Robotic Arm RFP
Final Report
Semester 2, 2014

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Abstract

This document provides an in-depth analysis of the robotic arm display requested by the Australian Museum for their “Ocean Explorers” Exhibition. After conducting widespread research, generating a variety of conceptual designs and verifying all requirements, a final product was produced. This report includes a detailed description of the final design and its verification through several testing methods, mathematical analysis and budget examination. The design replicates the actions of robotic arms used on board AUV’s today as well as being fun, intuitive and engaging. Along with satisfying all the requirements requested by the client, the final design ensures the highest level of safety and functionality to attain the most optimum solution.
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1.0 Introduction

A design for a robotic arm display was requested by the Australian Museum for an upcoming exhibition called "Ocean Explorers". The fun and interactive display is designed to educate children about manipulator arms used on board autonomous underwater vehicles of today. The children will use the arm to pick up specimens in the shape of fish or other sea creatures and place them into a receptacle. The arm must also have the following attributes:

1. Be able to move left to right and up and down
2. Safely isolated so that no harm can come to the children/operator
3. Fit in a 1.5x1.5x1.5m box
4. Have a working area of less than 1mx1m
5. Require minimal effort for the museum to install
6. Complies with all relevant safety requirements

Along with the functioning robotic arm, the display must also consist of a receptacle which can eject the specimens back into the working area randomly. The design must also be rugged and be able to withstand a large amount of abuse to account for the possibility of children hitting and bumping into the exhibit.

To achieve the final design, a design process was followed, starting with research into types of robotic arms, end effectors, actuators and the materials required for prolong underwater use. This research was then used to create a list of requirement specifications. In order to achieve the most optimal design solution, the final design is required to meet the list of client, safety, functional and environmental requirements. A variety of conceptual designs based on these requirements were created using a morphological matrix. Through the use of a Pugh section matrix, an articulated arm with four degrees of freedom and a three finger end effector was selected as the most optimal design solution. An ejection system and an interface was also designed to meet the client’s requirements. To verify and validate the final design, cost analysis and simulations were undertaken and prototype testing plans were proposed.

This report details an extensive application of the design process undertaken to generate and verify the robotic arm exhibit requested by the Australian Museum.
2.0 Research

2.1 Research Overview

There are many areas to consider when designing the exhibit, including the type of robotic arm, the type of actuators and end effectors as well as materials which can be used underwater. This research also aims to investigate existing solutions in order to learn about each design’s best attributes and the improvements which can be made to them.

2.2 Environment

For the museum display design, fresh water will be used to fill the tank and therefore the robotic arm and receptacle will be subjected to temperatures ranging from 7-40 degrees.

2.3 Materials

It is required that the robotic arm functions underwater. As a result, added mass due to weight of water, drag, buoyancy and sealing to prevent water leakage into the interior must all be addressed to ensure correct functionality (Red Sea Robotics Exploratorium, 2014). These direct implications can be solved through the correct choice of materials. There are many factors that need to be considered when deciding the material of the underwater robotic arm’s main frame. The process of creating the robotic arm must also be cost-efficient and easy to manufacture. The materials requirements are of the following:

- **High strength/density**: The material must have a density higher than that of water (i.e. more than 1000kg/m$^3$) to counteract the upward forces due to buoyancy. This is important because if the material had a lower density, a stronger support is required to fix the robotic arm to the base, thus increasing time and money. It will also affect the functionality/ movement of the robotic arm through the water. The robotic arm’s material must also be strong enough to withstand the hydrostatic pressures exerted by the weight of the water. Possible materials include metals and certain types of polymers.

- **Corrosion resistance**: Due to presence of oxygen and minerals in water, the material used must be able to withstand the corrosive effects of water in order for the robotic arm to continue functioning correctly and reliably. If corrosion occurs, the material's quality will deteriorate and its lifespan will significantly decrease. Possible materials include polymer based materials, composites, aluminium.

- **Cost of material & manufacturing process**: Cost must always be minimized where possible and the cost of materials is a large contributor to the overall costs. For the product to be cheap, the material used must be abundant and the manufacturing process must be simple and readily available. Possible materials include aluminium.

- **Manufacturability**: The material will need to be easily processed/shaped into the main frame of the robotic arm to reduce time spent on the actual manufacturing process. E.g. If the material is metal, it must be malleable to allow for it to be easily shaped into different designs.

