

## System for Corrosion Inspection and Monitoring

**Ryan Alexander<sup>1</sup>, Matthew Altamirano<sup>2</sup>, Saruul Batdorj<sup>2</sup>, Matthew Brooks<sup>1</sup>, Pascal Brun<sup>1</sup>, Antelmo Del Angel<sup>2</sup>, Alexander de la Rosa<sup>1</sup>, Craig Brewer<sup>1</sup>, and Michael Deible<sup>2</sup>**

<sup>1</sup>Department of Systems Engineering  
United States Military Academy  
West Point, NY

<sup>2</sup>Department of Civil & Mechanical Engineering  
United States Military Academy  
West Point, NY

Corresponding author's Email: Alexander.DeLaRosa@usma.edu

**Author Note:** The University Student Design and Applied Solutions Competition team representing the United States Military Academy (USMA) is a joint endeavor by cadets from the USMA Department of Systems Engineering (SE) and the USMA Department of Civil & Mechanical Engineering (C&ME).

**Abstract:** This paper contains has conducted research and analysis on different corrosion identification and monitoring methods to develop an autonomous corrosion inspection system to solve the challenge issued by the University Student Design and Applied Solutions Competition. This challenge is to build an autonomous corrosion detection and monitoring system to help provide new ideas and innovations to the Department of Defense. Using research and stakeholder analysis, this research produced a system to best meet the demands of the competition and determine the best possible solution to the design challenge. Our integrated team used a systems engineering approach to produce the design that will be fielded at the competition in April 2016.

**Keywords:** Corrosion, Inspection, Monitoring, Autonomous, System, Integrated Team, Value Modeling

### 1. Introduction

Corrosion monitoring and maintenance costs the United States Department of Defense (DoD) \$20.9 billion and more than \$500 billion annually across the nation through public and private entities (National Association of Corrosion Engineers, 2015). A large portion of senior level corrosion experts are nearing retirement in the DoD and corrosion industry; as such, the University Student Design and Applied Solutions Competition (USDASC) is supporting research and involvement in the industry to promote innovative applied technology solutions (University Student Design and Applied Solution Competition, 2015). With new cutting-edge technology being developed as the gap in energy and information storage begins to shrink, research and development of new systems for corrosion monitoring and prevention could potentially lead to billions of dollars in national savings. The USDASC challenge was to build an autonomous corrosion detection and monitoring system to help provide new ideas and innovations to the industry. This research will compete against colleges across the nation to design and build the best possible system capable of detecting and monitoring corrosion in difficult-to-reach or otherwise inaccessible areas.

Corrosion is a chemical process that results in the degradation of metal through oxidation between a surface and surrounding molecules that alter the molecular structure of a material. The importance of corrosion lies in both economic and conservative factors. Material losses in pipes, tanks, and other metal structures can lead to significant economic loss through replacement and repair. Furthermore, since metal resource supply is limited, and time to design and produce metal structures is often costly itself, conservation of resources and time is key (Uhlig, 1964). While there are many methods to detect the corrosion process, not all are feasible due to cost or technological limitation, resulting in a majority of corrosion inspections being conducted visually.

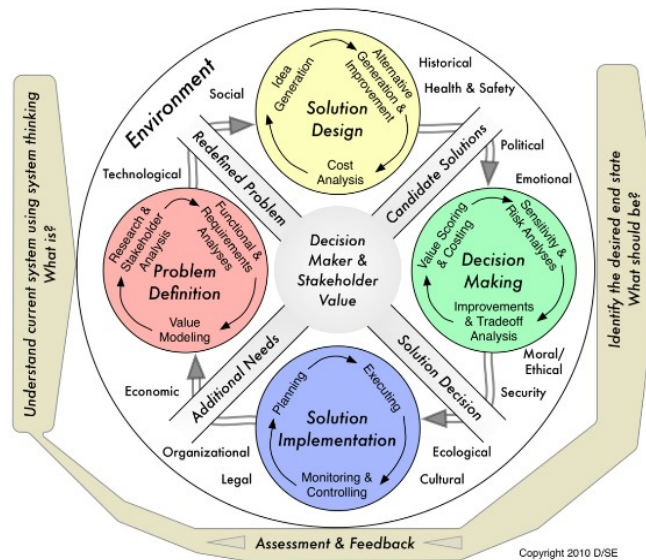


Figure 1. Systems Decision Process (SDP)

