements was created. The list of capable devices includes the five most used forms of corrosion detection devices and others, including:

1.) Visual Camera
2.) Electromagnetic Eddy Current
3.) Acoustic Ultrasonic
4.) Radiography
5.) IR camera
6.) Laser Displacement Sensor
7.) 3D Scanner
8.) Thickness Gauge
9.) RH Detector

A process of down selecting the best device/devices was created. The devices were compared to the judging criteria based on how well the device can perform the task. The factors that determined how well a device can perform the task were based on the data received from the device. Significant point deductions were applied based on an analysis of risk associated with the techniques abilities to reliably perform the task. In this design matrix, factors such as time, cost, size, etc were not factored in. Table II, below, is the design matrix evaluating the type of detectors with the summarized judging criteria.

Table II. Corrosion Detectors vs Judging Criteria

Types of Detectors	Red Rust Detection	Surface Measurements	Depth Measurements	Standing Water	Relative Humidity
Laser Displacement Sensor	0	2	4	0	0
Visual Camera	5	3	1	4	0
3-D Scanner	3	4	4	1	0
Ultrasonic	2	2	5	1	0
Eddy Current	2	2	3	1	0
Infrared Camera	3	2	1	4	0
Thickness Gauge	0	0	4	0	0
RH Detector	0	0	0	1	5

Expected performance is graded on a scale of 0-5.

0 = incapable of satisfying judging criteria

3 = satisfies "minimum" judging criteria

4 = satisfies "better" judging criteria

5 = satisfies "ideal" judging criteria

The laser displacement sensor is not capable of detecting red rust, standing water, and relative humidity. However, the tool does have the ability of making surface measurements and depth measurements. The measurement device works by reflecting a laser off of a surface and calculating the time it takes to return to the sensor. The data received can be related to the depth between the device and the sensor. To determine the depth of a hole, two readings would be taken, one with the laser pointed in the hole and one reading taken next to the hole. Subtracting the two readings would give the depth of the hole. The reason that detecting depth only received a score of 4 is the fact that the surface is glossy and metallic which could possibly distort the laser creating risk in the ability to receive back a signal. Surface measurements could potentially be created using a laser measurement device. To do this multiple measurements would have to be taken and triangulated to determine lengths. The need for controlled laser movement is key to get accurate measurements. The reason this device received a score of 2 for the surface measurements category is the risk in not having controlled device movement and/or an increased risk in receiving a signal from shining the laser on an angled surface.

The visual camera received a score of 0 for the relative humidity section and has the ability to detect red rust, measure the surface and depth, and locate standing water. With an appropriate camera and lighting it is possible to locate and image red rust which is why the visual camera received a score of 5 for this category. Through image processing it is possible to make surface and depth measurements. Photogrammetry software has the ability to turn an array of 2D pictures or a video into a 3D model. The reason the depth measurements received a score of 1 in this category is because the risk involved in getting an accurate model. Photogrammetry matches together two images that have like features. Repeating this multiple times a group of photos can be linked together and turned into a 3D model. In order for the software to match pictures, multiple pictures need to be taken side by side and simple changes such as lighting can hinder the software from creating matches. Proper camera movement is crucial in producing images that the program can link together to create the model. The lighting of the video or pictures needs to be consistent which would be difficult to obtain because of the glare off of the metallic and glossy surfaces. From the model, length measurements could be determined. The reason the length measurement category received a 3 instead of a 1 is because using image processing the area percent of corrosion can be determined. Taking the percentage of selected pixels that correspond to red rust and/or coating damage out of the total number of pixels would give the area percentage of the defects. The visual camera received a 4 for detecting standing water. The reason for not receiving a 5 is because of the risk in not being able to detect clear water. Using a filter lens could help block out some of the glare from reflections off the water but there would still be risk.

The 3D scanner would be able to detect red rust, make surface measurements, make depth measurements, and detect standing water. The 3D scanner received a 3 for the ability to detect red rust because of the risk assessment associated with its tolerance level. 3D scanning technology is fairly new and still underdeveloped causing most scanners to have low resolution. In this case it is unknown if red rust would show up on the scanner. Also, some 3D scanners do not produce color models therefore red rust would only show up as a texture if at all. The scanner received a score of 4 for its ability to detect both surface and depth measurements because of its unknown resolution. It is unknown if scratches or coating damages would show up on the produced 3D model. Standing water received a score of 1 because it is also unknown if the scanner would be able to detect water. Scanners work best with very textured material so a flat surface on the water would most likely not be detected. Scanners cannot measure %RH therefore it received a 0. Overall 3D scanners prove to be risky instruments to incorporate in the design.

Acoustic ultrasonic devices received a score of 0 for the %RH, have the ability to detect red rust, measure the surface and depth, and locate standing water. Ultrasonic devices would be able to locate red rust but, the devices cannot take images so the ultrasonic device received a 2 for that ability. Ultrasonic scored a 2 on its ability to make surface measurements as well. Measuring the movement of the device as it passes the length of a flaw would give the surface length measurement. To measure depths of a flaw is very easy for ultrasonic because of the fact that it uses sound wave to travel through the material to detect flaws. Ultrasonic devices have the ability to determine where the surface wall, inner material flaw, and back wall are all located with respect to one another which is why it received a 5 for the depth category.[6] The detection of standing water is unknown for using ultrasonic devices which is why it received a 1.

Eddy current devices have the ability to sense when red rust exists. Like ultrasonics, measuring the movement of the actual eddy current device would allow it to make surface measurements of defects. However, this would be difficult and an additional device would be needed which is the reason eddy current devices scored a 2. Depth measurements would be easily detected with eddy current. The reason it did not score a 5 is because its depth is limited and standards would be needed to compare data.[6] Eddy current devices may be incapable of detecting water which is why it received a 1 in that category. Lastly, eddy current devices cannot detect %RH.

Besides detecting the percent RH, infrared cameras have abilities to detect the rest of the judging criteria. Infrared cameras work on changes in thermal properties so they would be able to detect red rust. Infrared cameras can take pictures of the red rust; however, the detected area could be a flaw, not always red rust, which is the reason for receiving a 3 for this ability. Similar to using a visual camera, image processing techniques could be used to determine surface lengths and depths with an infrared camera. The poor resolution of infrared cameras is the reason why its ability to make measurements scored low. Infrared would be able to detect water due to that fact that the thermal conductivity of water is much different than air.

Thickness gauges and percent relative humidity sensors were included in this list because of the need to detect depth and percent relative humidity. Thickness gauges would be able to only detect depths and %RH sensors would only be able to detect the relative humidity. Relative humidity devices would be able to detect water, the reading would be 100%, but it would not be practical to use to locate water since the device would have to physically be in the water.

After the design matrix for evaluating each corrosion detection technique was created, each detection technique was compared to factors relating to motion. Figure 1, below, is a drawing with dimension provided by the competition of the structure that will be used in the challenge. The structure is fully enclosed except for 2 entrances, a circle cutout with a diameter of 18 inches and a square cutout that is 18 inches in length and width. This limits the size of the device to be less than 18 inches. Another limiting factor is the needed distance between the corrosion detection device and the structure in order to get the required reading. A device that needs to touch the surface in order to get a reading would be more limiting than a device that can obtain the same information from a few feet away.

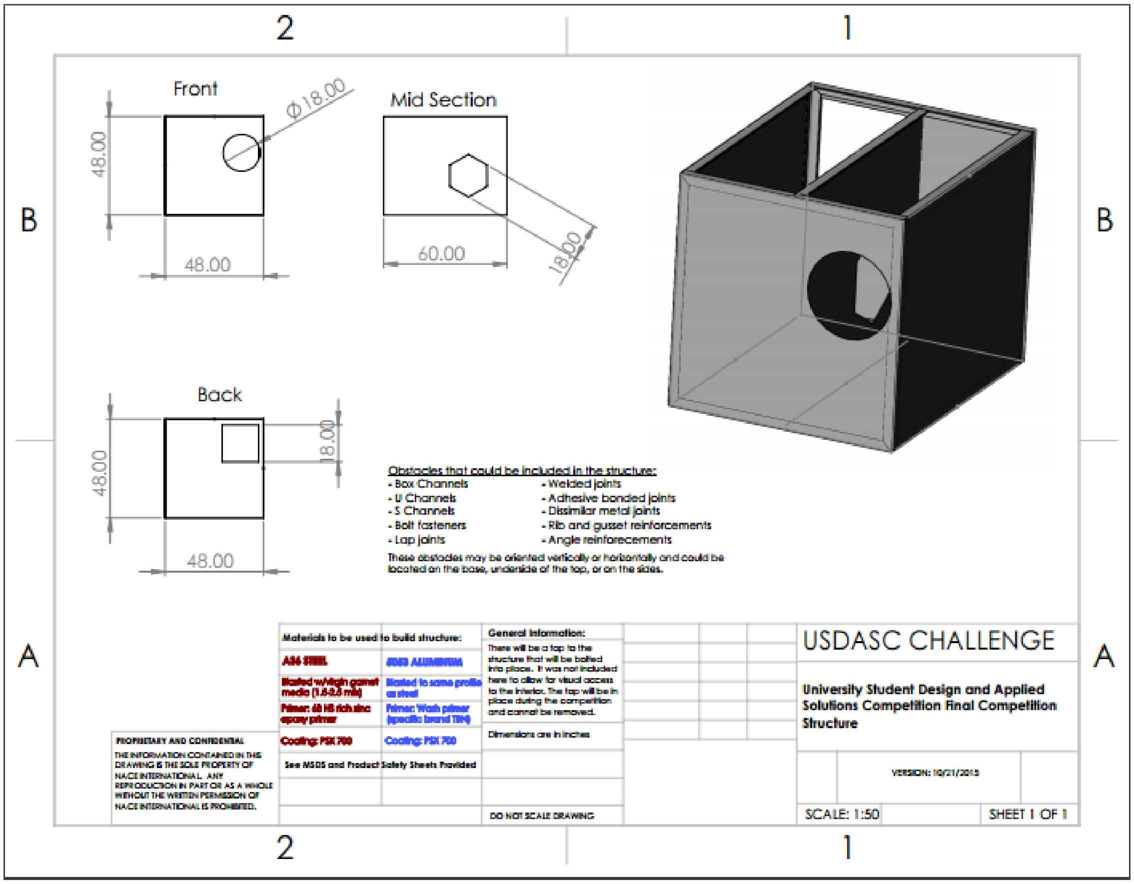

Figure 1. Drawing of the USDASC Structure. Accessed in May 2016. <http://www.usdasc.com/>[2]

Since the project has a limited budget, cost is a major factor in deciding the detection techniques. The project group estimated that not much more than $1000 was to be spent on the corrosion detection devices. Cost and size greatly vary for each device based upon make and model. Estimations, to the best of the team's ability, of the costs were made. Table III, below, shows the design matrix for the detection techniques relating to cost, size, and detection distance. Relative rankings are scored on a scale of 1-5, with 5 having the least negative impact on future design consideration.

Table III. Corrosion Detection vs Cost and Motion Requirements

Types of Detectors	Cost	Size	Detection Distance
Laser Displacement Sensor	5	4	5
Visual Camera	5	5	5
3-D Scanner	4	1	4
Ultrasonic	1	5	1
Eddy Current	3	5	2
Infrared Camera	2	3	5
Thickness Gauge	4	5	1
RH Detector	5	5	4

Summarizing Table III, the budget proves to be a very limiting factor in selecting a detection device. Further funds would be needed in order for the group to be able to utilize ultrasonic, eddy current, and thermography detection devices. The size of the 3D scanners is this devices main limiting factor. Ultrasonic, eddy current, and thickness gauges would limit the range of motion of the device because these techniques need to touch the surface in order to get a reading.

IV. Solution

The design matrix proved to be a very useful process to select the most efficient detection techniques. It was learned that not one device would be capable of providing the best solution so multiple devices would be used in conjunction with each other. Visual cameras and RH sensors were the devices chosen to be used in the competition.

