Autonomous Robot Arm Platform: Preliminary Report

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Executive Summary

Suez Advanced Water Solutions/Utility Service Company Inc. is a water systems company that provides water services to 7.5 million people in North America. In order to provide quality service, Suez maintains over 6,000 tanks by sandblasting and repainting over 100 water tanks per year. Suez aims to improve their current sandblasting process by utilizing an autonomous sandblasting robot arm to clean the inside surface of the water tanks. In order to use the sandblasting robot arm, Suez requires a platform that remains stable while the arm is sandblasting. Additionally, the platform will need to be both vertically and horizontally mobile so the floor, walls and ceiling of the ground water tank can be sandblasted.

The engineering team developed 5 preliminary design concepts that would meet Suez's requirements for their robot arm platform. A rail guided solution, a scissor lift platform solution, an electromagnetic wall climbing solution, a modular scaffolding solution, and an outrigger solution were evaluated to identify the benefits and potential risks of each design. Using an evaluation matrix with ten criteria used to quantitatively asses the designs, the Rail Guided Solution and the Outrigger Solution were selected as the most promising proposals. These solutions were individually analyzed for potential design challenges and performance failures. After redesigning to compensate for potential failures, the final proposed platform solution for the robotic sandblasting arm is a triangular platform design that combines the benefits of the Rail Guided Solution and the Outrigger Solution.

The initial CAD drawing depicts the final design for the robotic arm platform. The solution consists of a triangular base, three vertical truss towers and an arm platform that moves vertically along the length of the truss towers. The majority of the solution is made of aluminum 6061; however, a complete Bill of Materials is detailed in this report. An initial CAD model was developed and finite element analysis was run to verify that the design and material selection were capable of withstanding the thrust of the arm. The maximum displacement of the base plate was only 0.02 mm and the Von Misses stress was 1.859 MPa which will far below the maximum yield stress of the selected materials. The initial FEA suggests that the current design and material selection will support the robot arm and associated forces.

Preliminary success with the initial CAD model and finite element analysis of the triangular truss platform lead the engineering team to believe that the design will be successful in Suez's water tank application. In the following weeks, more detailed static analysis will be performed as well as advanced dynamic analysis to confirm the design selection. If necessary, design adjustments and improvements will be made to ensure the success of the robotic arm platform. Material selection will be finalized and a prototype will be fabricated in order to demonstrate proof of concept. The engineering team will continue to receive feedback from faculty and Suez in order to ensure the clients satisfaction with the final design.

Nomenclature

Ground Tank: A cylindrical water tank with a base that is fixed on the ground
Cycle time: The time that SABRE's autonomous sandblasting arm takes, start to finish, to complete sandblasting the 3 meter by 3 meter square section
CAD: Computer aided design
FEA: Finite element analysis

I. Introduction and Background

Suez Advanced Water Solutions/Utility Service Company Inc. is a water systems company that provides services such as clean drinking water, waste treatment and recycling to over 7.5 million people across North America. In order to provide quality water service, Suez maintains over 6,000 water tanks; maintaining water tanks requires cleaning the interior surfaces of the tank every 8 to 10 years. Currently, cleaning the water tanks requires sandblasting and repainting the tanks using manpower and manual hoses; this process is both inefficient and costly. Suez has acquired an autonomous sandblasting robot arm, developed by SABRE Autonomous Solutions, which will reduce both the time and financial requirements for cleaning ground water tanks. In order to utilize the autonomous robot arm, Suez requires a platform that remains stable while the arm is sandblasting and is easily moved to a new location after the cycle time has ended.

Figure 1: Autonomous Blasting Robot

The autonomous sandblasting robot is a six foot arm that has six degrees of freedom which enables it to sandblast a 3 meter by 3 meter square in one cycle. The robot scans the potential range for sandblasting using a structured light infra-red laser. An operator then selects the surface area to be sandblasted and activates the arm using a remote user interface. The arm has previously been used to sandblast bridges and Suez desires to expand the use of the technology to their water tanks. In bridge applications, the arm was mounted on a rail system which provided stability during blasting and the ability to move horizontally in between cycles. In Suez's application, permanent rail systems would compromise the integrity of the water tank and are not a feasible mounting option. Instead, Suez requires a mounting platform that can support the 25 kg arm, provide stability during the sandblasting cycle, and allow for horizontal and vertical movement in between cycles while not damaging the integrity of the water tank materials.

Applying the autonomous robot arm within Suez water tanks presents unique design challenges when conceptualizing a solution. For initial applications, Suez will be employed in ground water storage tanks. Ground tanks are cylindrical with dimensions ranging from 8 feet to 100 feet in diameter and 30 feet to 100 feet in height. All ground tanks are accessible through an entry hole with a diameter of 30 inches. In order to increase efficiency of sandblasting, the amount of human intervention in between cycles should be minimized. The proposed solution for the autonomous arm robot platform will be able to be assembled within the water tank; similarly, all parts necessary for the function of the robot must be able to be transported into the tank through the entry hole. A user interface with the ability to remotely control the movement of the platform between cycles will be included in the platform solution. Finally, visual feedback will be required for the operator to successfully maneuver the platform within the tank. With the successful creation of this stabilizing platform, Suez expects to increase efficiency of tank cleaning by 70%.

II. Existing Products, Prior Art and Applicable Patents

There are a plethora of existing solutions used for stabilizing robotic arms. Some of these solutions include: rails, sturdy tables, ground mounts, and a few others. The majority of these solutions are designed for robotic arms used in factories, labs or other relatively static environments. These solutions primarily use mounting brackets to secure the arm to a static surface. Currently, SABRE Autonomous Solutions, the company that created the technology, is mounting the autonomous robotic arm on rail systems. The rail system allows the arm to be moved once the cleaning cycle has finished the designated area while also providing an easy locking mechanism and stable base for the arm when in operation.