The two materials that can be used as part of the main frame of the robotic arm are: acrylic (Polymethyl Methacrylate) and aluminium. Polymethyl Methacrylate satisfies all the design requirements and it is within the correct density bracket i.e. denser than water but not so dense that
weight of the material becomes an issue with the functionality of the robotic arm. It is able to withstand the corrosive effects of water due to the properties of polymers and is used in many automated underwater vehicles. Aluminium also satisfies the material requirements exceedingly well and has been used in many underwater projects due to its excellent properties. Aluminium also “spontaneously forms a thin but effective oxide layer that prevents further oxidation” (Aluminium Design, 2014).

A sealant must also be considered for the robotic arm i.e. to close off any gaps to prevent water leakage into the internal components. A common sealant that can be used in the design is silicone. Silicone “resists temperature extremes, weathering, aging, oxidation, moisture, many chemicals, and ultraviolet radiation” (Dow Corning, 2014). It is also easily applicable in the manufacturing process due to its high flexibility.

The use of Syntactic foam padding for marine applications such as underwater robotics has been a common solution to improve buoyancy. This material consists of a composite of metals, polymers and ceramics that have been altered to include air particles within its microstructure. Thus, resulting in lower density, high specific strength and low water absorption (Red Sea Robotics Exploratorium, 2014).

2.3 Existing Design Solutions

2.3.1 Types of Robotic Arms

- The Cartesian (or Gantry) arm (Figure 1) consists of three joints with the standard x-y-z Cartesian axes. This allows the arm to only move linearly.

Advantages:
- Reach high speeds easily
- High positioning accuracy
- Easy to manufacture and program
- Cheap

Disadvantages:
- Structure is large and bulky
- Requires large work zone

- The SCARA (Selective Compliance Assembly Robot Arm) (Figure 2) refers to the fact that a SCARA’s arm segments, or links are ‘compliant’. That is, they can move freely, but only in a single geometrical plane (ProcessOnline, 2009). The two joints closest to the base of a SCARA rotate left and right in a horizontal plane. The third joint consists of a rod which holds the robot’s end effector.

Advantages:
- Fast and more precise performance
- High degree of rigidity
• Can be thoroughly sealed and safeguarded
• Most designs are quite small, therefore easily transportable and thus, lowers costs

Disadvantages:
• Limited in movement
• Third joint for end effector cannot tilt and change angles. Thus, limited to up and down movement.

- The **Articulated Arm** (*Figure 3*) contains two more joints than the four axis SCARA, therefore allowing for more freedom of movement. The first joint closest to the base moves in the horizontal plane like a SCARA, while the other two joints move in the vertical plane. In addition, the six-axis articulated robot has a ‘forearm’ and two ‘wrist’ joints, which allows it to perform the same types of movements as a human arm (Processonline, 2009). The additional joints allows the arm to pick up any specimen, no matter how it’s horizontally orientated.

Advantages:
• Maximum flexibility out of all the arms. The arm consists of three or more rotary joints.
• Superior manoeuvrability and agility.

Disadvantages:
• Most expensive due to the complexity of its assembly and parts.
• Difficult to manufacture and assemble

### 2.3.2 Existing Underwater Robotic Arms

The Schilling Robotics' TITAN 4 (*Figure 4*) and Predator Force Feedback Manipulator (*Figure 5*) were 2 existing design solutions found for the robotic arm. Their specifications can be seen in the table below.