The next step would be to determine what make and model camera and relative humidity sensor would be the most suitable for the project. A comparison of motion systems led the group to select a quadcopter over a robotic arm. The camera and the relative humidity sensor would have to be incorporated into the quadcopter. In this case the ideal camera would have the following specifications;

1.) Lightweight, < 100g
2.) High Resolution, 1080p
3.) Compact
4.) Built-in battery
5.) Live feed
6.) On-board recording
7.) Low cost < $200

Similarly, the relative humidity sensor would have to have the following specifications;

1.) Lightweight < 100g
2.) Wi-Fi
3.) Built-in battery
4.) Compact ~2”X2”x2”
5.) Low cost <100

The camera and RH sensor the group selected were the RunCam2 video camera and the Monnit Wireless RH Sensor, respectively. The RunCam2, Figure 2, weighs about 50g, can produce 1440p at 30 frames per second, has a built-in battery, live feed, on-board recoding, and is relatively compact. Additionally, the RunCam2 can be purchased under $100. The Monnit Wireless RH Sensor, Figure 3, is lightweight, has wifi, built-in button cell battery, is relatively compact, and costs a total of $207 for the sensor, receiver, and software.

Figure 2. RunCam2

Figure 3. Monnit Wireless RH Sensor

Without image processing the process can image red rust, image standing water, and calculate the %RH. With proper image processing the system has the abilities to measure surface lengths, calculate percent area coverage, and measure depths. MATLAB software, Image J software, SketchUp software, and multiple photogrammetry software programs, such as Agisoft Photoscan, Photomodeler Motion, and Pix4D Mapper were trialed. The reason the group could not use photogrammetry is because of the abilities of the quadcopter. The quadcopter was not able to fly in a clean path to receive a usable video. The group also ran into problems in getting the software to function properly. Parameters of the camera used are needed for the software to work. Parameters for the Runcam2 camera used were not easily available so the group was unsuccessful in getting the software to function properly. MATLAB and Image J were successful in calculating the percent area coverage. MATLAB and ImageJ in conjunction with SketchUp were successful in measuring surface lengths. Unfortunately, the group was unable to find a solution to incorporate photogrammetry software programs to determine depths and more accurately measure surface lengths. ImageJ was chosen to be used over MATLAB because of the user friendliness of a GUI.

The general process for calculating percent area coverage of corrosion and determining lengths of corrosion in an image is shown in Figure 4, below.

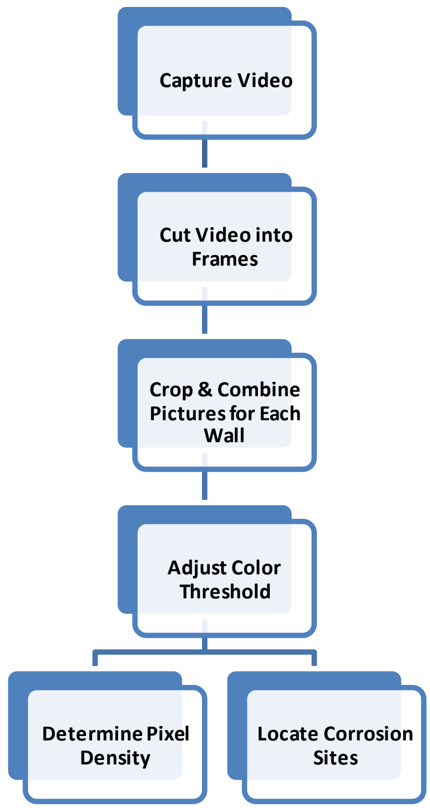

Figure 4. General Image Processing Flowchart

The video is first captured by the quadcopter and then uploaded to the computer through the use of an SD card. The video is then loaded into VLC media player and cut into frames. Useful frames could then be chosen for further image processing. For this application, an ideal image would be an image that is taken perpendicular from each wall and is then cropped so only that wall can be viewed. This is crucial for determining accurate lengths using SketchUp software. Next, the pictures are loaded into ImageJ and the color threshold of the images is adjusted to highlight the areas of corrosion.

Research in image processing of corrosion to select only the defected areas was studied. Corrosion essentially has two visual attributes, color and texture. Corrosion can be detected through image processing by selecting the pixels in that image that correspond to the texture and color attributes of corrosion. The process the group used to detect corrosion does not account for the texture attributes and the location of corrosion is based on the user's discretion to which pixels in the image correlate to corrosion. The process the group chose, selects pixels using the HSB color space to highlight pixels based on their hue, saturation, and brightness (HSB). Batch processing with ImageJ is recommended so the same color threshold is applied to every picture keeping consistency in the images only if each image has the same lighting. Other color spaces, such as RGB, Lab, and YUV, could also be used to receive similar results. The HSB color space is the easiest to use because it is how humans naturally respond to color.[7] In a corroded surface, the hue falls between the yellow and the red wavelengths. The color is usually highly saturated due to the fact that most metallic surfaces are painted light colors.[7] Lastly, corrosion usually has a low brightness due to the metallic surface being painted with light colors.[7] Since the color attributes fall in such a large range, texture attributes could improve locating the corrosion. The reason for being able to use the texture of corrosion in image processing revolves around the idea that corrosion creates a more textured surface than the original non-corroded surface. When a picture of corrosion is taken, the highly textured corroded area creates shadows creating a lot of entropy in pixels around the corroded area. Entropy describes how similar one pixel is compared to the pixels surrounding it. Pixels in a grayscale image each have a corresponding number from 0-255 so there are 256 different combinations.[8] When an image of corrosion is taken, the shadows that are created from corrosion receive no light and are black in color therefore, correspond to the number 255. From the pixels that are 255 in color, neighboring pixels can be selected that are closely related in magnitude. A large difference in the numbers between neighboring pixels means the color is much lighter representing the non-corroded area. Combining the color attributes and texture attributes associated with corrosion, the number of false positives, selected pixels that are not corroded, can be reduced.[8] Figure 5 below is of red rust. Figure 6 below is an image that has its color threshold adjusted to select areas of corrosion.

Figure 5. Red Rust [image reproduced from <https://eamonnj.wordpress.com/care-and-storage-basics/corrosion-and-other-common-damages/>][9]

Figure 6. Selected Areas of Corrosion Using Color Threshold Method [image reproduced from <https://eamonnj.wordpress.com/care-and-storage-basics/corrosion-and-other-common-damages/>][9]

After the corrosion areas are selected in each picture, the pixel density can be determined. The picture first needs to be converted into a picture composed of only 2 colors, usually black and white. The black pixels will represent the corroded areas and the white pixels represent the non-corroded areas. Figure 7, below, is the same image as Figure 6 except it is converted into a binary image, meaning it only has black and white pixels. A histogram of the number of black pixels and white pixels can be created. A percentage of the number of black pixels out of the total number of pixels can be calculated which correlates to the percent area of corrosion.

Figure 7. Binary Image of Selected Corrosion Area [image reproduced from <https://eamonnj.wordpress.com/care-and-storage-basics/corrosion-and-other-common-damages/>][9]

Using the color threshold adjusted images, the lengths of the corrosion can be determined. A pre-made model to scale can be produced in SketchUp. Images can then be overlaid onto the walls of the structure. Once the images are overlaid, points can be placed where corrosion exists and distances between them can be found using the SketchUp software. There are two requirements to obtaining accurate data using this process.

1.) Dimensions of the structure need to be previously known

2.) Any camera distortion in images needs to be removed

V. Discussion

The above stated solution has the abilities to detect all aspects of the judging criteria except depth related measurements. Directly, the solution can image red rust and water using the RunCam2 video camera and also detect percent relative humidity using the Monnit wireless RH sensor. Image processing techniques can further expand the ability of the solution to fulfill more judging criteria. Adjusting the color threshold of the images relative to locations of corrosion can be accomplished using ImageJ software. The adjusted picture can then be converted into a binary image and the density of corrosion can be calculated. The images can be overlaid on pre-made 3D models to locate the selected defects.

Error in the solution exists largely due to limitations in the motion system and the detectors. Poor image quality from the camera would result in misinterpretation during image processing. Limitations in the quadcopters abilities to image photos directly perpendicular to the structure would also create error in making surface measurements. There is error in the color threshold adjustment process because the process is selecting pixels solely based on the color. Pixel color can attribute to corrosion, but the same pixel color could be a location of corrosion and a location of non-corrosion. When overlaying images to determine lengths the stretching from using a fisheye lens first needs to be removed as well. Also, dimensions of the structure needs to be known prior to imaging the structure.

The inaugural University Student Design and Applied Solutions Competition, held on April, 19th 2016 consisted of five teams. Connection issues with the custom-made drone forced the contingency plan in place. The contingency plan drone was flown into the structure and video was received. However, the image quality was not good enough to notice any defects in the structure. The second contingency plan was then set in place and high resolution cameras were tossed into the structure. Better images were extracted using the cameras. Except now, the images were not perpendicular to the structure restricting the group from being able to determine surface measurements. Image quality was still an issue in being able to notice the red rust and time constraints hindered the group from taking a picture worthy of image processing. The percent RH was successful and data was received and processed from the Monnit wireless RH sensor.

To improve results the group could instead of focusing on imaging the whole structure and trying to process every defect, focus on getting a good image of one location of corrosion. From the one image, the group could focus the rest of the time image processing and receiving as accurate data as possible. The rules of the competition did not say that every defect needed to be located and analyzed. Focusing more time on one defect in the structure would have reduced confusion and congestion. The group would still have been able to prove how the system could be used to locate and analyze corrosion with analyzing just one area of corrosion.

VI. Conclusion

The solution was formulated around criteria created by the University Student Design and Applied Solutions Competition. A quadcopter equipped with a camera and an RH sensor was the solution to a controlled down selection process comparing multiple detection techniques and motion systems. The proposed solution proved worthy of solving the problem but was hindered by technical difficulties and time constraints during the actual competition. Future work in photogrammetry, and 3D cameras would greatly improve the current solution by having the ability to more accurately measure lengths and would increase the abilities of the current solution to making depth measurements.

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I. Appendix A. Alfred University USDASC Written Report

Detecting Corrosion in an Enclosed Environment

For the University Student Design and Applied Solutions Competition

Alfred University

Name	Major	Expected Graduation
Eric Nelson	Materials Science and Engineering	May 2016
Madison Wilson	Mechanical Engineering	May 2016
Nicholas Roberts	Materials Science and Engineering	May 2016
Scott Ciabattari	Renewable Energy Engineering	May 2017
Jacob Townsend	Ceramic Engineering	December 2016

Advisor:
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Submitted:
May 9, 2016

Table of Contents

Abstract

The infrastructure of the United States has seen rapid modernization and growth, along with an increasing need to maintain and protect it. In order to properly preserve and monitor the infrastructure, routine inspection for corrosion is a necessity. New inspection platforms are required in order to reduce inspection time and improve corrosion data quality. Currently, corrosion inspection can be performed via many different technologies, such as thermography, ultrasonic, radiography, magnetic, and visual inspection. Each technology has different benefits and drawbacks, and none is best suited for examining corrosion under all potential conditions. The goals of our group were to research corrosion detection methods and build a system to remotely inspect an enclosed structure for the University Student Design and Applied Solutions Competition. In addressing corrosion detection through the creation of a remotely operated vehicle, we constructed a highly maneuverable quadcopter drone with multiple sensors to detect corrosion and corrosive conditions. With further research, a quadcopter, such as the one that we have built has the potential to operate autonomously and detect corrosion in many potential environments.

Introduction

For the University Student Design and Applied Solutions Competition, teams were tasked with designing and operating a remotely controlled vehicle that would be able to access a confined structure, detect corrosion, and report back the locations and types of corrosion present. The structure that was analyzed for corrosion was comprised A36 steel and/or 5053 aluminum panels. These panels were primed and then coated with PSX 700, a PPG product that provides long-term protection from corrosion[1]. Some problems associated with PSX 700, which may lead to corrosive conditions, are the temperature and humidity requirements that must be maintained for a good, long lasting coating[2,3].

This competition required the identification and location of various corrosion induced defects. These defects were outlined by the rules of the competition, and included red rust, pitting, scratches, scribe creep, and holidays. Two other requirements were to detect standing water and percent relative humidity. High relative humidity and standing water can accelerate corrosion, particularly in PSX 700 and other siloxane based coatings, which makes the monitoring and detection of relative humidity and standing water extremely important[4]. The steps taken by our group to develop a comprehensive corrosion detection system are detailed in this report.

Time Table Associated with Project

Our group outlined a schedule which would help us satisfy the guidelines and milestone dates laid out by the University Student Design and Applied Solutions Competition rules[5]. In conjunction with these long term goals, we organized regular meetings and wrote weekly progress reports which were designed to keep our group active and productive.