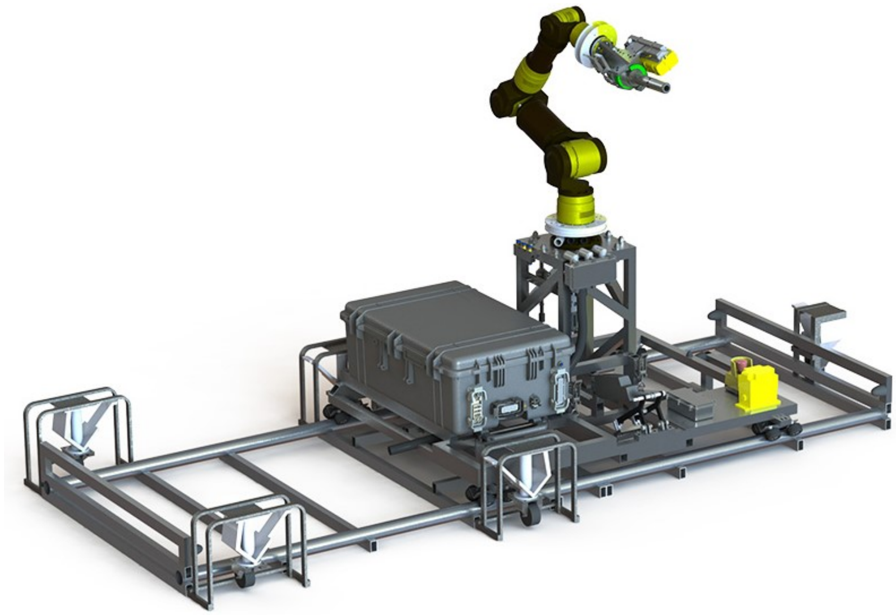


Figure 2: SABRE Autonomous Solution's Rail Mounting System

There are few applicable patents addressing the current design problem that Suez is facing. Patent number US4518437A, assigned to Sommer Schenk AG, covers a method and apparatus for cleaning a water tank. The patent describes an apparatus that has caterpillar tracks for movement. These tracks move by direction of a controller which has a compass and can be set on a course. The claim for this patent states that this is for an underwater cleaning apparatus. Additionally, this patent has a priority date of July 5th, 1982 and therefore is not currently enforceable.

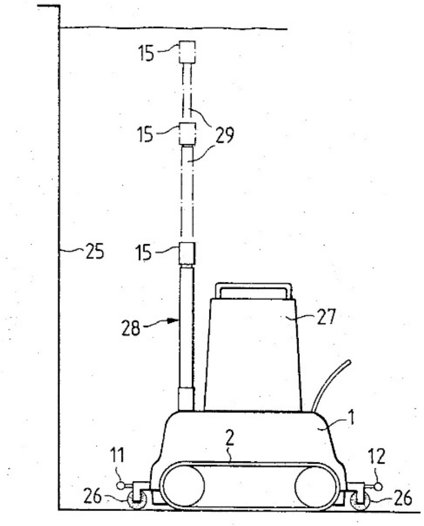


Figure 3: Drawing for Patent Number US4518437A

Patent number US3527336A (assigned to Associated Millwrights Inc.) is for a guide rail system. The invention covers a system in which a device runs on rails horizontally and vertically. This is a similar type of design that is being considered for the robotic arm. By using the rail system, the device on the cart can remain very stable. The filing date for this patent is 1968, so it does not have an effect on this project. Considering the current technology available, there are no applicable patents that will hinder the design solution for the autonomous robot arm platform.

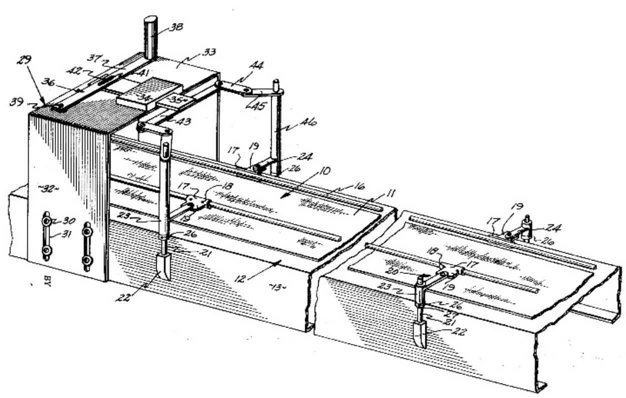


Figure 4: Drawing for Patent Number US3527336A

III. Customer Requirements and Engineering Design Specifications

The main stakeholder for this project is Suez Advanced Water Solutions/Utility Service Company Inc. Suez; they have both a high interest and a high influence. The workers responsible for cleaning the tank, or tank cleaners, have a high interest but low influence. The municipalities have a low interest but a high influence. The citizens in the municipality have a low interest and a low influence.

Table 1: Stakeholder Matrix

	Low Interest	**High Interest**
High Influence	Municipalities	Suez
Low Influence	Municipality Citizens	Tank Cleaners

Suez has provided the following requirements for the project. The product must:

1. Stabilize the robotic arm during sandblasting. Testing steps:
    a. The location of the base of the robotic arm should have no measureable displacement or rotation during the sandblasting process
2. Maneuver the base of the robotic arm within 5 m of every surface of the inside of a ground water tank. Testing steps:
    a. The base of the robotic arm should be able to be positioned such that the entire floor can be sandblasted.
    b. The base of the robotic arm should be able to be positioned such that all walls can be sandblasted.
    c. The base of the robotic arm should be able to be positioned such that the entire ceiling can be sandblasted.

There are a number of constraints that have been provided by Suez. The product must:

1. Be transported/assembled by a 3 man team
2. Fit within a 24 inch diameter round hole for tank ingress
3. Withstand the forces generated by the arm during sandblasting
4. Withstand the sand and moisture generated by sandblasting

The following detailed engineering design specifications have been created based on the requirements and constraints above:

Table 2: Design Specifications

No.	Changes	D/W	Requirements	Responsible	Source
1		D	Stabilize the robotic arm during sandblasting		Suez
2		D	The base of the robotic arm should be able to be positioned such that the entire floor can be sandblasted		Suez
3		W	The base of the robotic arm should be able to be positioned such that all walls can be sandblasted		Suez
4		W	The base of the robotic arm should be able to be positioned such that the entire ceiling can be sandblasted		Suez
5		D	Break down into parts weighing less than 25 kg each		Suez
6		D	Be assembled in under 6 hours by a 3 man team		Suez
7		D	Each part must fit within a 24 inch diameter round hole		Suze
8		D	Withstand a maximum torque of 30 kg·m generated by the sandblasting arm		Suez
9		D	Withstand the sand and moisture generated by sandblasting		Suez

The importance of each specifications have been determined to be:

Table 3: Specification Ranking Matrix

Specification	Importance
Stabilize the robotic arm during sandblasting	Main function
The base of the robotic arm should be able to be positioned such that the entire floor can be sandblasted	Main function
The base of the robotic arm should be able to be positioned such that all walls can be sandblasted	Secondary function
The base of the robotic arm should be able to be positioned such that the entire ceiling can be sandblasted	Secondary function
Break down into parts weighing less than 25 kg each	Hard requirement
Be assembled in under 6 hours by a 3 man team	Hard requirement
Each part must fit within a 24 inch diameter round hole	Hard requirement
Withstand a maximum force of XXX N generated by the sandblasting arm	Hard requirement
Withstand the sand and moisture generated by sandblasting	Hard requirement

IV. Market Research

In order to provide 7.5 million people with water service, Suez maintains over 6,000 water tanks across North America. In order to maintain quality service, the interior tanks must be cleaned and repainted every 8 to 10 years. On average, Suez treats over 100 tanks per year. The cost of cleaning varies with the dimensions of the tank; however, sandblasting and repainting these water tanks can cost more than $200,000 per tank.