*Table 1: Existing Manipulator Arm Design Specifications*

<table>
<thead>
<tr>
<th></th>
<th>Kraft Electronics Predator</th>
<th>Schilling Robotics TITAN 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Actuators</strong></td>
<td>Hydraulic</td>
<td>Servo-Hydraulic</td>
</tr>
<tr>
<td><strong>Degrees of Freedom</strong></td>
<td>Six plus gripper</td>
<td>Six plus gripper</td>
</tr>
<tr>
<td><strong>Material</strong></td>
<td>Anodized aluminum and</td>
<td>Titanium</td>
</tr>
<tr>
<td></td>
<td>stainless steel</td>
<td></td>
</tr>
<tr>
<td><strong>Reach</strong></td>
<td>2013mm</td>
<td>1922mm</td>
</tr>
<tr>
<td><strong>Maximum lift capacity</strong></td>
<td>227kg</td>
<td>454kg</td>
</tr>
<tr>
<td><strong>Lift capacity at full extension</strong></td>
<td>91kg</td>
<td>122kg</td>
</tr>
<tr>
<td><strong>Wrist torque</strong></td>
<td>135Nm</td>
<td>170Nm</td>
</tr>
<tr>
<td><strong>Weight in Seawater</strong></td>
<td>51kg</td>
<td>78kg</td>
</tr>
<tr>
<td><strong>Operating Depth</strong></td>
<td>3000msw</td>
<td>4000msw</td>
</tr>
</tbody>
</table>
Both the existing designs are designed for deep ocean applications and use a six degree of freedom replica arm controller (Figure 6). The intuitive master control allows inexperienced operators to perform work tasks with human like motion. The force feedback allows the operator to perform more complicated tasks at higher speeds.

**Advantages:**
- Superior maneuverability and agility
- Corrosion resistance
- Highly durable and reliable in harsh subsea environments
- Acute precision control with six degrees of freedom
- Can operate at depths of up to 6000m
- High lift-to-weight ratio

**Disadvantages:**
- Complex design due its six degrees of freedom, means several actuators are needed
- Heavy
- Difficult to manufacture and thus increases cost
- Product is priced around $160,500 (FMC Technologies 2014)
2.3.3 End Effectors

The robotic arm will also consist of an end effector which will operate in the working area. There are several existing solutions that can be considered:

- A **Vacuum Gripper** is highly flexible and uses a rubber or polyurethane suction cup to pick up objects. This gripper is ideal for fast loading and unloading processes.
- A **Hydraulic Gripper** exhibits the most strength and is often used for applications requiring significant amounts of force. They generate their strength from pumps, however the oil used to operate these pumps requires a lot of maintenance.
- A **Servo-electric Gripper** includes electric motors which control the movements. It is easy to control and more flexible than other designs.
- A **Finger Gripper** consists of two or more opposing mechanical fingers that are powered by actuators. The surface of the claws/fingers can be either curved or flat in order to suit particular specimens which need to be retrieved. This gripper is ideal for replicating those that are seen on AUV’s and is also much more ‘fun’ for the children users.
- The **Shape Deposition Manufactured (SDM) Hand** (*Figure 7*), is an under-actuated, four fingered gripper that adapts to the picked up object. This is achieved by using a single actuator, along with a cable and pulley system (*Figure 8*). This operates through the polymer fingers which feature passively compliant joints that can continue to move even after contact has been made with the object. Thus, eliminating the need for sensors and complex feedback loops to moderate the forces applied. This solution is effective because it is cheap, simple, adaptable, versatile and easy to install onto an existing robotic arm. Also, it is able to easily grip objects even with inaccurate positional input, since each finger moves freely in relation to the others. However, a negative is due to the lack of a wrist joint, meaning objects of further distance must be approached from the front rather than the from the top (Dollar, A 2010).

*Figure 7: SDM Hand*
2.3.4 Actuators

Different actuators need to be considered in order to control and move the robotic arm. An actuator is a type of motor that can be operated by different sources of energy. The energy, either electric current, hydraulic fluid or pneumatic pressure is converted into motion, moving the desired mechanism. There are different actuators available, each with their own pros and cons:

- **An Electric Actuator** is powered by a motor that converts electrical energy to mechanical torque. The actuator can be rotary or linear.

  **Advantages:**
  - Higher level of precision
  - Reduced replacement costs
  - Greater accuracy
  - Low operational cost

  **Disadvantages:**
  - High component cost
  - Easy to create overheating of the motor
  - Average failure rate is higher than the pneumatic actuator

- **A Pneumatic Actuator** uses stored energy from compressed air held through a metal piston system to control the linear motion of a mechanism. This is a common type of actuator that is used in the field of robotics in order to control claws of robotic arms (David Greenfield, 2014).

  **Advantages:**
  - Offers high pressurized air, allowing it to generate high forces and speed at a low cost.
  - Light weight
  - Powerful
  - Low component costs
  - Fast start up times
  - The high pressure enables quick movement

  **Disadvantages:**
  - High operational costs
  - Noise pollution
A Hydraulic Actuator converts hydraulic fluid pressure into linear motion. Hydraulic actuators are able to generate extremely large forces (at lower speeds) due to the incompressible property of liquids.