Fall Semester Milestones

General research and idea gathering……………………………………….... October-November 10
Down-selection of potential technologies…………………………….……….... November 11-22
Development of preliminary design……………………………….……….... November 23-December 6
Submission of design concept to USDASC……………………………….……….…... December 7

Spring Semester Milestones

Review of USDASC comments on design……………………………….…....………... January 18-31
Purchasing of supplies…………………….……….……….……….……….……….... February 1-14
Construction, initial testing……………………………….……….……….....……. February 15-March 6
Primary testing, practice trials……………………………….……….....……….... March 7-April 10
Write official project report……………………………….……….……….……..……….. March 7-25
Submit written report to USDASC………………………….…...…………….…………. March 25
Ship completed project to competition site……………………….…………….……….…. April 11
Competition begins…………………………….……….……….……….……….……….…. April 17
Alfred undergrad research symposium…………….……….……….……..……….……... April 28

Background

To understand the rules of the competition and the field of corrosion science, considerable background research was performed. Our group focused on understanding the terminology associated with corrosion defects as outlined in the rules, and the various corrosion detection devices that are commonly used.

I. Terms

Red Rust is the term used to describe corrosion that occurs in iron and plain carbon steel. Rust is a hydrated ferric oxide, and it appears as red or dark brown in color. In contrast, “white rust” is a term used to describe the powdery white corrosion which occurs in zinc or galvanized steel, and did not require identification for this competition[6].

Pitting describes the localized breakdown of coatings and the subsequent attack on the underlying metal at those sites. Sites which experience pitting can cause the initiation of cracking when under mechanical stress, and can be extremely small and difficult to detect[6].

Scribe Creep is the term used to describe the propagation of under-paint corrosion that results in coating delamination. Modern coating research attempts to address corrosion by preventing scribe creep formation[7].

Coating holidays is the term used to describe any flaw or defect in a coating which can lead to regions of disbondment and corrosion[8].

II. Detection Methods

Pulsed eddy current (PEC) utilizes a square pulse excitation to induce transient eddy currents on a target material. The current is sensed, by pickup coils, and analyzed for determination of signal features which indicate the presence of a crack. PEC methods have been investigated for use in a number of applications that require detection of defects at greater depth of penetration in multi-layered aluminum structures[9].

Ultrasonic detection uses high frequency waves to detect corrosion related defects. Guided wave monitoring systems usually operate at low frequencies, below the cut-off frequencies for higher order wave modes, to generate only the fundamental wave modes, simplifying signal interpretation. The low operating frequency range necessitates larger wavelengths and thus limits sensitivity for the detection of small defects. This type of ultrasonic waves allows for the inspection of structures over reasonably long distances[10].

Radiography utilizes x-rays and gamma rays to detect corrosion in the interior of materials. Unlike ultrasonic testing, radiography can be carried out without removing insulation, and temperature does not play much role in accuracy of quantification of corrosion. The minimum detectable thickness is a function of radiation quality, specimen thickness, radiation scatter, and film characteristics[11].

Thermography can be used to detect corrosion by analyzing thermal properties which are affected by the presence of different elements. It is a powerful non-destructive technique (NDT) method, with benefits including high accuracy, fast response times over large inspection areas, and intuitive results[12].

Capacitive and resistive humidity sensors are popular methods used to detect relative humidity. Relative humidity is the amount of water vapor present in air and is a percentage ratio of the amount of water vapor needed for saturation at the environment's temperature.

III. Location Methods

A laser displacement sensor measurement device works by reflecting a pulsed laser off of a surface and calculating the time it takes to return to the sensor. The data received can be related to the depth between the device and the sensor. To determine the depth of a hole, two readings would be taken, one with the laser pointed in the hole and one reading taken next to the hole. Subtracting the two readings would give the depth of the hole. Surface measurements could also potentially be created using a laser measurement device. To do this multiple measurements would have to be taken and triangulated to determine lengths.

IV. Hybrid Methods

A visual camera allows for the capture of still images in any environment as long as sufficient light is present. Images of a space can be manually inspected for corrosion, or can be combined with image processing methods to allow the computer to detect irregularities within the image on its own[13].

Terrestrial 3-D Laser Scanning Technology (TLS) can acquire three-dimensional spatial information. It works by scanning objects through the distribution of a multi-point field and developing a high-fidelity, high precision 3-D model. Some systems combine this technology with a visual camera to create a fully colored 3-D model[14].

Design Approach

Following the identification of a large number of detectors, our group researched different methods of locomotion in order develop a theoretical system in which they could all work together. Selecting the best final design for a corrosion detecting vehicle meant not only choosing the most comprehensive detection methods, but incorporating a viable method of locomotion while remaining within a budget and limited timeframe.

I. Corrosion Detection and Analysis

The team evaluated candidate corrosion detection techniques to determine the most viable method(s) for satisfying the rules of the competition. The different corrosion detectors were graded on their ability to achieve each of the judging criteria laid out by the rules (Table 1).

Table 1. Corrosion Detector Method

Types of Detectors	Red Rust Detection	Surface Measurements	Depth Measurements	Standing Water	Relative Humidity	Total
Laser Displacement Sensor	0	2	4	0	0	6
Visual Camera	5	3	1	4	0	13
3-D Scanner	3	4	4	1	0	12
Ultrasonic	2	4	5	1	0	12
Eddy Current	4	3	3	1	0	11
Infrared Camera	3	2	1	4	0	10
Field Signature Method	0	4	3	0	0	7
Thickness Gauge	0	0	4	0	0	4
RH Detector	0	0	0	1	5	6

Expected performance is graded on a scale of 0-5.
0 = incapable of satisfying judging criteria, 3 = satisfies “minimum” judging criteria, 4 = satisfies “better” judging criteria, 5 = satisfies “ideal” judging criteria
Subsequent point deductions were applied based on risk analysis

Grades were applied based on the prior research[15] and knowledge of device operations. Each category carried the same weighting value of 1, as the scoring system given to us by the competition did not indicate a direct point value for the detection of specific types of corrosion. Rationales for each device are as follows:

- The laser displacement sensor is not capable of detecting red rust, standing water, and relative humidity. The reason that detecting depth only received a 4 is due to the high amount of control required to get a steady reading. The need for controlled laser movement is key to get accurate measurements. The reason this device received a 2 for the surface measurements category is due to the risk in not having 100% controlled device movement and the possibility of receiving an inaccurate signal from the laser.
- The visual camera received a 0 for the relative humidity section, but has the ability to detect red rust, measure the surface and depth, and locate standing water. With an appropriate camera and lighting it is possible to locate and image red rust which is why the visual camera received a 5 for this category. Through image processing it is possible to make surface and depth measurements. Photogrammetry software has the ability to turn an array of 2D pictures or a video into a 3-D model, yet the reason the depth measurements received a 1 in this category is because of the difficulty involved in getting an accurate model. The reason the length measurement category received a 3 instead of a 1 is because by using image processing the area percent of corrosion can be determined. Taking the percentage of selected pixels that correspond to red rust and/or coating damage out of the total number of pixels would give the area percentage of the defects. The visual camera also received a 4 for detecting standing water. The reason for not receiving a 5 is because of the risk in not being able to see water under poor conditions.
- A 3-D scanner would be able to detect red rust, make surface measurements, make depth measurements, and detect standing water. The 3-D scanner received a 3 for the ability to detect red rust because of the likelihood of poor color contrast. It is also unknown if red rust would show up on the scanner, as this depends on whether the scanner is camera or laser based. Laser based 3-D scanners do not produce colored models, and therefore red rust would only show up as a texture if at all. The scanner received a 4 for its ability to detect both surface and depth measurements because of its unknown accuracy in measuring very small features. It is unknown if scratches or coating damages would show up on the produced 3-D model. Standing water received a 1 because it is unknown if the scanner would be able to detect water. Scanners work best with very textured material so a flat surface on the water would most likely not be detected. Scanners also cannot measure %RH therefore it received a 0. Overall 3-D scanners appeared to be risky instruments to incorporate in the design.
- Acoustic ultrasonic devices received a 0 for the %RH and have the ability to detect red rust, measure the surface and depth, and locate standing water. Ultrasonic devices would be able to locate red rust but, the devices cannot take images so the ultrasonic device received a 2 for that ability. Ultrasonic scored a 2 on its ability to make surface measurements as well. Measuring the movement of the device as it passes the length of a flaw would give the surface length measurement, but constant contact with the surface is required. To measure depths of a flaw is very easy for ultrasonic because of the fact that it uses sound

wave to travel through the material to detect flaws. Ultrasonic devices have the ability to determine where the surface wall, inner material flaw, and back wall are all located with respect to one another which is why it received a 5 for the depth category. The detection of standing water could be damaging to an ultrasonic devices if it gets wet, and would likely be discovered with a camera guiding the device which is why it received a 1.

- Eddy current devices have the ability to sense when there's red rust. Unlike ultrasonic, measuring the movement of the actual eddy current device would allow it to make surface measurements of defects. However, this would be difficult and an additional device would be needed which is the reason eddy current devices scored a 2. Depth measurements would be easily detected with eddy current. The reason it did not score a 5 is because its depth is limited and standards would be needed to compare data. Eddy current devices would have difficulty in detecting water which is why it received a 1 in that category. Lastly, eddy current devices cannot detect %RH.

- Besides not detecting the %RH, infrared cameras have abilities to detect the rest of the judging criteria. Infrared cameras work on changes in thermal properties so they would not be able to detect red rust directly. Infrared cameras can take pictures of the red rust however; the detected area could be a flaw, or red rust, which is the reason for receiving a 3 for this ability. Similar to using a visual camera, image processing techniques could be used to determine surface lengths and depths with an infrared camera. The dependence on other software to make measurements is why it scored low. Infrared would likely be able to detect water due to that fact that the thermal conductivity of water is much different than air.

- Thickness gauges and percent relative humidity sensors were also included in this list because of the need to detect depth and percent relative humidity. Thickness gauges would be able to only detect depths and %RH sensors would only be needed to detect the relative humidity. Relative humidity devices would be able to detect water, but the reading would locked be 100%, so it would not be practical to use to locate water since the device would have to physically be in the water.

Since devices were now ranked on their ability to detect corrosion, the next step was to determine the viability for use during the competition. To further evaluate the available detector candidates, devices were again graded, this time with respect to cost, size, and detection range. These were the three traits we determined to be most important for their viability as a part of a corrosion detection vehicle (Table 2).

Table 2. Corrosion Detector Decision Matrix

Types of Detectors	Cost	Size	Detection Distance	Total
Laser Displacement Sensor	5	4	5	14
Visual Camera	5	5	5	15
3-D Scanner	4	1	4	9
Ultrasonic	1	5	1	7
Eddy Current	3	5	2	9
Infrared Camera	2	3	5	10
Field Signature Method	1	4	1	6
Thickness Gauge	4	5	1	10
RH Detector	5	5	4	14

Relative rankings are scored on a scale of 1-5, with 5 having the least negative impact on future design consideration

Based on this analysis it became apparent that the budget would prove to be a very limiting factor in selecting a detection device. Further funds would be needed in order for the group to be able to utilize ultrasonic, eddy current, and thermography detection devices. The large physical size of most inexpensive 3-D scanners available on the market was deemed to be a possible limiting factor. Ultrasonic, eddy current, and thickness gauges would all greatly limit the range of motion of any device they were attached to, because these techniques need to touch a surface in order to get a reading. With this analysis completed the use of a 3-D scanner or visual camera in combination with photogrammetry software, and a relative humidity sensor stood out as the best options because of their high point scoring potential and economic value.

II. Motion

A very similar design process was conducted to determine the best method for the locomotion of the sensors. Characteristics of inspection equipment movement were brainstormed in order to further refine the design concept. Attributes of the two possible means of motion were identified, and specific traits of each method were compared (Table 3).

Table 3. Comparison of Devices Located Outside Versus Inside the Structure

Device Inside Looking Around	Device Outside Looking In
• High Range of Motion • Entire Structure Potentially Accessible • Large Area to Explore • Risk of Irretrievability • Limited Payload Capacity	• Range of Motion Limited by Number of Joints • Must Remain at Access Points • Unlimited Sensor Possibilities • Large Size Required to Examine Entirety of Structure

Comparison of the two possible modes of operation revealed that with a device looking around from the inside there would be few restraints as to where it could move[16]. As long as such a device fit inside the structure, it would have a high range of motion. However, with a device that could only reach in and look around, the inspection areas would be limited to the length of an arm or gantry system and the number of joints on it.[17,18]. The major benefit of a system that is on the outside looking in, is it's payload capacity. A large robot could potentially carry many times its weight in additional sensors, making its potential for the use with multiple corrosion detection methods greater than with a smaller bot roaming around inside[16].