Currently, Suez uses manpower and handheld hoses to sandblast and clean the inside of these water tanks. The manpowered cleaning and painting process currently being employed requires 4 weeks for completion. With the recent acquisition of the SABRE Autonomous Blasting Robot, Suez has the opportunity to automate the sandblasting process therefore increasing the efficiency of the cleaning process. However, until a stable base for the arm is created, the arm cannot be utilized. Based on the number of tanks Suez currently maintains and the estimated addition of 25 tanks per year, there is ample opportunity for the autonomous sandblasting arm and the stabilizing platform to advance the cleaning process. With SABRE's estimate of increased sandblasting productivity by 70%, there is substantial financial benefit in Suez's adaptation of autonomous arm and base support. Once a prototype is developed, a study will be conducted with Suez operators to get feedback on the user interface and system.

V. Design Concept Ideation

Suez has the need for a platform system capable of supporting an autonomous robotic arm to sandblast the inside of water storage tanks. The functions of the design considerations must be able to remain stable while the robotic arm is operating. In addition, secondary functions include horizontal movement, vertical movement, and visual feedback to the operator to adjust position.

The primary function of the platform is to remain stable while the robot is in operation. Ideas for stability include the use of electromagnetics, retractable legs, locking wheels, outriggers and a rail system. Secondary functions of the platform include horizontal and vertical mobility within the tank. Ideas concepts for horizontal mobility include a system of wheels, a rack and pinion system with electromagnetics, and a rail system. Idea concepts for vertical mobility include a scissor lift system, a rack and pinion system with electromagnetics, and a rail system. The morphological chart below shows the various functions as well as the proposed solutions to solve the functions.

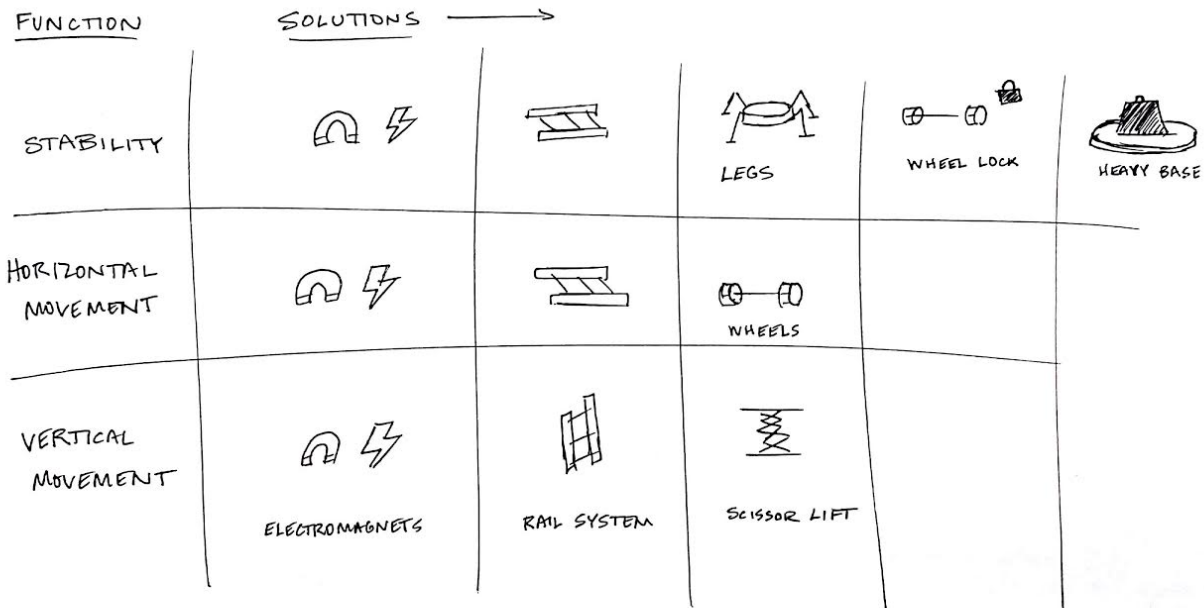


Figure 5: Morphological Chart

Combining the categories from the morphological chart, five design concepts were created as possible functional solutions. The proposed solutions include a rail guided solution, an elevated platform solution, a wall climbing solution, a modular scaffolding solution, and an outrigger solution. The rail guided solution combines the rail system from the stability and vertical movement functions to create a ladder-like system for the arm to move up and down.

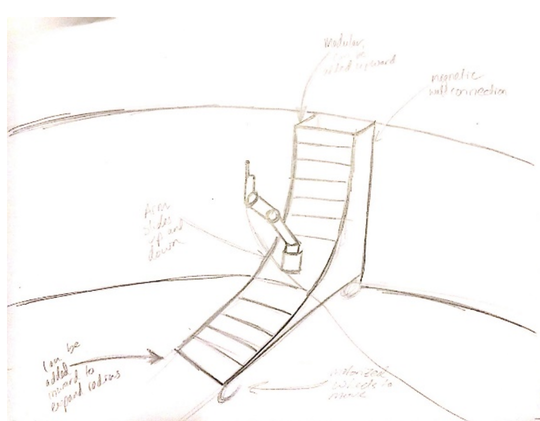


Figure 6: Rail Guided Solution

The elevated platform system uses the wheels for horizontal movement and scissor lift for vertical movement. In addition, wheel locks will stabilize it on the ground, while electromagnets will stabilize the structure when vertically extended.

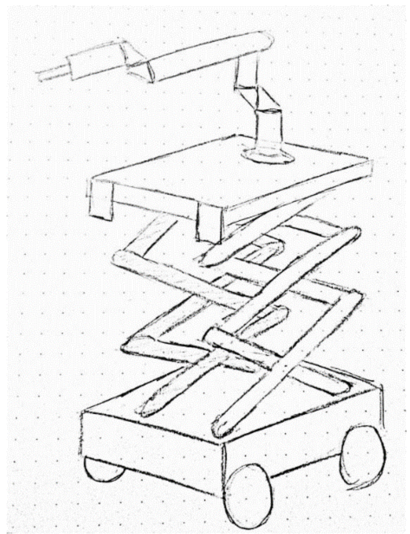


Figure 7: Elevated Platform System Sketch

The wall climbing solution combines the electromagnets with a rack and pinion system to simulate the motion of an inchworm. Two electromagnets will alternate being active for the structure to move.