Our research began with identifying techniques using electrochemical polarization methods. We learned that electrochemical methods are quite accurate; however, they would require that the metal being inspected be submersed in an aqueous solution (Yang, 2008) (Garboczi et al., 2014). Our research and discussion with experts in the field of corrosion inspection and monitoring determined that the best method of inspection remains visual in terms of cost and practicality. Thus, we initially determined that detection and monitoring of the corrosion process on an automated system would best be solved by using a high quality digital camera.

This paper introduces the decision process that our team used to create a solution to the problem of autonomously identifying and monitoring corrosion. This process, known as the Systems Decision Process (SDP) (Figure 1) encompasses the initial problem definition, solution design, the decision-making process, and solution implementation. Additionally, we describe the systems and mechanical engineering tools which we used in each phase to generate alternatives and assess the effectiveness of our solution designs. In turn, our decision process and engineering tools allow us to develop an optimal design and solution to the USDASC challenge.

## 2. Problem Definition

We began our decision process with the problem definition phase. In this phase, we analyzed the challenge presented to us by the USDASC and the potential constraints that we anticipated. Research & Stakeholder Analysis, Functional & Requirements Analysis, and Value Modeling were conducted during the Problem Definition phase. The functions and requirements for the design were obtained from the rules and regulations posted online by the USDASC coordinators. The USDASC outlines that the system needs to be able to operate autonomously, be able to inspect and identify various forms of physical corrosion, detect presence of standing water, and communicate this back to the operator in detail. Our functions and requirements mirror these demands. During the Research phase, we furthered our understanding of corrosion detection methods that have previously been developed and which of these methods are most commonly utilized in the work force. Our team also conducted personal research and sought out various stakeholders. After the initial research and analysis phase, the information we had collected thus far was modeled into a Context Diagram (Figure 2) – a visual representation of our detection system and its interactions with environmental factors.

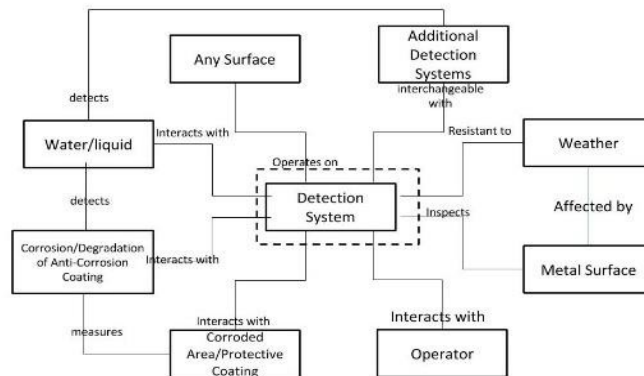


Figure 2. Context Diagram

With our problem better defined and represented in the Context Diagram, we were able to create a Functional Hierarchy (Figure 3). Functional Hierarchy is a presentation of the fundamental objective that the system is intended to accomplish, sub-levels of the hierarchy are added to highlight the multiple functions that are essential to the system completing the fundamental objective (Parnell et al., 2010). The Functional Hierarchy is a presentation of the underlying sub-levels of each function. The Functional Hierarchy helped us identify and specify exactly what the system would need to do. Furthermore, the Functional Hierarchy helped us prioritize the functions for the system in order to know the major areas of concern for the design, which we determined to be: 1) Deployment, 2) Inspection and 3) Data Report or Communication. We then formulated the Qualitative Value Model (QVM), using the functions from the hierarchy as a base to expand on the values integral to the fundamental objective and to allow the team to hone in on the key stakeholders' major areas of focus for the design. The QVM enabled us to create the non-numeric values of what our system needs to achieve. The QVM and Functional Hierarchy were helpful in giving us a full understanding of what we needed out of our design. With these tools, we developed an understanding of what we would need to consider when coming up with alternatives, as well as an understanding of similar systems that had been previously developed. From here, we transitioned into the Solution Design phase of the SDP.