A device that would be free to move inside the structure would likely require wireless capabilities to take full advantage of its potential range of motion, while one which remained outside might not. A side by side comparison of traits pertaining to wired and wireless devices was developed to evaluate how relying on one method or another might affect the performance of the final design (Table 4).

Table 4. Communication Methods for the Device

Wired	Wireless
• Allows for High Powered Sensor Packages • Limits Range of Motion • No Lag in Communication	• Battery Capacity Impacts Operation Time, Ability to Use High Powered Sensors • Essentially Unlimited ROM • Lagged Communication

The wired vs. wireless comparison showed that the largest impacts of the selection would be on range of motion and operation duration. With a wired system, you can have unlimited operation time, but also a potential to get cables snagged on obstacles[16]. A wireless design would allow for freedom in its range of motion, but a limited operation time, which would have to be monitored regularly so as to not lose contact with the system.

The result of these two characteristic comparisons for the motion system resulted in a decision between use of a robotic arm that could reach inside of the box to inspect, and a multirotor drone that would fly into the box to inspect. Based on research[17,18,19,20,21,22], robotic arm based designs and multi-rotor drone based designs each had some negative and some positive attributes associated with them. A direct comparison was made between the two design types by determining the pros and cons of using a robotic arm compared to a multi-rotor drone if operated under the expected competition conditions (Table 5).

Table 5. Sensor Scaffold Comparison

	Pros	Cons
Robotic Arm	• Stable • High payload capacity • Can be wired, allowing for high power sensors	• Large size of testing environment requires advanced engineering solutions • Range of motion limited by degrees of freedom • Large base limits navigation path
Multi-rotor Drone	• Small and compact • Can access hard to reach places	• Difficult to control • Limited operation time • Weight limitations lead to sensor limitations • High accident risk

Range of motion was deemed to be an important factor after this qualitative analysis, a multi rotor drone allows for unparalleled access to hard to reach areas, whereas a robotic arm is limited by its size and its number of joints. After performing this side by side analysis of the two motion systems, we determined the different locomotion traits that would have an impact on our ability to collect results during the competition.

To determine which motion system we would use in the final design, we conducted a final down selection by evaluating multi-rotor drones and robotic arm based on their traits. Each of the two candidates were graded to determine what was objectively best. The team decided that the highest ranked option would be the technology that we would pursue for our final design (Table 6).

Table 6. Motion Systems Final Evaluation

Motion System Candidates	Communication (1)	Payload Capacity (4)	ROM (5)	Operation Time (3)	Precision of Control (3)	Risk of Failure (4)	Price (5)	Speed (2)	Total
Multi-rotor Drone	**4**	**2**	**4**	**3**	**2**	**2**	**5**	**5**	**90**
Robotic Arm	**5**	**4**	**2**	**5**	**4**	**4**	**2**	**2**	**88**

Criteria are weighted on a scale of 1-5, with 1 being least important and 5 being most important
Expected performance is graded on a scale of 1-5, with 1 being the lowest performing and 5 being the highest performing

The motion characteristics were weighted as follows:

- Communication was given a weight of 1 due to the vast amount of communication systems on the market and no matter the motion system communication would not be a large limiting factor[16].
- Payload capacity was given a 4 due to the idea that a higher payload capacity would allow for larger, higher quality, sensors.
- Range of motion was given the highest value of 5. This is because without a high range of motion a system would not be able to inspect all aspects of the enclosed environment.
- Operation time was weighted with a value of 3 as a longer operation time would allow more time for data to be collected[16].
- Precision of control was given a value of 3 as without precise movements navigation would increase in difficulty and accurate data points on locating corrosion would be limited.
- Risk of failure is essentially the risk of crashing the motion system. It was given a weight of 4 because if a system had a high likelihood of crashing it would not be a reliable motion solution.
- Price was weighted a 5 as we were working with a limited budget and every expense had to add value to the motion system.
- Speed was not as big of a factor as the environment wasn't very large and seemed like the 45 minute time allotment given by the competition would be ample time to inspect the environment no matter the speed. It was weighted a 2.

With these weighted categories, both the multi-rotor drone and robotic arm systems were graded, and their score was totalled to quantitatively decide our best motion solution.

- The multi-rotor drone and robotic arm communication scores were very close. The separating factor was the inability for the drone to be wired for communication and power purposes. However wireless communication technology is very accessible and available for drone use, so the wired vs. wireless characteristics did not change the score significantly[16].

- A robotic arm would theoretically be able to carry much more than a multirotor drone of the size required to fit in the competitions enclosed environment. For this reason the robotic arm was given a higher score than the drone[18,20].

- The range of motion for a multirotor drone is much higher than that of a robotic arm as a multi rotor drone can navigate with infinite degrees of freedom whereas a robotic arm is limited to its number of joints[17,22,23].

- The wired vs. wireless characteristics were brought about again when comparing operation time. A robotic arm could easily be wired and provided power whereas a multirotor drone would have to carry an onboard battery[16,23]. However, battery capacity could vary with design and could easily swapped out depending on the drone design. For these reasons the drone scored a 3 and robotic arm scored a 5.

- The precision of control of a robotic arm compared to a multi-rotor drone was much higher. A robotic arm would be fairly firmly mounted to the ground allowing for a stable base whereas a drone would be flying in the air leaving it susceptible to wind currents[23].

- The risk of failure of a drone was much higher than that of a robotic arm. This is due to a drone being inside the enclosed environment completely, without much room to correct for pilot error. A robotic would be based outside and looking it in leaving it less susceptible to potential obstacles within the structure.

- The multi rotor drone significantly outscored the robotic arm on both price and speed. The drone would be a much smaller system than a robotic arm leading to less raw material required to assemble the system. A robotic arm would need to be fairly large to fully inspect the enclosed environment which would lead to a higher cost and slower speed.

Taking into account the weightings of the categories, scores for the multi-rotor drone and robotic arm were tallied and the multi-rotor drone edged out the robotic arm by two points, with a score of 90 to 88. This is not a huge margin of victory compared to the possible 135 points. The drone concept was solidified as the winning design by its innovative nature, as no drone that we had encountered had been developed for the purpose of detecting corrosion.

Given the analysis of both the detection methods and motion system it was determined that a combination of both a visual camera and relative humidity sensor mounted on a multi rotor drone had the highest potential score while maintaining our budget. The 3-D scanner was eliminated as a viable detection solution due to its size, power requirements and communication needs that could not be accommodated on a small multirotor drone.[21] A visual camera and relative humidity sensor could easily be mounted onto a drone and produce an ample amount of data within the time allotment given by the competition. With this conclusion further development and refinement of the design was conducted.

Concept Development

With the desired corrosion detection methods and motion systems narrowed down, more specific characteristics had to be attributed to the system in order to develop a final design. This was done by developing a theoretical plan of attack on how to manage the 45 minute time allotment given to inspect the structure. We envisioned a procedure that would allow us to fly the drone into the box and capture footage, then after about 10 minutes fly it back to a ground station where the data could be physically unloaded from the drone and image processing could begin. This would be repeated around 3 times to give an ample amount of data, and allow us to successfully inspect all aspects of the environment. This high level theoretical operational procedure let us develop three critical specifications for the motion system. It needed around a 10 minute flight time, and a high definition camera with on board recording and live feed output that the pilot could use to navigate. Also, in order to navigate the environment, physical dimensions of no greater than 10”x10”x6” were desired. This would allot 4 inches on either side of the multirotor drone if perfectly centered to navigate through the 18” openings on the structure itself. A fast and efficient image processing system and procedure would also be required to make this method of inspection viable within the time constraints. These specifications allowed us to take the next step towards designing our cohesive system.

I. Corrosion Detection and Analysis

Since it was determined that a visual camera offered the most efficient means of scoring points at the lowest cost, data analysis methods were researched to generate results based on visual data[13,24,25]. After research was conducted it was determined that multiple image processing techniques had to be used in conjunction with one another to maximize possible points. Without the use of a 3-D scanner, locating the spots of corrosion became a large issue. To address this, we investigated methods of converting

2-D photographic and video data into 3-D models. This field of image processing, called photogrammetry, involves taking photographs or videos and creating three dimensional models from them. There are numerous software programs that have been created for this purpose. Each software package that we researched had benefits and drawbacks, including the accuracy in the models, ability to convert video versus only still images, processing time, and cost. The use of a photogrammetric process would allow us to make a detailed physical model of the environment. Ultimately, these procedures were found to require excessive time, equipment, and camera control, and we decided that creating a 3-D model of the expected structure before the competition would be preferable to creating one during the competition.

Beyond modeling the shape and scale of an observed site, an important feature of a corrosion detection device is having the ability to distinguish corroded regions from non-corroded regions. Being able to identify corrosion can be challenging and time consuming when studying a large area, but there are some solutions based on visual inspection techniques are aimed to address this. Most visual analysis procedures use a combination of color and texture patterns to verify the presence of corrosion[13,26,27,28]. A simplified version of these image processing methods, which we ended up using in our final solution, is based solely off of hue, saturation, and brightness differences. Such a method can be used to detect rust, cracks, pitting and material defects associated with corrosion under the correct conditions. The resulting images from this type of procedure show post-processed data that highlights detected corrosion regions in a specified color.

A combination of 3-D modelling and image processing would be the extent to which our visual inspection method would be conducted. These two methods would allow us to obtain as many possible points while remaining within the time limit. A relative humidity sensor would also be required as it is the only direct means by which one can monitor the RH level.

II. Motion

After determining that a drone would be the best theoretical motion system to navigate the enclosed structure under the guidelines of the competition, our group began researching drone manufacturers and parts to determine whether we should design and construct a custom drone or purchase a fully or partially built drone. It was concluded that designing and constructing a custom drone with a modular design would maximize the potential to obtain points in the competition while also remaining within our budget. An off the shelf solution would drastically reduce the workload involved in getting the drone built and flying, but it would not allow for the required amount of customization brought on by our detection solutions. Off the shelf solutions that fit the size constraints induced by the enclosed environment did not have video cameras with acceptable resolution for our image analysis process, nor enough payload capacity to carry a relative humidity sensor while maintaining an acceptable flight time. With a custom design we would be able to fully customize each characteristic of the drone including but not limited to size, weight, flight time, payload capacity and communication system.[20,21,22,23] With rapid prototyping technology available, parts for the frame could easily be manufactured and potentially replaced in the event of a crash. Our research on drone technology and theory[21,22,23], along with consideration to our budget and a team member's previous experience building drones, showed that a four rotor, quadcopter, would be the best design. A larger number of props would induce the need for more components and at the anticipated scale it was deemed inefficient. If any fewer number of props was chosen the stability of flight would drastically be reduced and most flight control boards are not designed to handle a 2 or 3 motor configuration. 4 rotors is the perfect balance of size and efficiency.

Solution

I. Corrosion Detection and Analysis

An image processing procedure was developed and optimized to make a fast and efficient process that would be useful during competition.The corrosion identification process was broken down into two categories: corrosion identification and corrosion mapping. A combination of multiple softwares were used to complete the required operations. Since all visual data that was collected during flight would be in video form, we selected VLC Media Player to cut the video into individual frames. ImageJ was the software chosen to manipulate images so that corroded areas could be identified. This software is popular in the image processing and editing market. These two free softwares did not have all of the capabilities of expensive photo and video editing softwares such as Adobe Photoshop and Premiere Pro, but their capabilities met our needs. We did not need highly complex functionality, given our proof of concept design and these softwares allowed us to highlight corroded regions based only on the color thresholds in an image. In order to locate the corrosion a 3-D modelling process was needed.

Dimensions of the test environment were provided to us by the competition, and Google SketchUp was used to create a 3-D model of the expected environment. Microsoft Paint was used to crop and combine multiple images to generate a singular image for each individual wall. Microsoft Paint was chosen due to its easy to use nature to crop and combine multiple images, and much like VLC Media Player it was readily available and team members already had a background knowledge of how to use it effectively. This combination of Paint and SketchUp allowed us to create complete images of each wall and then overlay them onto a pre-existing model of the system. This method allowed us to indicate the location and size of corroded areas relative to the entire test environment with SketchUp dimensional tools. A detailed procedure on how images would be processed can be seen in Appendix D.