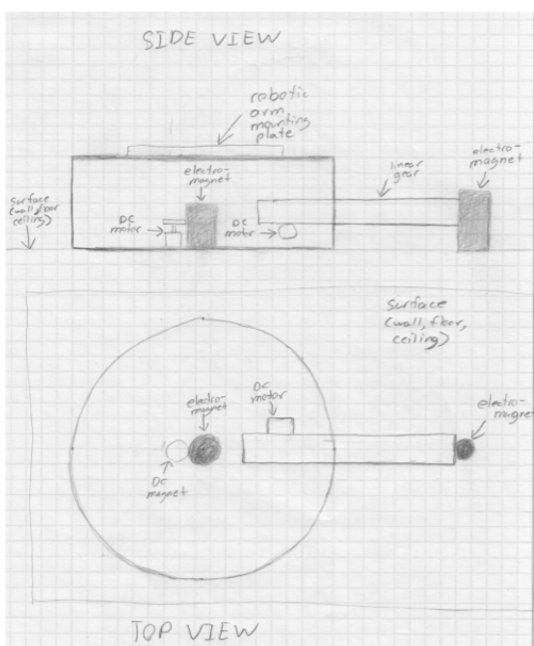


Figure 8: Wall Climbing Solution Sketch

The modular scaffolding solution involves automated wheels and wheel locks for motion and stability. The wheels will be linked to communicate together and offer a flexible solution for future application.

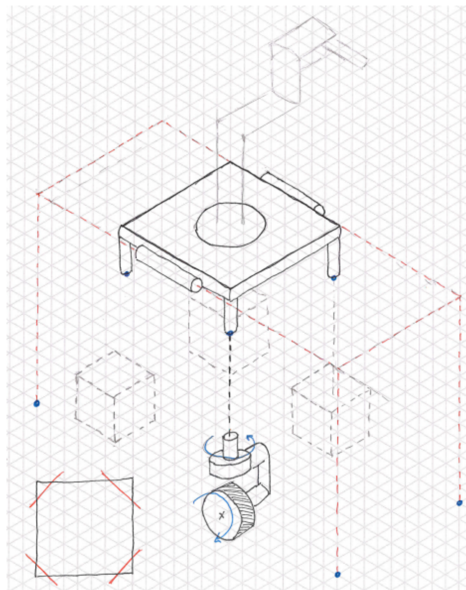


Figure 9: Modular Scaffolding Solution

The outrigger solution uses retractable legs similar to a crane to stabilize the platform during operation. This solution has the ability to be vertically adaptable and provides horizontal mobility without compromising stability.

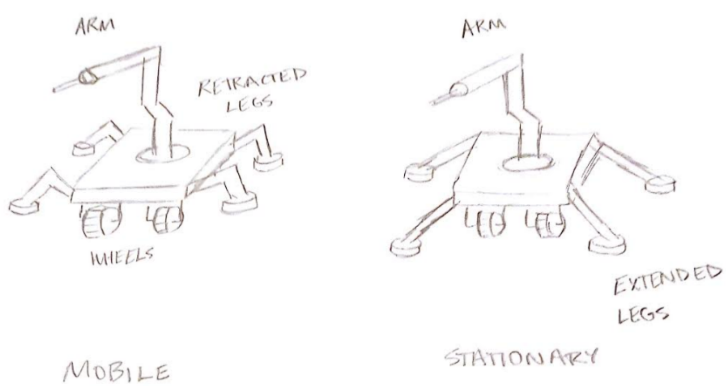


Figure 10: Outrigger Solution

From the preliminary concept designs, the outrigger solution appears to be the most feasible followed by the rail guided solution, the elevated platform solution, the modular scaffolding solution, and finally the wall climbing solution. The existing technology for hydraulic legs is already applied to cranes and would be applied in a similar manner for the platform base. The next feasible solution is the rail guided solution since Sabre is already using rails to service bridges. The main challenge presented in this solution would be automating the movement along the rails. The third solution is the elevated platform solution. Challenges of this proposed design involve the scissor lift fitting through the entry hole of the tank, and providing stability at the peak height of the lift through electromagnets. The fourth solution is the modular scaffolding solution. Although scaffolding is currently used in Suez's prototype design, the main challenge would be developing a series of wheels that can communicate together. Finally, the wall climbing solution appears the least feasible. Challenges with this design include having electromagnets strong enough to hold the weight of the arm and withstand the forces during operation and fabricating a prototype. However, the ability to tether the power source rather than batteries helps solve the problem of current wall climbing devices. In addition, this type of technology used in this application could push the standard in this industry.

VI. Concept Selection and Justification

In order to select designs for further development, the concepts were assessed using a decision matrix with criteria such as efficiency, portability, and stability. The evaluation matrix is displayed below in Table 4. The project team decided on 10 criteria upon which the concepts will be assessed. Each criterion was given a weight between one and five, depending on its perceived importance to the success of the solution, with a weight of five indicating "Very Important". The concepts were then given a score between one and five, with a score of one indicating "Poor Performance" and a score of five indicating "Excellent Performance" in each respective criteria. As a result of this assessment, the Guided Rail Solution and Outrigger Solution scored the highest with scores of 155 points and 150 points, respectively.

Table 4: Evaluation Matrix

		Designs				
Criteria	**Weight**	**Guided Rail Solution**	**Elevated Platform Solution**	**Wall Climbing Solution**	**Modular Scaffolding Solution**	**Outrigger Solution**
Portability	4	4	2	4	3	3
Stability	5	4	2	4	3	5
Reach Height	4	4	3	3	5	3
Creativity	2	3	2	5	3	3
Existing Technology	3	3	5	1	4	5
Efficiency	4	5	3	4	2	4
Durability	3	5	2	2	3	5
Assembly	4	4	2	2	1	3
Safety	5	5	5	3	4	5
Simplicity	4	4	2	1	2	3
Total Weighted Score		155	108	110	114	150

The feasibility of the five proposed designs was also analyzed in order to determine the design with the highest potential success. The Guided Rail Solution draws inspiration from the rolling ladders typically found in a library setting. Given that the current applications of the Sabre robotic arm utilizes rails for stability and mobility, the use of rails in the water tank application is promising. The rail system can be designed in such a way that it breaks down into long components, capable of passing through the small entry hatch of the ground tank. The cross members of the rail system would provide support points for the arm platform to mechanically hold its elevation. To increase stability, pneumatic pistons could be added to the cantilever end of the horizontal track, wedging the assembly between the ground and the floor.

The Outrigger Solution draws inspiration from firetrucks that use outriggers for additional support when the ladder is extended from the truck. Due to the prior success that these trucks have had with supporting the thrust of man powered water hoses when reaching the top floors of buildings, outriggers prove to be a promising solution to resisting thrust at extended heights. The Outrigger Solution allows for ease of assembly in that outriggers are readily manufactured by a multitude of industrial companies and do not have to be custom manufactured for this solution. Additionally, these assemblies are retractable which will allow for the platform to be easily moved between cycles without compromising stability during sandblasting. The Outrigger Solution has potential for vertical mobility and stability when combining a lift system and using guide wires for additional support. Finally, the assembly of the outrigger solution is relatively easy in that the outriggers and subassemblies for the platform can be passed through the entry hole.

Along with feasibility, the associated potential risks were evaluated with respect to each design concept. The current design of the Guided Rail Solution's ramp positions the arm in in such a way that the base is facing away from the surface of the wall. This positioning may reduce the effective area of the arm at each ramp position, impacting the solutions efficiency. The reach of the arm will need to be investigated in this position to determine if the efficiency is negatively impacted. A possible resolution of this issue is a redesign of the ramp to position the base of the arm tangentially or facing the wall but would require a more complex assembly and would limit the access to the floor of the tank.