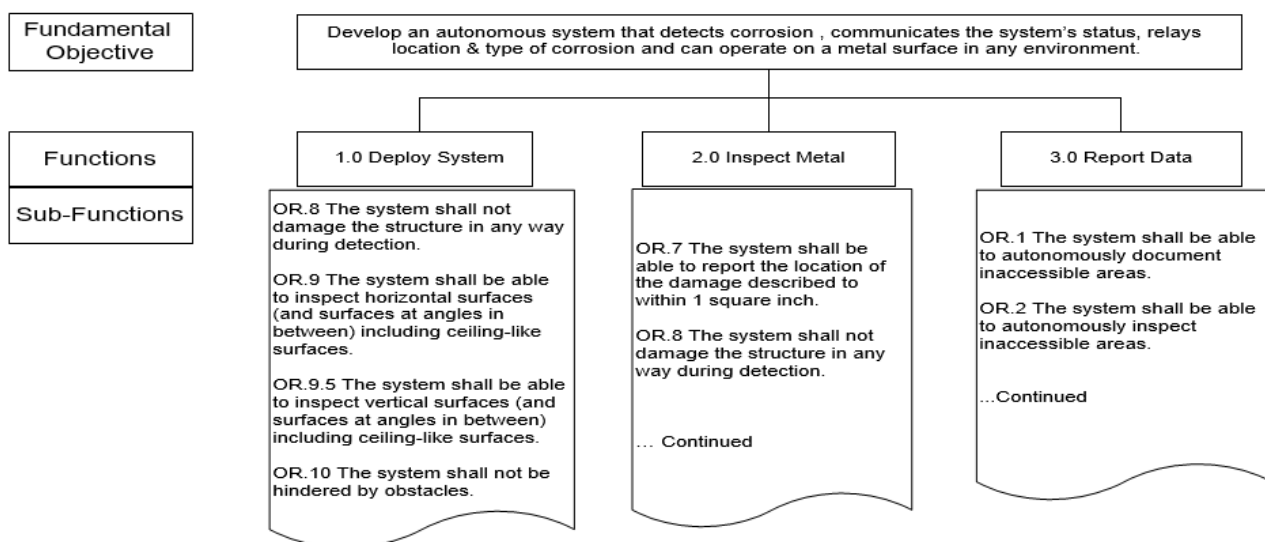


Figure 3. Functional Hierarchy

### 3. Solution Design

The solution design phase of the Systems Decision Process is comprised of three sections. First, we begin the phase with Idea Generation, followed by Alternatives Generation and Improvement, and finally Cost Analysis. This allows us as systems engineers to make an educated decision on the alternatives. Cost Analysis may lead back into more idea generation if the previous alternatives are cost-prohibitive.

Idea generation was executed after researching design alternatives through various channels such as academic research and searching the internet for videos of similar systems. An alternative is a proposal with a complete description of objectives and requirements to explore opportunities for further analysis (Blanchard & Fabrycky, 2011). Using our Functional Hierarchy, we adhered to the originating requirements as closely as possible. Brainstorming was crucial to our idea generation, and no idea was immediately dismissed. The first function that the research focused on was movement of the system, and the sub-function to climb vertical surfaces. When creating ideas for the system's wall-traversing function we looked into alternatives such as, adhesive tape, van der Waals force (commonly seen on geckos), magnets, aerial maneuver, and suction cups. After eliminating systems that would be mounted on fixed rails and fixed attachments - due to the rigidity of their movement - our two improved alternatives were wheeled/tracked and aerial. Further consultation from the Department of Electrical Engineering, USMA, aided our research in determining that aerial vehicles were not suited for the confines of the competition structure and were subsequently eliminated. These design alternatives match the originating requirements of the competition to alternatives that we generated.