To determine the relative humidity, a sensor would have to be attached to the drone and brought into the environment and either collect data and return with it, or feed back data wirelessly. With our detection methods solidified into two required components, a video camera and relative humidity sensor, we selected our detection components, a RunCam 2 and wireless Monnit RH sensor. Details on these components can be seen in Table 7 on page 18.

II. Motion

Throughout our research on off the shelf quadcopters, notes were taken on their design characteristics. These characteristics helped us when designing our drone which would have to fit comfortably in the test environment and have all sensors and components attached to it. Components were selected based off of their size, weight, and modular characteristics. Below is a table outlining the critical components selected for the initial drone design.

Table 7. Critical parts list for initial design

Item	Description	Mass (grams)	Dimensions (mm)
Camera	RunCam 2	34.9	66x38x21
Relative Humidity Sensor	Monnit RH Sensor	13.7	27x27x20
Flight Controller, ESCs, PDB	TBS Power Cube	70.2	36x36x30
Controller and Receiver	FrSky X9D & X8R	16.8	47x34x25
OSD	TBS PNP50	37.1	27x47x12
Video Transmitter	TBS Unify GreenHorn 25mW	7.2	40x19x7
Motors	4 DYS 1104 Motors	5.5	NA
3” Props	4 DYS 3020	.6	NA
Battery	Pulse 4S 1550mAh	162.7	87x34x25
Central Frame and Ducts	3-D Printed ABS Plastic	80.2	203x229x102

Besides size and mass, our budget and availability also played a large role in what components were used. Each component was compared to a multitude of other products on the market and the best product suited for our application was selected.

- The RunCam 2 was selected because of it high definition video capturing capabilities as well as its on board video recording ability and live feed output. It could record 1440p video at 30 frames per second or 1080p at 60 frames per second on board and output a NTSC or PAL live video feed. It also was one of the cheapest products on the market while performing with some of the most expensive ones such as the GoPro. Other products on the market did not compete at this price point and with a confined budget like ours it was a huge factor in picking this component.

- The Monnit RH Sensor was selected because of its modular design. It could be easily integrated into any design because of its size and with built in wireless capabilities nothing on the market competed with it. It's software component allowed for a 1 second sample rate and could produce graphs of relative humidity versus time. This would provide us with an ample amount of data to use in the final report.

- The Team Black Sheep (TBS) Power Cube was selected also because of its modularity, compact design and abilities. With a built in accelerometer and gyroscope it could maintain control in most situations thrown at it. It also had four integrated electronic speed controllers (ESCs) allowing for an easy install and very little troubleshooting to get it working. The ESCs had a 20 amp max output allowing for many possible motor combinations. Also the configurator associated with the flight controller is an easy to use software that allows complete access to all aspects of the flight control system. The flight control board also had multiple ports available for use so extra sensors could be configured into the control system if funds were available.

- The FrSky X9D and X8R controller and receiver combination was chosen because of it mid range price but top of the line performance. With integrated communication functions and 16 channels available for configuration this controller allows for all potential controls required to operate this drone. The receiver also has an SBUS output so there is no need for a PPM inverter for it to communicate with the flight controller.

- The TBS PNP50 was chosen as the on screen display (OSD) module as it could be easily integrated with the other TBS components on the drone. It allowed the video feed back to the pilot to have an overlay outlining the power consumption, radio connectivity and current output. This in flight data is critical for insuring a safe and reliable flight within the structure. It also served as a power distribution board for the video camera and video transmitter.

- The TBS Unify GreenHorn 25mW video transmitter was chosen because of its size and ease of integration with all of the other TBS products on the drone. It also has 32 frequency channels to choose from so there are many options to choose from in the event of any signal interference.

- The motors and props were selected as a combination package. They were selected because of their small size and power consumption. Their output was rated at 200 grams of thrust each so there was theoretically an adequate payload capacity.

- Given the selected motors and props the Pulse 1550mAh battery was chosen to supply power to the drone. This battery had a better advertised capacity to mass ratio than most other batteries on the market. It also was cheaper than other batteries on the market with the same capacity and cell count.
- The frame was chosen to be 3d printed out of abs plastic because of its availability on campus and good strength to weight ratio.

These components would theoretically work together seamlessly and with minimal troubleshooting. With the components chosen, the frame was able to be modeled around the parts in a way that incorporated them into the modular design of the system. Figure 1 displays a model of the initial drone design.

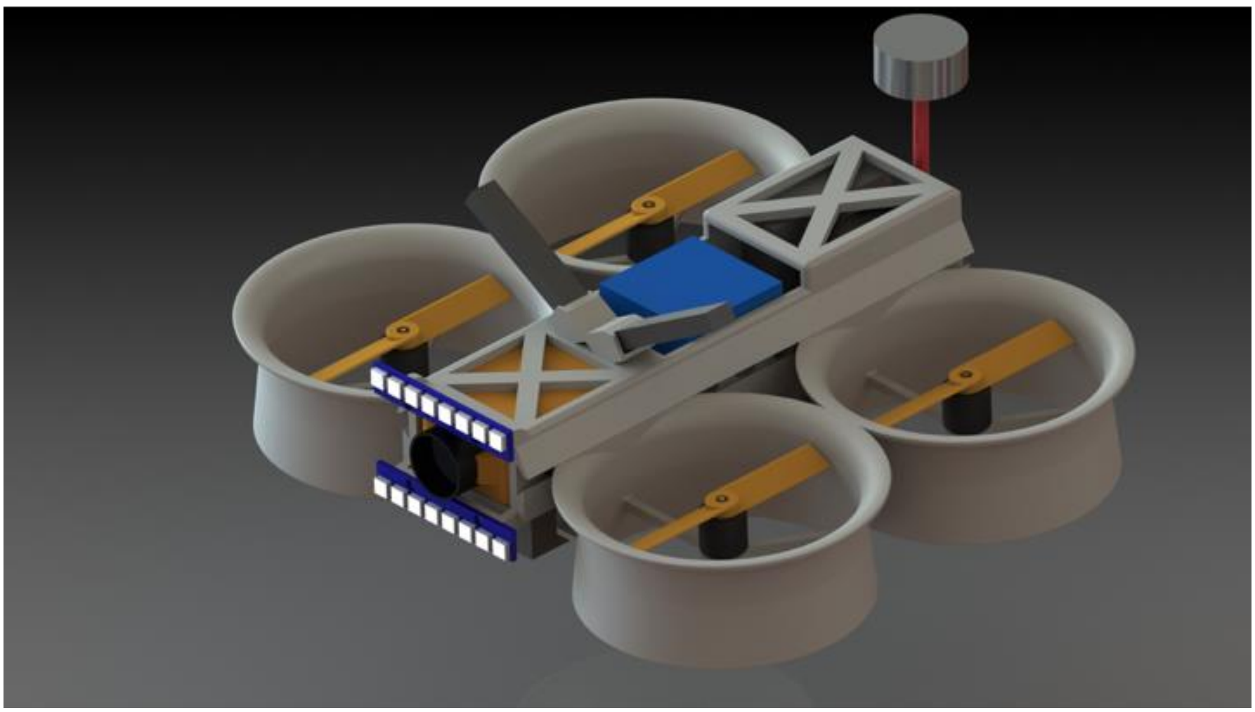

Figure 1. 3-D Model of Initial Proposed Solution

The modular design of our drone had two key sections to it. The central frame contained all sensors as well as the power and communication systems. This was the core of the design, and was designed with extreme detail as to allow for easy assembly and high strength. Outwardly mounted ducts were attached to the central frame, as can bee seen in Figure 2, and detailed in Appendix C. The design of the ducts was initially shaped to maximize the efficiency of the props in turn increasing thrust and flight time[29,30]. However, this was not the result, the motor and prop combination that was initially purchased did not produce the amount of thrust advertised which even when combined with the efficient ducts were unable to give us the lift required, drastically decreasing flight time. Specifications on this initial design can be seen in Table 8.

Table 8. Initial Multirotor Drone Design Specifications

Item	Specification
Mass	Approx. 480 grams
Theoretical Thrust	Approx. 800 grams at 22 amps
Theoretical Flight Time	7.5 Minutes
Maximum Operating Distance	200 Meters Direct Line of Sight
Dimensions	216mmx229mmx127mm

This initial design fit comfortably into the box, allowing ample room to maneuver potential obstacles. The operating distance was limited by the video transmitter strength. For this competition a long range was not required, but if applied elsewhere, the video transmitter could easily be swapped and operating distance drastically increased. The control system operating distance is advertised at over a kilometer. However, as previously mentioned not enough thrust was being generated at an acceptable power level, so flight time was brought down to an unacceptable range. As advertised the initial motor and prop combo would produce 200 grams of thrust each giving a 800 gram total thrust output for the quadcopter. The actual tested output of the motors and props only output around 160 grams of thrust each leading to a 20% reduction of expected thrust. Though the thrust was only reduced by 20% flight time was cut in half resulting in an actual 2-4 minute flight time. A further iteration of the design was needed. With a rushed timeline, the design had to be fast-tracked, and a design with larger motors and generic protective ducts was created. Propeller based propulsion theory states that the amount of thrust produced is directly related to the swept area and pressure differential on either side of the blade.[31] This knowledge was used to drive our decision to enlarge the props as a sure shot for obtaining the thrust required. The larger motors and props added mass to the quadcopter as can be seen in table 9.

Table 9. Additional Parts List for Larger Quad

Item	Description	Mass (grams)	Dimensions (mm)
Larger Motors	DYS 1806 Motors	21.3	NA
4” Props	Gemfan 4045	1.5	NA
Large Ducts	3-D SLS Nylon	17	NA
	Additional Mass	87	

With these additional components a thrust of over 1600 grams was produced, giving adequate lift to account for the increased weight of the quadcopter. The motors were selected because of their availability to the group, a team member pulled them off of his personal drone and lent them to the team. The ducts were printed out of nylon this time because the school's 3-D printer had a long waiting queue and we needed them as soon as possible. The production was outsourced and the fastest turnaround time was by a company that used selective laser sintering 3-D printing technology. The larger items caused the mass of the entire quadcopter to increase as expected. These additional items were added to the 3-D model of the drone and can be seen in Figure 2.

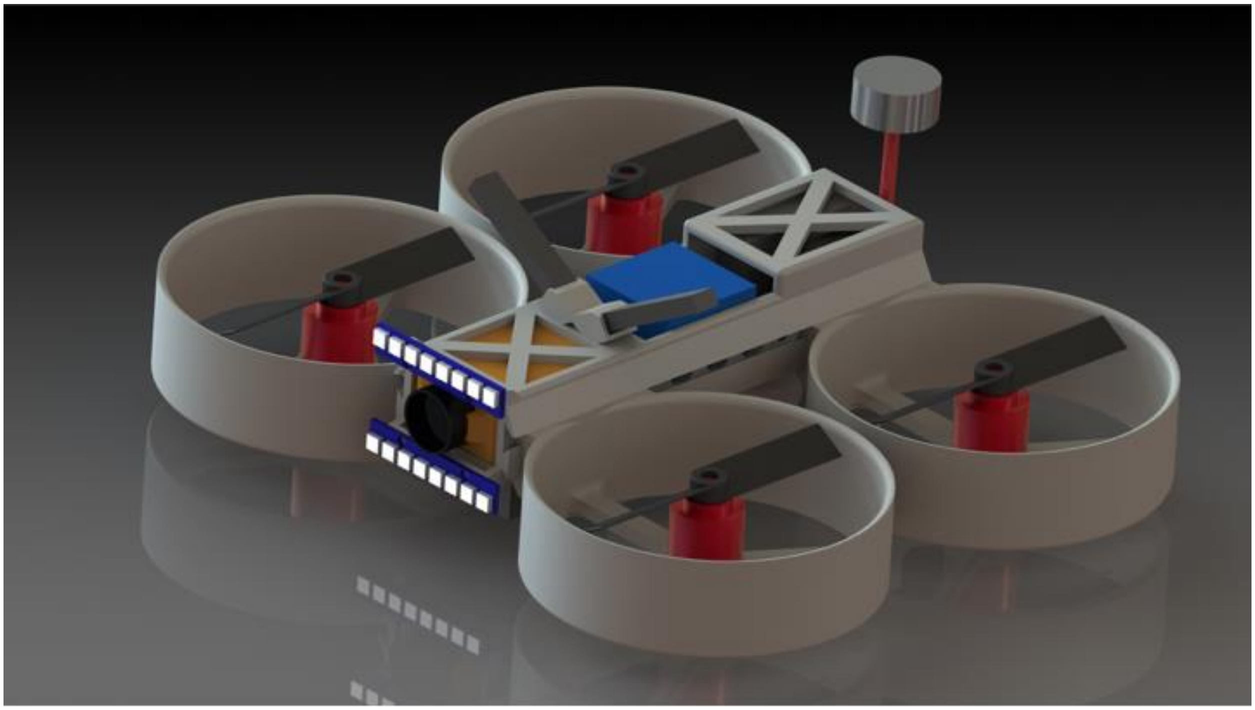

Figure 2. 3-D Model of Proposed Solution

The benefit of having a modular design came in handy with this iteration, as only the ducts had to be redesigned and could still slide on the central frame rail system without modification to any other components. The motors were also a direct plug in to the TBS PowerCube reducing setup time significantly. Specifications on this design can be seen in Table 10.