The Outrigger Solution's potential risks were considered, evaluated and will be accounted for in the final proposed design. There is a possibility of compromised stability if the floor surface of the tank is covered with debris which would inhibit the outriggers solution to evenly balance the platform. Further testing will be performed in order to evaluate the effect of the potential debris on stability and design adjustments will be made. Similarly to the Guided Rail Solution's mounting position is oriented parallel to the floor of the tank. This orientation may make sandblasting the floor of the tank difficult which negatively impacts the efficiency of the design. A potential solution to this risks include reconsidering the orientation of the platform.

VII. Industrial Design

Due to the nature and use of the robotic arm platform, the industrial design considerations for this product are primarily influenced by assembly considerations. Because the platform is used in an industrial environment, the target demographic are those responsible for assembling the platform. One of the most critical human factors of this product is the weight, which derives its importance from the entry constraints into the ground tank. With only a 24” diameter entry hatch, the pieces of the platform must be manually passed through the hole and be assembled inside the tank. Repetitive lifting and extended reaching into the tank pose injury risks for crew members. In terms of material selection, lightweight materials with structural integrity will be evaluated for use in the final solution. For example, 6061 aluminum extrusion could provide adequate structural integrity for the solution while avoiding the weight of a similar design constructed with steel. Additionally, the cross-sectional design of the 6061 extrusion provides additional strength and stiffness over more traditional aluminum box channel or c-channel.

Weight considerations are not only required for the material selection but the subassemblies of the platform. Ideally, the solution will be designed in such a manner that it can be broken down into the minimum number of equally weighted parts that can be easily passed between crew members. Each part weight is not to exceed the OSHA recommendation for heavy lifting of 50 lbs. Risk of injury is significantly elevated when the object weight exceeds this threshold. In the case of heavy components that are unable to be broken down into smaller components, ergonomic lifting aids will be used.

Due to the nature of the product, assembly is a very big concern. The device must fit in a 24” diameter hole for tank ingress. This will likely require that the device is disassembled for entry and then reassembled inside the tank. The goal of this project is to decrease the amount of time workers have to spend inside water tanks by creating a platform for a robotic arm. If the assembly of the platform is difficult and time consuming, there will be little benefit to the workers. In order to aid assembly, color choices for different subassemblies will be made so that subassemblies are easily labeled and legible. The water tanks are grey in color when unpainted and beige when painted; additionally, the water tank is filled with sand and debris during the sandblasting process. Bright colors will be utilized when labeling different subassemblies in order to compensate for debris and stand out against the dull colors that are abundant inside the tanks. Similarly, Suez’s water tanks are often vast in dimension; therefore, small parts will be entirely coated in bright colors so that they are easily identified in the large tanks.

An assembly guide with detailed instructions will be provided to the tank cleaning crew in order to aid in constructing the platform. The assembly guide will include easily legible font as well as 2D CAD drawings to provide visual direction for assembly. The instructions will refer to the parts with a combination of letter and number representations. These labels will be referenced in the written instructions and visible on the 2D drawings. The labels on the actual pieces being assembled will be large enough to be easily legible from a distance. The assembly instructions will be available in the languages required by Suez.

VIII. Engineering Analyses and Experiments

SABRE's six degree of freedom arm functions in a manner that makes predicting the motion of the robot impossible. The program maneuvers the arm in the most convenient way possible given the position the arm is currently in and the next position the arm needs to move to. The configuration and motion of the arm changes frequently and is unpredictable making performing engineering analysis difficult. In order to ensure the design will remain stable regardless of the motion of the arm, the engineering analysis was performed assuming the worst case scenario of the arm motion. SABRE provided the engineering team with a spreadsheet of the necessary moments and inertia calculations of the worst case robotic arm configuration. The worst case scenario for SABRE's robotic arm consists of the arm fully extended at joint 2, shown in Figure 11.

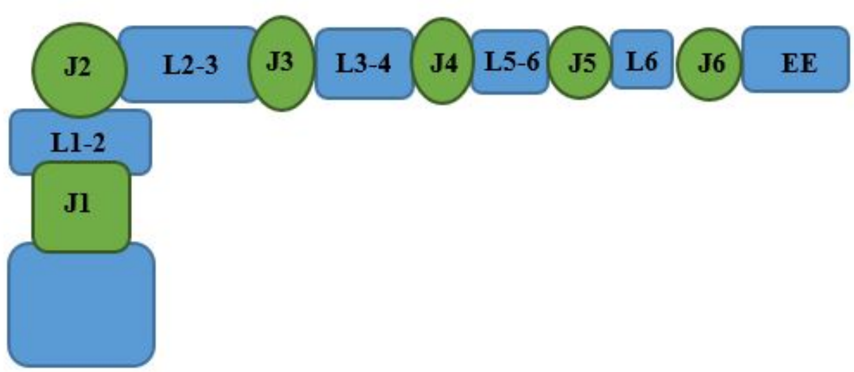


Figure 11: Diagram of Worst Case Arm Scenario

Static Load					
Moment @ J2		0	0.6468	0.77	0.79128
Total Moment @J2	27.88468	kg.m			
	273.5487:	N.m			
Total Torque					
	Deg/s	Rad/s			
Initial Anglular Velocity	40	0.698131:			
Final Anglular Velocity	0	0			
Time to Stop	0.5	s			
Angular Acceleration	1.396263·	rad/s			
Torque (	38.61897ε	kg.m			
	378.8521ε	N.m			

Figure 12: SABRE Robotic Arm Worst Case Scenario Data

Basic hand calculations were performed in conjunction with the free body diagram in Figure 12 to determine the moments at the edges of the base plate. The force of applied to the base is from the weight of the arm (25 kg) and the base of the mounting plate (25 kg). The moment about point A and the moment about point B were calculated to be 295.02 N-m. The moment about point C was calculated to be 594.24 N-m. The total inertia at the base is 7.688 kg•m^2.

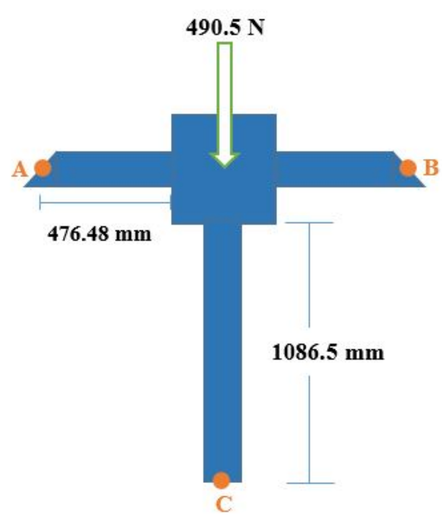


Figure 13: Free Body Diagram of the Platform's Base

The base plate of the model was used in a finite element analysis (FEA) to determine if the chosen material (Aluminum 6061) and preliminary design could withstand the weight of the 25 kg arm and the 25 kg base plate.