Alternatives for our radio communication function were based on the range of the transmitter and receiver. A wired connection was considered but dismissed after this alternative was researched and deemed unsuitable for the competition environment. The alternative that we decided upon was the Ts-353 wireless transmitter, due to its small size and low cost. Of the detection components that we considered, the High-Definition Camera was the most feasible for the purposes of our team. The Spectrographic camera system was determined to be too large for the purposes of the competition structure. Furthermore, the 3-D Laser Scan required an excessive amount of data transmission to the observer for small areas and was also cost-prohibitive. The more expensive camera alternatives were more effective at communicating corrosion, but ultimately our research showed that the HD camera's smaller size would allow us to make it mobile. Finally, we added a relative humidity sensor component to fulfill the relative humidity detection requirement.

Our group's primary determination for Cost Analysis was limited to items readily available through our engineering department or through online retailers like Amazon. This eliminated alternatives from specialized robotics companies and other contractors that sold ready-made maneuver platforms but were exceedingly expensive and required extra proprietary software to integrate into the system. Our initial alternative of aerial maneuver was cancelled before the order went through due to the lower cost and better value of our final platform alternative - the Dagu Rover 5, a tracked remote controlled chassis.

### 4. Decision Making

Once we determined that our alternative would have to be housed on a rover, we then began using value-focused thinking to determine which alternative components would result as our solution. Given our time constraints, we assessed which of the components we acquired would be most feasible to integrate onto our Arduino microcontroller. Arduino has a significant online community of users who help each other find solve programming problems. We eliminated the components that had little to no online community documentation, to include one of two humidity sensors we acquired from the electrical Engineering department and began learning how to code it to function with our wireless communication adapter to the Arduino. We applied this same process to two different options for wireless communication with the rover and decided to use a radio controller made for radio controlled planes that had a significant online community base. Finally, we selected the HD camera with infrared filming capabilities as this satisfied our use of the system in dark environments, especially considering our test structure will be enclosed by walls during the competition.

## 4.1 Test Plan

Our test plan falls in the Decision-Making and Solution Implementation block of the SDP. Initial tests were conducted on the individual components of the rover chassis, HD camera, transmitter, and humidity sensor to ensure proper performance in accordance with the requirements built by the team. The component testing affirmed the design choices made by the team. We first created a verification cross-reference matrix to ensure that each of our originating requirements were satisfied by a function of one or more of our remaining components. With this systems tool, we determined that all of our originating requirements were being met by the components we selected.

The next step we took to assess our components was to conduct real-world tests. Our integrated team developed a test plan for each component in accordance with the originating requirements. We numbered the tests, related them to their originating requirement, and determined the entry and exit conditions of a successful test. This process was completed to ensure that each component matched the needs of the system, and gave us an opportunity to objectively assess their performance. We based the performance assessment on the threshold and objective score values given by USDASC for an ideal system. Each component met each of the minimum criteria on the test plan. However part of the difficulty of our project was determining how to reach the objective values. For instance, the objective criteria for identifying pitting, corrosion on metal surfaces that results in craters or pits potentially leading to perforation of the metal surface (Roberge, 2008), are to measure a pit diameter down to one millimeter. While the affinity in our camera allows us to visually determine whether rusting, cracking, or pitting is occurring, the detail objective distance from the corrosion point makes it difficult for us to record exact measurements. There are high-tech and expensive equipment pieces available for professionals in the corrosion inspection business that allow inspectors to gain accurate measures. However, given our coding abilities and time limitations, visual inspection remained the most feasible inspection method given the scope of our project. Our integrated team developed such tests for each component in accordance with the originating requirements.