Table 10. Final Multirotor Drone Specifications

Item	Specifications
Mass	567 grams
Actual Thrust	1600+ grams at 23.2 amps
Actual Flight Time	7-10 Minutes

Maximum Operating Distance	200 Meters Direct Line of Sight
Dimensions	229x279x91

This motor and prop combination had an ample thrust, over 1600 grams total, which was more than enough to carry the additional mass of the larger motors and ducts. This generated a flight time of between 7 and 10 minutes, depending on flight pattern and aggressiveness, which achieved our goal of having around a 10 minute flight time. The downside to this larger design was that the width of the drone was enlarged to around 11”, a size that was not unacceptably large, but did not fit into our ideal dimensions. All parts used on the construction of the drone can be seen on the bill of materials in Appendix B. The final system can be seen in Figure 3 below.

Figure 3. Finished Quadcopter

The final drone came out exactly as modeled and planned. All dimensions were accurate to the 3-D model, and everything was able to be assembled and connected with ease. A circuit diagram of how all components were connected can be viewed in Appendix C and detailed instructions on assembly and setup can be found in Appendix E.

III. Testing

While the drone was being built, a testing environment was also constructed. The test structure had identical dimensions to the contest structure, and was made for testing the efficiency of our quadcopter concept and to hone our proficiency with controlling the drone (Figure 5).

Figure 5. Testing Environment- top left: completed structure, top right: interior with black corroded sample from USDASC, bottom left: view from outside of circular entry point, bottom right: view from inside showing small blue corrosion panel from USDASC on left

The structure was built to scale and included key design features such as the three differently shaped entry holes and the middle bisecting wall. The material used was plywood for cost savings, but the environment was made to match the test environment as closely as possible. Samples of corrosion sent to us by USDASC were mounted to the walls, the structure was covered to mimic the dark environment, and some obstacles were added. From using the practice structure the group learned how the quadcopter would react to flying in an enclosed environment. Also, information pertaining to video quality and lighting was found. This test structure was used to perform rigorous tuning of the flight control board and system, in order to optimize the flight controls and characteristics. While testing, the entire control system was customized in an attempt to make the flight characteristics of the drone match those required to enter a confined space such as the one used in the competition. With the corrosion samples present, the structure also allowed for image processing procedures and methods to be tested in an environment close to the anticipated competition conditions.

While testing the drone, the expected flight pattern and data collection process was developed and was very close to the one that was originally planned. Within the 45 minute time allotment the drone would fly into the testing environment, collect data for approximately 7 minutes and then fly back to a ground station where the images were processed. The battery on the drone would be swapped out for a fully charged battery and this procedure would be repeated 3 to 4 times or until sufficient visual data was collected. A Gantt chart showing how time would be partitioned during the competition can be seen in Appendix F.

IV. Contingency Plans

Towards the end of the flight testing, the drone had obtained considerable damage due to repeated crashes inside the test structure. These crashes were caused by the extreme turbulence in the box, which the flight control system was unable to account for. After multiple crashes the damage to the flight controller left the quadcopter inoperable. We devised a contingency plan that consisted of purchasing a micro drone, the Estes Proto-X FPV in the event that the drone we designed was unable to salvaged. This drone was significantly smaller than our designed solution, and measured in at no larger than 6”x6”x2”. It had a 720p camera that was capable of on board recording and sending out a live feed to the pilot. The only modifications that were done to it were the taping of a small led light and coin cell battery to the top of it, lighting the enclosed environment, and the addition of a weighted fishing line tether for retrieval. However, with this contingency plan not guaranteed to work due to turbulence still being created in the box, two more methods of data collection were devised once at the competition. A group member’s GoPro, the RunCam 2 and Monnit RH sensor were covered in weather stripping to provide a cushioned casing, and tied to fishing line tethers for retrieval. The plan was to toss these cameras and sensors into the box and drag them through the environment. In a time crunch we thought that these methods of data collection, used in conjunction with one another, could support our data processing system.

Results and Discussion

During the competition, the official structure was similar to the one given to us as a model, with the exception of a few added obstacles on the ground and the walls, and some minor dimensional differences. The entire box was evenly coated with PSX 700 except for a few visible spots of corrosion where the bare metal showed, so visual inspection, as expected, was suitable. The interior of the box was painted with a glossy yellow color, which we expected to have an impact on our color threshold modification in the corrosion highlighting part of the procedure. We had to resort to the contingency plan during the competition because of a malfunction with the primary drone which caused it to receive power, but not the signal for control. During the first fifteen minutes of the challenge the contingency quadcopter did not record video which made it impossible to start our image analysis. Once the quadcopter began to film properly, the video was able to be analyzed and broken down. The quadcopter video was found to be very grainy due to a combination of poor lighting and low camera resolution. In an attempt to simultaneously record video in both compartments the two extra cameras wrapped in protective foam were tossed into the structure. These higher quality cameras were able to give us good images however due to the nature of us pulling the cameras from a tether, it was hard to get good camera angles. Relative humidity was recorded using the same method but provided good, accurate data. With the data collected the relative humidity data was plotted vs. time and video where corrosion was spotted was able to be processed. Video was broken down into frames, and when corrosion was seen in a frame it was added to the final report. However, the final steps for image processing were not fully completed due to time constraints and malfunctions in the data collection process during the competition.

Problems encountered during the competition were largely due to limitations with the motion system and the detectors. Poor image quality from the camera on the backup quadcopter resulted in misinterpretation during image processing. Limitations in the quadcopters abilities to image photos directly perpendicular to the structure made it difficult to generate accurate dimensional measurements. There was error in the color threshold adjustment process because the highlighting of pixels was based solely on the color. Pixel color can be attributed to corrosion in some cases, but the same pixel color could cover a location of corrosion or simply a shadow on a wall of the structure. This came down to not having ample lighting in the environment. When overlaying images to determine lengths the stretching from using a fisheye lens first needed to be removed to have perfectly accurate measurements, and was not included in projected image processing procedure. Also, dimensions of the structure were estimated prior to imaging the structure and proved to not be fully accurate.

Problems existed in the motion system mainly relating to flight stability. The unforeseen amount of turbulence created by the rotors greatly reduced flight control. Lack of experience with flying the contingency quadcopter led to difficulties in both entering and exiting the test structure as well as maneuvering it around the inside.

To improve the data processing sequence a better division of tasks during the competition would have improved our results. Instead of focusing on inspecting the whole structure at once and trying to process every defect together, members could have focused on obtaining single images of each location of corrosion. From the lessened data load, the time spent on image processing would have been greatly reduced, and accuracy could have been improved. The rules of the competition graded teams on their ability to locate and analyze a high volume of corrosion, so a focus on imaging known corrosion regions would have improved our score.

Summary and Conclusion

The first stages of this project were to understand the problem at hand and learn about the established fields of corrosion detection and autonomous systems. Next, detection techniques with remote systems were compared using the judging criteria for the project as a reference. A suitable system was selected to help achieve the maximum number of required goals, while also remaining within the defined budget. Time was spent to further design the components required for the system so they could operate as intended, parts and supplies were purchased, and ultimately the final device was built. Following completion of the physical construction, the system was tested and methods were refined for collecting and analyzing the outputted data. The system had the ability to navigate in an enclosed area, around various obstacles, and complete our goal generating a comprehensive report of the detected corrosion.

For this project to continue a “smarter” drone would be required. The addition of more sensors designed for navigating an enclosed environment would significantly improve the entire design. If optical flow and ultrasonic sensors could be incorporated into the design of the drone, it would have the ability to locate itself in space and account for and sudden movements induced by the turbulence in an enclosed environment. More effective props would also improve the size of the drone. A smaller prop and propulsion system would allow for an easier fit in the testing environment. All of this said, a significant increase in funding and time would be required to turn these concepts into reality.

As a proof of concept project our designed system had potential to be applied in not only the competition environment but also other environments in the real world, giving legitimacy to the practicality of our detection and motion methods. This project as a whole was a very hard task to handle, and given the circumstances the team had to operate under, we were able to construct a fully functional design. For this project to continue at a top-tier level, a team made up of more mechanical and systems engineers would be suggested, as the motion aspect of the design proved to be very significant compared to what was initially anticipated. Success in all systems relied on the motion system to operate. Also, a designated computer science or software engineer would be helpful, as they would be able to better manage the image processing side of the design. However, the current team gained a lot of knowledge during the design process and more importantly brought home some hardware after being awarded 3rd place at the competition.

Appendix A. Drawings of Competition Structure

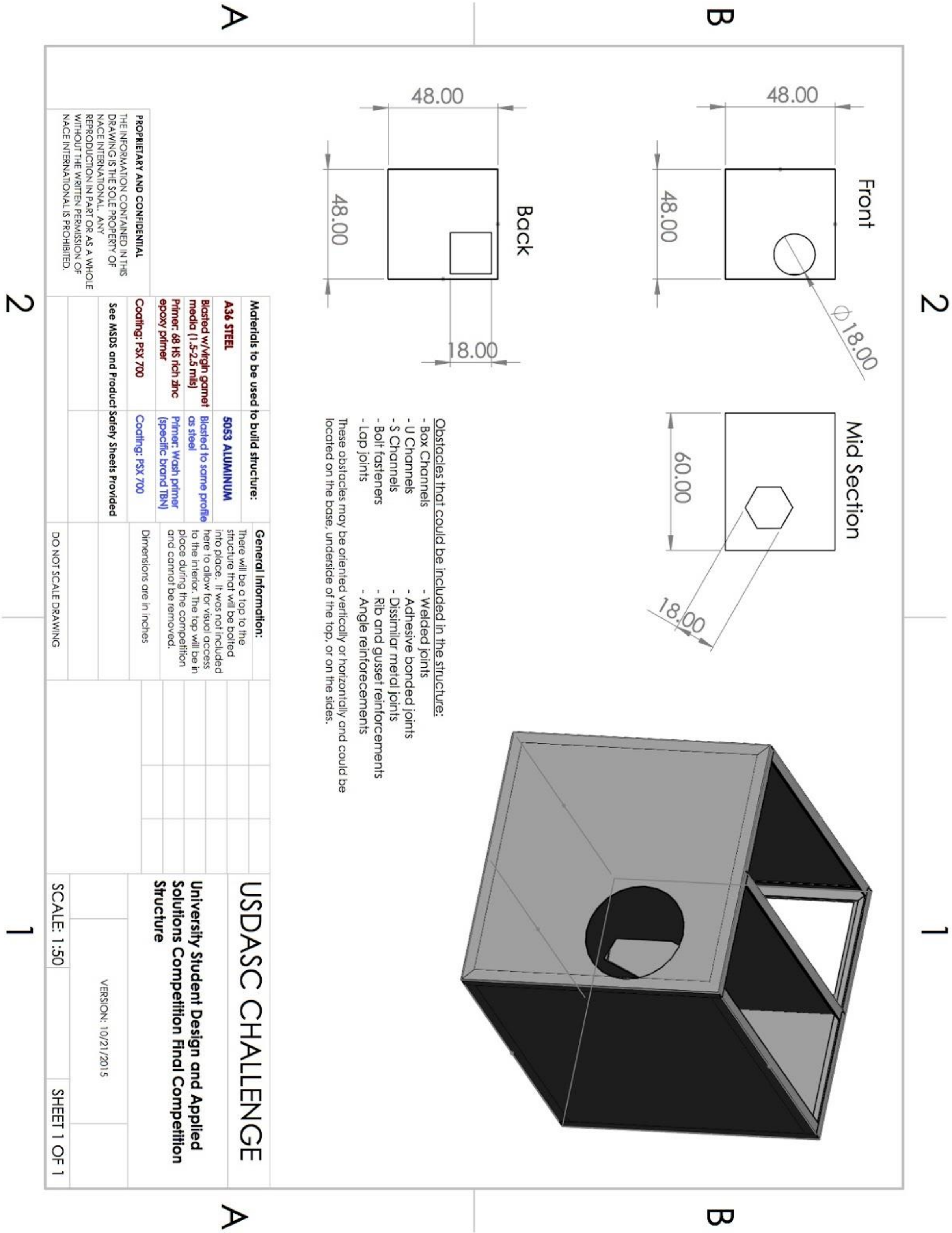

Figure A1. CAD Drawing of Competition Structure

Appendix B. Bill of Materials

Table B1. Bill of Materials, Motion-based Components

Item	Description	Price	Quantity	Total
Flight Controller, ESCs, PDB	TBS Power Cube	$139.95	1	$139.95
Controller and Receiver	FrSky X9D & X8R	$209.99	1	$209.99
OSD	TBS PNP 50	$64.95	1	$64.95
Motors	DYS 1104 Motors	$11.99	4	$47.96
Larger Motors	DYS 1806 Motors	Borrowed	4	$0.00
3” Props	DYS 3020	$3.99	2	$7.98
4” Props	Gemfan 4045	$13.99	1	$13.99
Battery	Pulse 4S 1550mAh	$27.99	4	$111.96
Frame and Small Ducts	Custom 3-D Printed ABS Plastic	$80.00	1	$80.00
Larger Ducts	3-D SLS Nylon	$226.77	1	$226.77
			Subtotal	$903.55