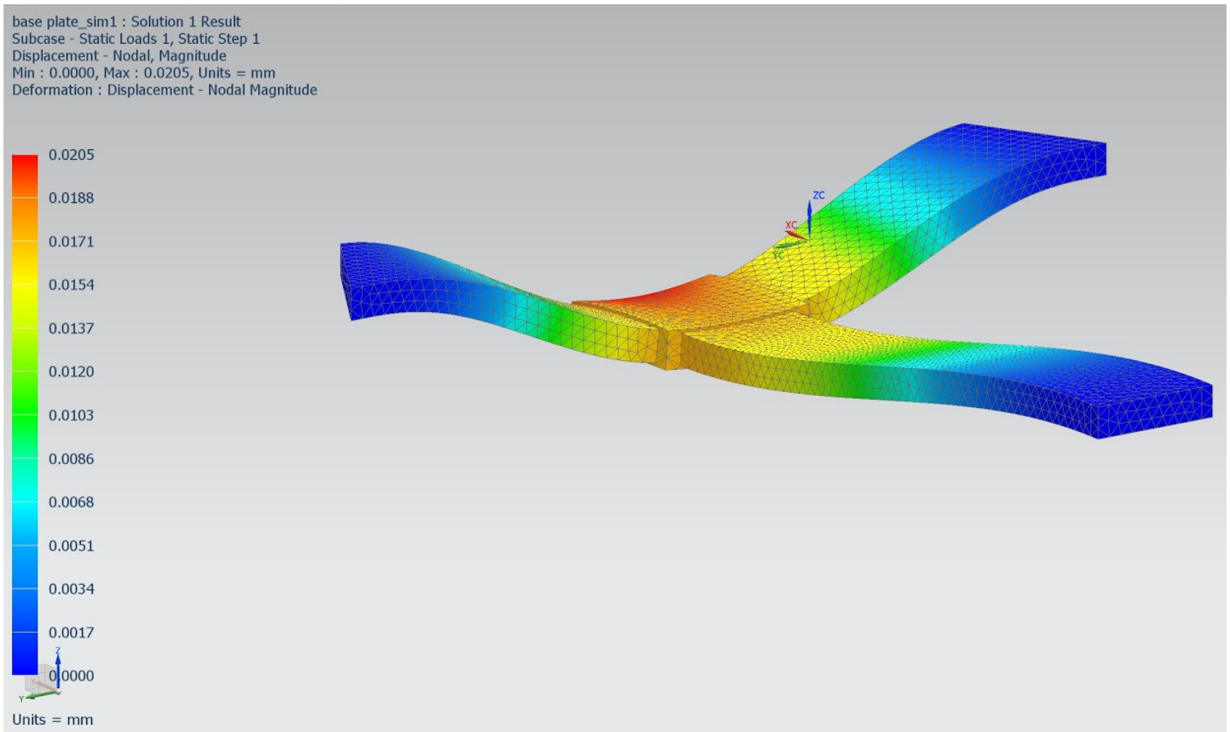


Figure 14: Displacement of base plate part due to weight of arm

The results of the analysis are promising in the respect that the maximum displacement is only 0.02 mm and the maximum Von Misses stress is 1.859 MPa. For Aluminum 6061 the maximum yield stress is 276 MPa which means the design is well under the maximum stress the material can handle. These basic FEA runs are a good preliminary measure to ensure the design team is on the right track as the final design begins to be developed.

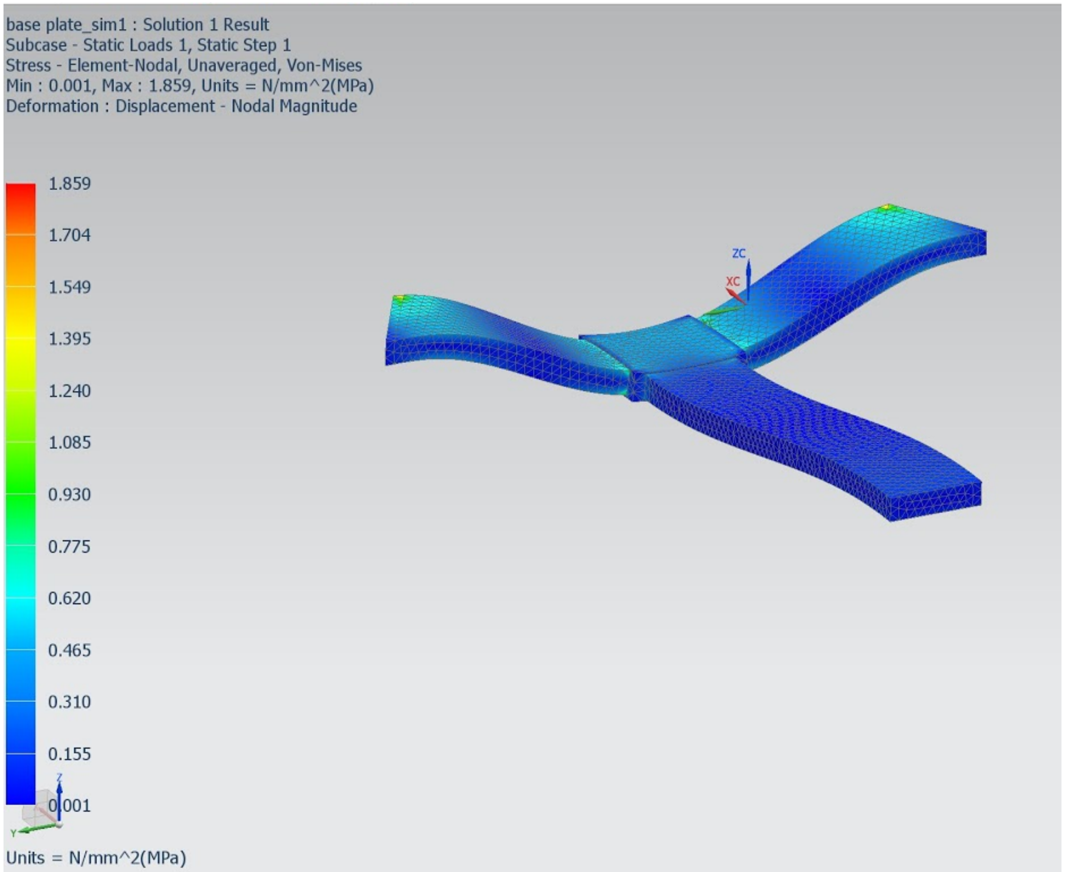


Figure 15: Von Mises Stress of Base Plate Due to Weight of Arm

IX. Initial Drawing and Fabrication Package

The entirety of our solution can be broken down into three large subassemblies: the outrigger base, the truss tower, and the arm platform. The bulk of the structure will be constructed from aluminum alloy 6061 due to its high yield strength to weight ratio and weldability. High load components will be fabricated out of steel as needed to ensure the structural integrity of the solution.