## 4.2 Risk Assessment

The individual components of the system each have their own associated risks. Each risk will factor into the success of the system's ability to detect and communicate the presence of rust on a metal structure. The purpose of assessing risk is to identify and categorize them, then manage them appropriately. Risk is assessed by identifying two components, the likelihood and severity of an event. Both components are scored on a 1-10 scale. Those scores are then multiplied to give the risk priority number (RPN) which allows us to rank our risks by a component's combined severity and likelihood. Using the RPN to gauge the priority of the event, we determined methods to mitigate the sources of risk appropriately for each of our individual components. We identified fourteen discrete risks. These risks were measured on their severity, probability, and detectability. Based on our Composite Risk Matrix our radio communication control system and the sensors on the Arduino are the most vulnerable to risk. The highest risk we assessed had an RPN of 70, which we based on a likelihood of 7 and a severity of 10. Thus, consulting the Robotics experts in the Electrical Engineering Department to verify proper wiring and coding of our components would prove the most effective method in mitigating the risks of human error in our transmitter device.

## 5. Solution Implementation

The first step of our test plan was to build the exact competition structure, put forth by the governing body of the USDASC. Wood was used to build the test structure. A36 Steel and 5053 Aluminum panels were placed inside the structure in order to evaluate the performance of our design. Robotics experts were consulted to ensure proper programming of the design. Upon completion of our design prototype and the test structure, we started testing our design against our test plans and performance matrices.

## 6. Conclusion

The costs of corrosion monitoring and maintenance throughout the DoD and the nation at large present significant incentives to create a feasible corrosion detection system. Our team intended to design and create an autonomous corrosion monitoring and inspection device within USDASC regulations and create the best system for the competition. To do so, we have conducted problem background research, defined the problem, and worked towards an optimal solution design. Based on our analyses, we have chosen a Rover system that consists of magnetic tracks, an infrared HD camera, a digital humidity sensor, battery power, and wireless communication.

We will continue to practice and improve upon our device up until the USDASC competition, which will allow us to get an accurate evaluation of our corrosion system's ability to perform in a challenging real-world scenario. We believe that our system design holds great potential; our current design has an estimated cost of only \$699 so far, which makes it very capable of being reproduced and thus attractive to stakeholders. Our low-cost design also suggests a large capacity for improvement: more expensive, higher quality materials would likely result in better performance, as would a staff of experienced robotics experts. We are optimistic about our design, and excited to continue to measure and improve upon its performance as we approach the competition.

## 7. Acknowledgement

This paper was previously published and presented in the Donald R. Keith Memorial Capstone Conference at USMA in May of 2015.

## 8. References

- Blanchard, B. S., & Fabrycky, W. J. (2011). *Systems Engineering and Analysis* (5th ed.). Upper Saddle River: Prentice Hall.
- Garboczi, E., Stutzman, P., Wang, S., Martys, N., Hassan, A., Duthinh, D., & Stiles, M. (2014). Corrosion Detection in Steel-Reinforced Concrete Using a Spectroscopic Technique. *Proceedings from AIP '13: American Institute of Physics Conference*, (pp. 769-772). Baltimore, Maryland.
- National Association of Corrosion Engineers. (2015). *Corrosion Costs and Preventive Strategies in the United States*. Retrieved from NACE: <http://www.nace.org/uploadedFiles/Publications/ccsupp.pdf>
- Parnell, G. S., Driscoll, P. J., & Henderson, D. L. (2010). *Decision Making in Systems Engineering and Management*. Hoboken: John Wiley & Sons, Inc.
- Roberge, P. R. (2008). *Corrosion Engineering: Principles and Practice*. New York: McGraw-Hill.
- Uhlig, H. H. (1964). *Corrosion and Corrosion Control*. Hoboken: John Wiley & Sons, Inc.
- University Student Design and Applied Solution Competition. (2015). *Overview: Official Rules, Regulations, Policies*. Retrieved from USDASC: <http://www.USDASC.org>
- Yang, L. (2008). *Techniques for Corrosion Monitoring*. Woodhead Publishing.