Table B2. Bill of Materials, Sensor-based Components

Item	Description	Price	Quantity	Total
Video Camera	Runcam 2	$99.00	1	$99.00
Memory	16 gb	$10.00	2	$20.00
Video Transmitter	TBS Unify GreenHorn 25mW	$29.95	1	$29.95
Video Antennas	Aomway Circular Antenna	$14.79	1	$14.79
RCA to USB	EasyCap	$26.06	1	$26.06
Video Receiver	Eachine 7" LCD	Borrowed	1	$0.00
Lights	Ws2812 LED Strips	$11.99	1	$11.99
RH Sensor	Monnit RH Sensor	$79.00	1	$79.00
Gateway	Monnit USB Gateway	$49.00	1	$49.00
Software	IMonnit Express Basic	$79.00	1	$79.00
			Subtotal	$408.90

Appendix C. Drawings of Airframe and Circuit Diagram

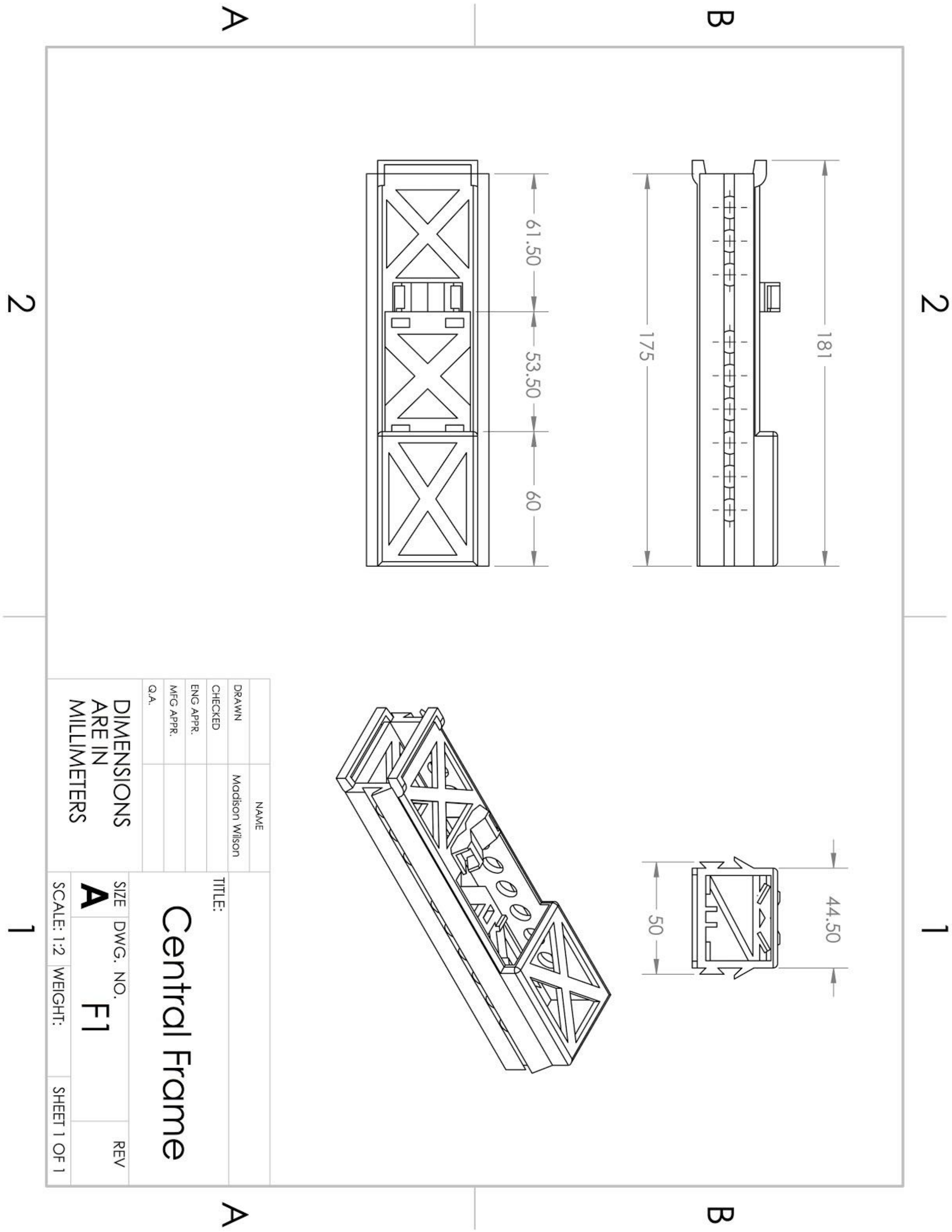

Figure C1. CAD Drawing of Quadcopter Central Frame

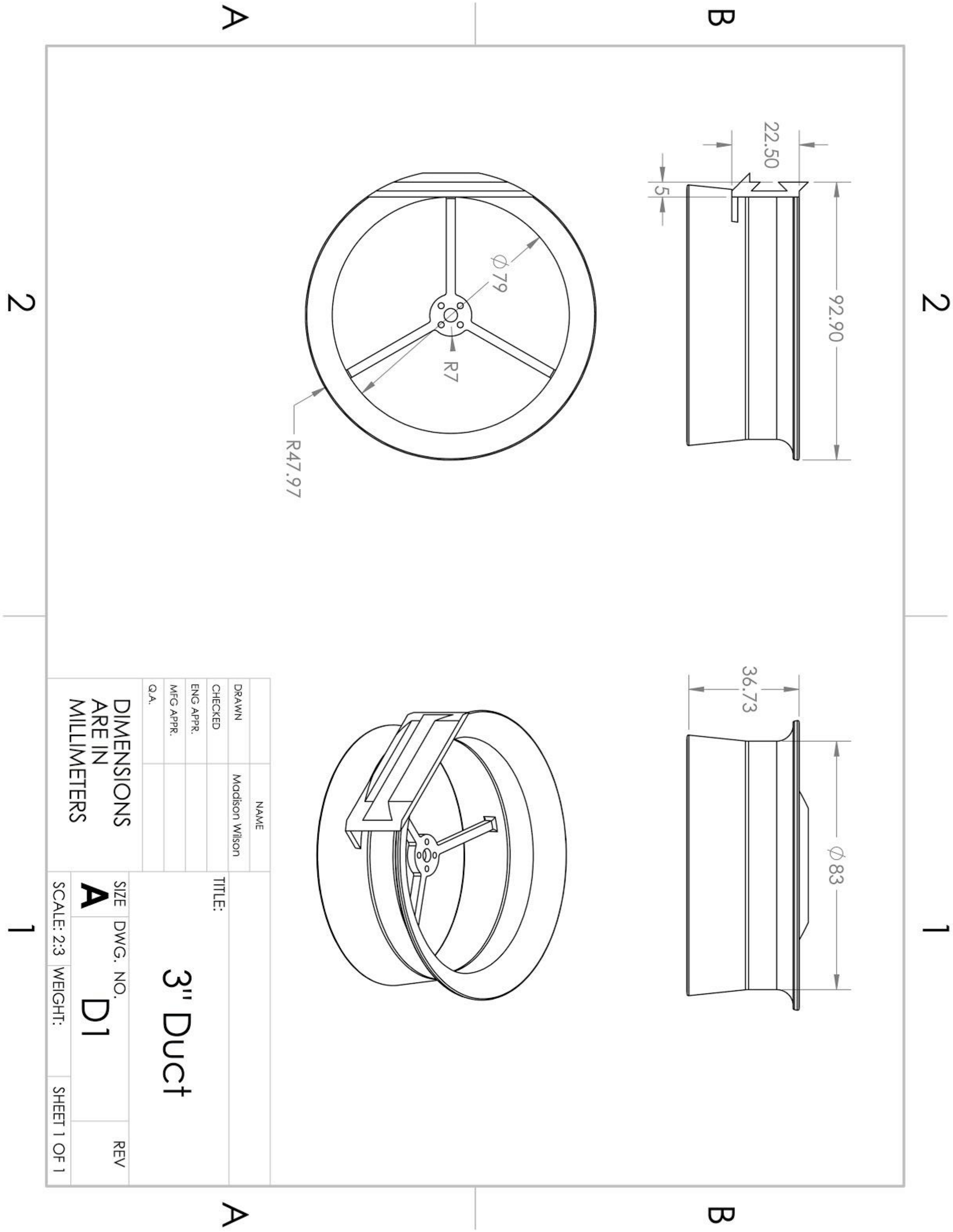

Figure C2. CAD Drawing of Efficient Duct

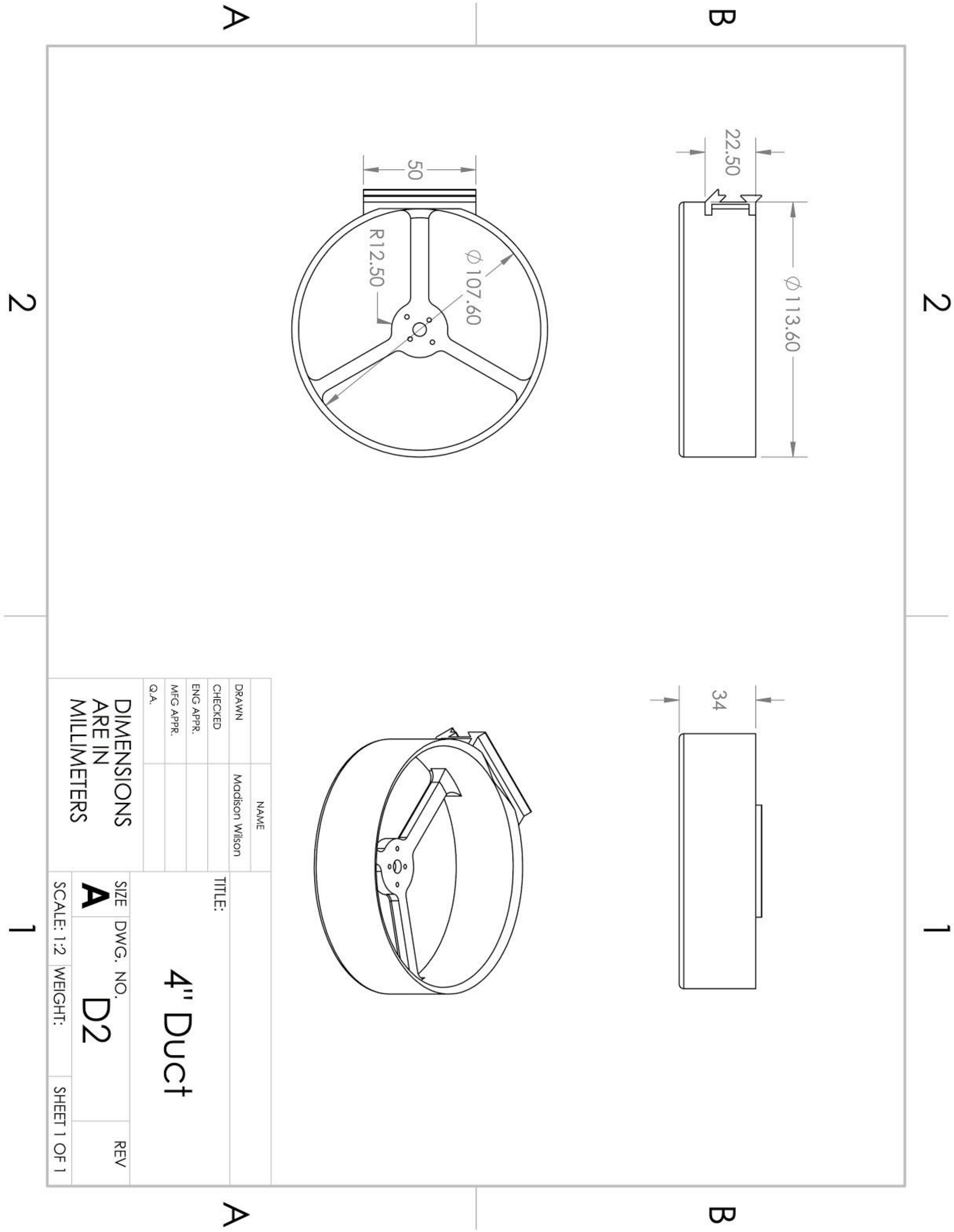

Figure C3. CAD Drawing of Enlarged Protective Ducts

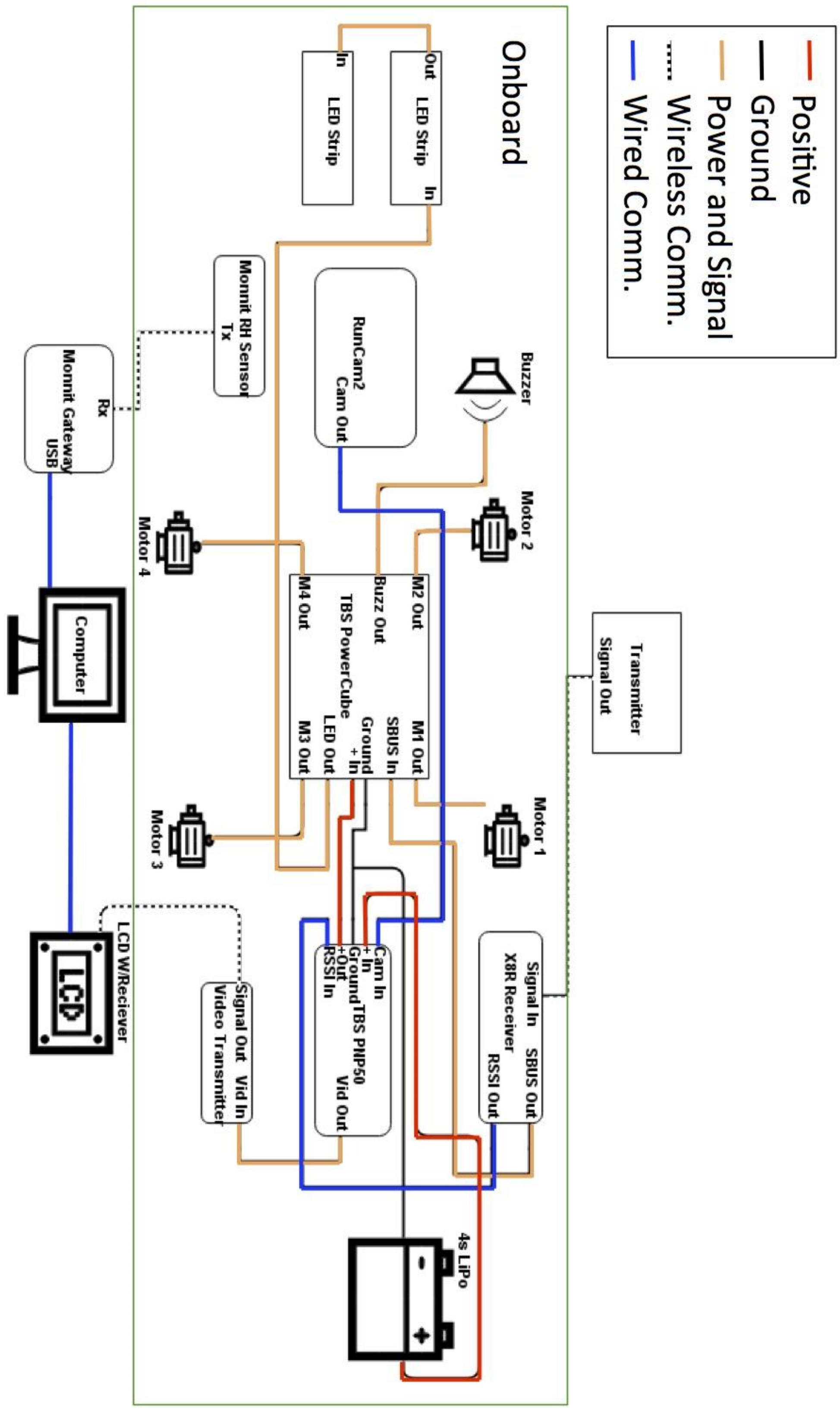

Figure C3. Circuit Diagram of Quadcopter

Appendix D. Data Processing Procedure

1. Capture videos at 1080p at 60 frames per second
2. Load video files into VLC Media Player
    1. Cut into still images at a rate of 5 frames per second
    2. Sort through frames to find images in focus
    3. If corrosion can be seen or image is necessary for forming a complete image of a wall select them and move to the next step
3. Load images into MS Paint
    1. Crop images and use common features on each picture to form a single image for each wall
4. Load cropped image into ImageJ
    1. Adjust hue, saturation, and brightness to highlight corroded regions, save these images to for future use
    2. Change images to a binary color scheme
        1. A properly modified binary image will only show corroded regions
    3. With the binary image, generate a histogram of colors in the image
        1. Because only two colors are present, a value for pixels with corrosion vs. pixels with no corrosion is obtained
5. Import pixel ratios into Microsoft Excel
    1. Generate tables containing the percentage of corrosion that cover each wall of the structure
6. Generate models of the test structure using Google SketchUp
    1. Overlay ImageJ modified pictures of corrosion onto their respective walls
    2. Add dimensions to overlaid pictures to show their location and size
7. Compile data for final report submitted to judges

Appendix E. Setup and Operation Instructions

Motion

Setup

1. Setup FrSky X9D

a. Flash firmware

i. Download and open OpenTX Companion and appropriate drivers for comm. port on computer (depends on operating system)

ii. In OpenTX configure settings for firmware
    1. Ensure correct controller model is selected
    2. Apply custom splash screen
    3. Customize sounds

iii. Connect controller to computer

iv. In OpenTX download latest firmware package
    1. Should automatically upload to controller
    2. If error, comm drivers most likely didn't install correctly

b. Create new model in controller

. Once firmware has been upgraded follow onscreen steps to configure controller to individual preferences
    1. For basic use only elevator, pitch, yaw, and roll need to be assigned on 4 channels

2. Bind X8R Receiver

. Turn on controller and select model wanting to be bound

. In menu select "bind" controller should start beeping constantly

a. While holding down the failsafe button, supply power to receiver

b. Once led flashes a steady red it has been bound

c. Exit out of bind mode on controller

d. Power down the receiver and power back on

. LED should be a constant green signifying connectivity

3. Configure TBS PowerCube

. Download, install and open Cleanflight software

a. Plug in PowerCube to computer using micro USB cable

b. Once connected configure flight controller as required

. The TBS PowerCube comes pre-flashed with firmware and can be updated if liked

i. Be sure to select SBUS comm. for receiver input

c. Plug in receiver then battery to PowerCube and test connectivity through Cleanflight software

4. Assemble and connect all components in preferred configuration

. Solder wires and connectors as appropriate