The outrigger base has an equilateral triangular footprint with one side facing the wall tangentially. It is constructed from aluminum ladder truss lengths bolted the vertical trusses. The outriggers are attached to the rear two ladder trusses via bolt attachment and are of steel construction. The handles on each outrigger actuate the outrigger mechanism allowing the leg height to be adjusted manually. The purpose of these outriggers is to increase the footprint of the tower to prevent toppling during arm movement. The additional contact of the outrigger feet with the tank floor increase the friction between the two, preventing sliding of tower under the thrust load of the arm. The outrigger arms will support cable winches that will be used to lift the arm platform.

The truss tower is constructed of three vertical lengths of triangular aluminum truss. The cross sectional profile of these truss pieces is an equilateral triangle with side lengths of 457 mm (18 in). This small area allows for each length of truss to be passed through the 24” hatch of the tank with. These trusses will be supported along their height and at the top to minimize twisting deformation. At the top of the tower, pulleys will be fastened to support the chains from the winches at the base.

The third subassembly of the solution is the arm platform. This is the structure that spans the three trusses of the tower and supports the arm, enabling it to move vertically on the tower. Each corner of the arm platform will have roller wheel connected to interface with the vertical trusses. The mounting plate for the arm will be bolted to the horizontal span closest to the wall. Cables running from the winches at the base and over the top of the tower will connect near the center of the platform.

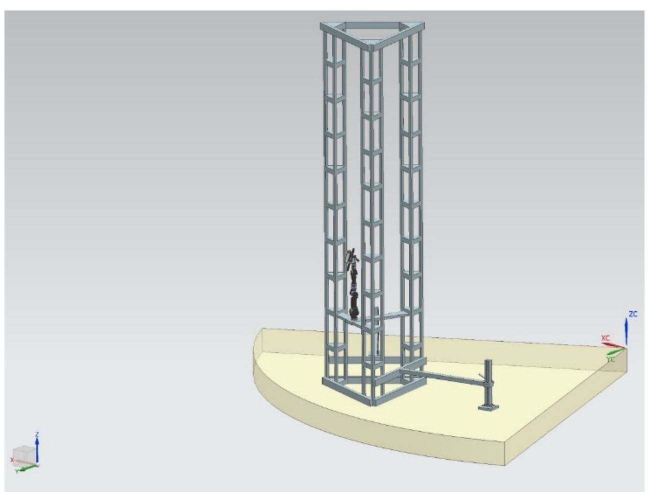


Figure 16: Isometric View of Preliminary CAD Model

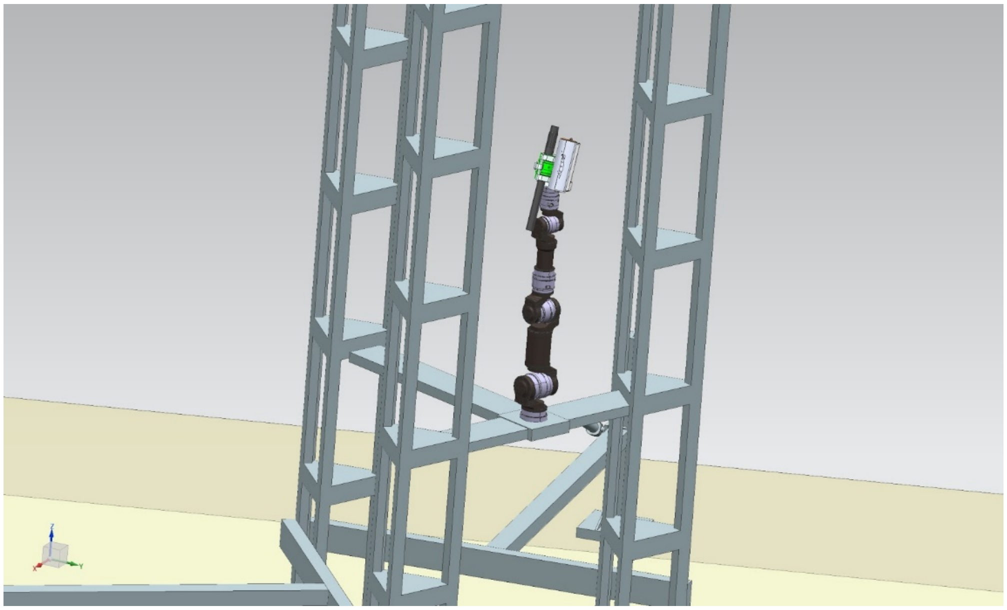


Figure 17: Zoomed in View of Robotic Arm

The Bill of Materials and the anticipated supplier for each subassembly is detailed in Table X.

Table 5: Bill of Materials

Qty.	Item	Manufacturer	Supplier	Notes
4	FT43 triangular aluminum truss	Truss Aluminum Factory	Truss Aluminum Factory	3.5m sections
9	FT43 ladder truss 60 deg. corner	Truss Aluminum Factory	Truss Aluminum Factory	For tower support
6	FT43 ladder truss – straight segment	Truss Aluminum Factory	Truss Aluminum Factory	2m sections
1	FT43 ladder truss – horizontal 3-way connection	Truss Aluminum Factory	Truss Aluminum Factory	For arm mounting plate
3	FT43 ladder truss – straight segment	Truss Aluminum Factory	Truss Aluminum Factory	1m sections
2	Electric vertical lift winch	Unknown	McMaster Carr	120 Volts AC
6	2 ½” high-load track rollers	Unknown	McMaster Carr	For arm platform rolling
TBD	Truss clamps - various	Truss Aluminum Factory	Truss Aluminum Factory	Various
3	Vertical jack with footplate	REESE	Haydocy Airstream	Outrigger lifting mechanism

X. Summary & Next Steps / Project Deliverables

Based on the understanding of the problem and market research, multiple design concepts have been developed and analyzed. After consulting with Dr. Lipkin and Suez, a triangular truss system with outriggers and a liftable base appears to be the optimal solution for stability at elevated heights. The truss system provides a stable triangular shape, while the outriggers provide stability when the base moves vertically. The vertical trusses will be small enough in width to fit through the hatch for assembly inside the tank.

As the project continues to move forward, the next steps include running more static and advanced dynamic FEA to confirm the design selection. In addition, material selection will be finalized from these analyses and prototyping will begin. Based on input from Suez, Dr. Lipkin, and further analysis of the design, a final CAD design will be produced with the mathematic calculations demonstrating the proof of concept.

References

Ground-level Water Storage Tank. 2009. *Navajo Nation Environmental Protection Agency Public Water Systems Supervison Program*. Web. 15 Sept. 2016. <http://navajopublicwater.org/public_notification>.

Johnston, Kenneth H. Guide Rail System. Associated Millwrights Inc, assignee. Patent US3527336A. 8 Sept. 1970. Print. https://patents.google.com/patent/US3527336A/en?q=rail&q=systerm

Sommer, Peter. Method and Apparatus for Cleaning a Water Tank. SOMMER, SCHENK AG, A SWISS CORP., assignee. Patent US4518437A. 21 May 1985. Print. https://patents.google.com/patent/US4518437A/en?q=water+tank&q=cleaning

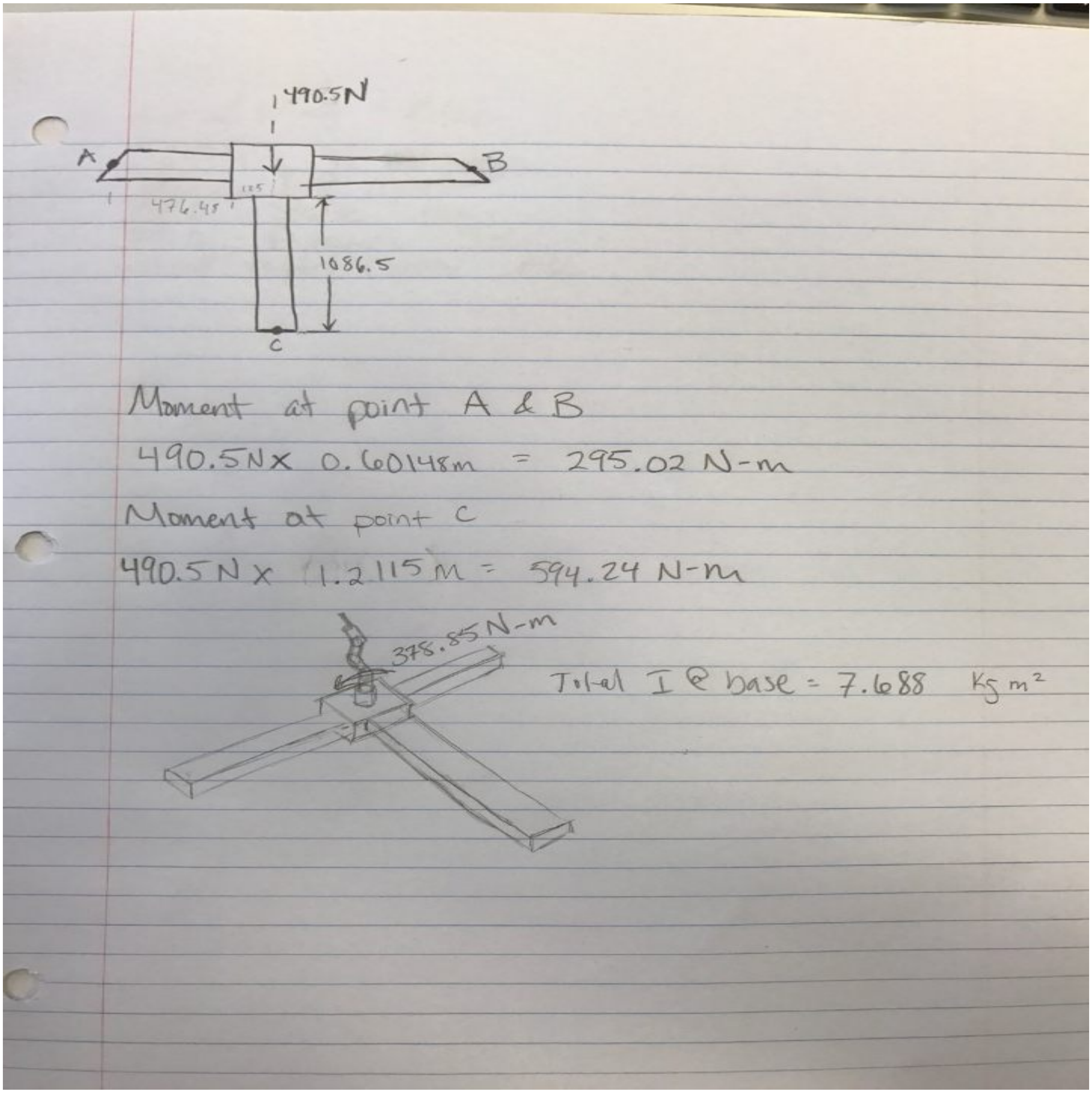
"Water Services." *SUEZ Water Advanced Solutions*. N.p., n.d. Web. 18 Sept. 2016. http://www.mysuezwater.com/about-us/water-services

Appendices

Appendix A: Images

Figure 1: Ground Water Storage Tank

Appendix B: Calculations



Hand calculations of moments and inertia about the base of the platform

$$Linkages\ modeled\ as\ rod\ I = \frac{1}{12} M_l L^2 \quad Servos\ \&\ EE\ modeled\ as\ Cylinder\ I = \frac{1}{2} M_s R^2 \quad Parallel\ Axis\ theorem\ I_{j2} = I_{cm} + M_s (d)^2$$

Equations used by SABRE to calculate worst possible scenario data

ynamic Load													
	J1	J2	L2-3	J3	L3-4	J4	L4-5	J5	L5-6	J6	L6-EE	EE	Thrust
dius (m)		0.066	0.06	0.056	0.4	0.061	0.4	0.045	0.04	0.045	0.04		
ngth (m)			0.385		0.172		0.272		0.211		0.064	0.2	
M Dist from J2	0	0	0.1925	0.385	0.471	0.557	0.693	0.829	0.9345	1.04	1.072	1.204	1.2
ss (kg)	3.6	3.6	3.36	2	1.68	2	1.68	1.2	1.68	1.2	0.3	1	
ss (N)	35.3052	35.3052	32.95152	19.614	16.47576	19.614	16.47576	11.7684	16.47576	11.7684	2.9421	9.807	147.1
out Self		0.0078408	0.041503	0.003136	0.00414176	0.003721	0.01035776	0.001215	0.00623294	0.001215	0.0001024	0.00333333	
allel Axis		0	0.124509	0.29645	0.37269288	0.620498	0.80681832	0.8246892	1.46712762	1.29792	0.3447552	1.449616	
out J2		0.0078408	0.166012	0.299586	0.37683464	0.624219	0.81717608	0.8259042	1.47336056	1.299135	0.3448576	1.45294933	
al I @ J2	7.687875												
tatic Load													
ment @ J2		0	0.6468	0.77	0.79128	1.114	1.16424	0.9948	1.56996	1.248	0.3216	1.204	18.
al Moment @J2	27.88468	kg.m											
	273.5487	N.m											
otal Torque													
	Deg/s	Rad/s											
al Anglular Velocity	40	0.6981317											
al Anglular Velocity	0	0											
me to Stop	0.5	s											
gular Acceleration	1.3962634	rad/s											
que (	38.61898	kg.m											
	378.852182	N.m											

SABRE worst case scenario calculated data for each joint and linkage