a. When assembling be sure to use SBUS output on X8R receiver

Operation

1. Turn on X9D controller
2. Plug battery into drone to power on all systems, should bind to controller
3. Use assigned controls as assigned in previous steps to control motion and maneuver

Sensors

Setup

8. Video Feed
    1. Install and set up camera
        1. Determine if built in battery will be used or power will be supplied through micro USB port and PNP50

            1. If power is being supplied by the PNP50 solder all outputs from cam port
            2. If not only solder yellow video and ground wires to micro usb cable and remove excess wires
        2. Insert microSD card for video recording and image capture
        3. Camera preferences can be configured through the RunCam phone app and built in wifi or through system OSD
    2. Be sure to activate constant recording on camera for HD images and video for later processing
    3. Install and configure video transmitter
        1. Install antenna onto video transmitter and receiver
        2. Connect video transmitter to PNP50 using appropriate cable
        3. Configure switches to output desired band
        4. Power on the system, blue light on transmitter should be on
    4. Connect to video receiver
        1. Power on receiver
        2. On receiver, search for feed, will automatically connect to emitted signal
    5. Connect receiver to computer
        1. Connect receiver outputs to EasyCap inputs
        2. Install EasyCap software on computer
        3. Plug in EasyCap USB device to computer
        4. Live feed will show up

9. RH Sensor
    1. Download Imonnit software
    2. Plug in usb gateway
        1. Configure gateway as wanted
    3. Power on RH sensor by installing battery
    4. In software sensor bind sensor and gateway
    5. Configure software to obtain data samples as preferred

<u>Operation</u>

1. Once battery is installed on drone, systems will power on and connect automatically
    1. If camera is not powered by PNP50 install battery and power on
2. Power on necessary computers and receivers to obtain in-flight data
3. When flight is complete remove microSD card from camera and open in software to process

<u>Appendix F.</u> Gantt Chart of Competition Time Management

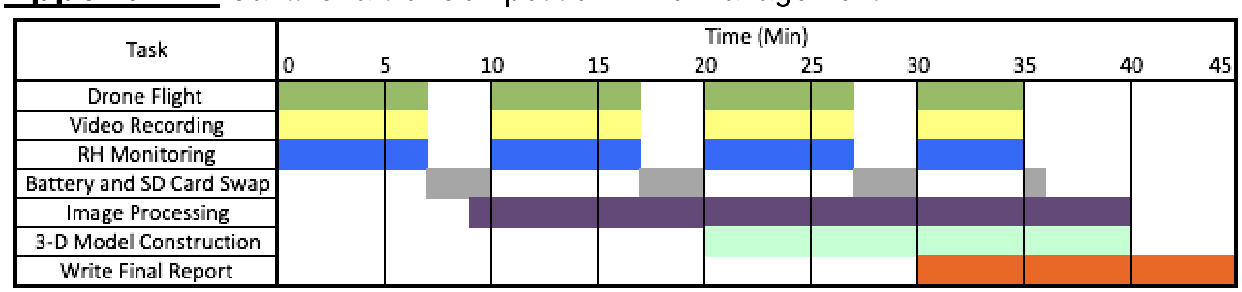

Figure F1. Gantt Chart Showing How Time Will be Partitioned During the Competition

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Contributions

The team was broken up in two main sub-teams. Eric Nelson(EN), Nick Robert(NR) and Jacob Townsend(JT) made up the corrosion detection “department”. Max Wilson(MW) and Scott Ciabattari(SC) made up the motion team. EN, NR, and JT were responsible for determining the most viable methods for corrosion detection whereas MW and SC were responsible for determining the most viable motion solution. EN, SC, and JT contributed to the construction of the test environment. NR and EN headed the image processing and photogrammetry system development. EN developed methods for identifying, measuring, and locating corrosion through different software programs and established a standard operating procedure for doing so. MW lead the mechanical and electrical system design of the drone doing all 3-D modeling for the project. MW also did all motion system calculations and created the parts list. MW did all assembly and testing of the motion system. MW and SC both researched a theoretical tethering system for the drone which was not used. MW and SC both contributed to the development of the contingency plans. JT and SC did not focus in one area significantly and contributed small amounts to multiple aspects instead of major accomplishments for a few things. EN was the primary editor for most written reports. JT also produced weekly reports on the team progress after each team member wrote their contributions. During the competition, EN and NR performed visual data processing. JT collected data using the humidity sensor. SC managed the contingency plan devices. MW was the designated pilot. EN assembled final report for judges.