Advantages:
- Provide greater lifting force

Disadvantages:
- Reduced speed
- Expensive due to high pressure
- Tendency to leak and thus requires constant surveying and reinforcement
- High replacement costs

2.3.5 Electric Servo Drives

Much similar to actuators, electric servos also adds additional degrees of movement for the AUV’s robotic arm. Electric servo drives enable elements or components to freely rotate typically from 90 to 360 degrees (Engineers Garage). Servos are often powered by a DC current with a gear consisting of a number of teeth to effectively transfer torque from the drive to desired rotating component.

Advantages:
- Light weight
- Small in size
- All internally housed
- Low cost
- High precision movements

Disadvantages:
- Low torque outputs
- Normally not water tight and not suitable for submersion
3.0 Requirements

3.1 Requirements Overview

For each subsystem of the exhibit, a list of requirements is described in Tables 1 to 6. Using the research conducted in section 2.0, safety, functional, client and environmental requirements were proposed in order to achieve the most optimal design solution.

3.2 Requirements Table

**Table 2: Requirements Key**

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>C</td>
<td>Client Requirements</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>Functional Requirements</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>S</td>
<td>Safety Requirements</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>M</td>
<td>Material Requirements</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td>Environmental Requirements</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>High Priority</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>N</td>
<td>Medium Priority</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>L</td>
<td>Low Priority</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td></td>
<td>Request for Proposal</td>
<td>(28/07/14)</td>
</tr>
<tr>
<td>B1</td>
<td></td>
<td>Meeting with Clients</td>
<td>(31/07/14)</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>Meeting with Clients</td>
<td>(07/08/14)</td>
</tr>
</tbody>
</table>

**Table 3: End Effector Requirements Table**

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>CLAW_F1</td>
<td>Shall pick up 500g objects</td>
<td>B1</td>
</tr>
<tr>
<td>N</td>
<td>CLAW_F2</td>
<td>Shall pick up objects of inconsistent shape and orientation</td>
<td>A1</td>
</tr>
<tr>
<td>N</td>
<td>CLAW_F3</td>
<td>Must pick up specimens of maximum size of 15cm x 15cm</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>CLAW_F4</td>
<td>Will respond correctly to input i.e. open and close</td>
<td>A1</td>
</tr>
</tbody>
</table>

**Table 4: Arm Requirements Table**

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>ARM_C1</td>
<td>Shall aid in the retrieval of metal specimens resembling fish and deposit them into the receptacle</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>ARM_C2</td>
<td>Robotic arm must be isolated from the operator</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>ARM_F1</td>
<td>Will operate within maximum 1m x 1m working area</td>
<td>A1</td>
</tr>
<tr>
<td>N</td>
<td>ARM_F2</td>
<td>Must not come into contact with walls or ceiling of water tank</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>ARM_F3</td>
<td>Will have 3 degrees of motion (up, down, left, right, forwards and backwards)</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>ARM_F4</td>
<td>Top of the arm should be located as to not obstruct vision of operator</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>ARM_S1</td>
<td>Shall have adequate shrouding of electrical components and wiring</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>ARM_M1</td>
<td>The material must be rigid and not be porous</td>
<td>B1</td>
</tr>
<tr>
<td>H</td>
<td>ARM_M2</td>
<td>The material should be resistant to the corrosive effects of water</td>
<td>B2</td>
</tr>
<tr>
<td>N</td>
<td>ARM_M3</td>
<td>The material must be readily available and abundant to minimise costs</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>ARM_M4</td>
<td>Sealant material will be flexible when applied to conform to the shape of the design</td>
<td>B2</td>
</tr>
<tr>
<td>N</td>
<td>ARM_M5</td>
<td>The manufacturing process to create the design should be easily available</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>ARM_E1</td>
<td>A non-conductive oil or mineral oil will be used to fill the interior sections of the robotic arm in order protect the arm from further electrical damage</td>
<td>B2</td>
</tr>
</tbody>
</table>
malfunction due to the water environment.

Table 5: Receptacle Requirements Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>CONT_F1</td>
<td>Will be able to hold all 5 to 6 specimens</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>CONT_F2</td>
<td>Must be able to return all objects back into the working area simultaneously</td>
<td>A1</td>
</tr>
<tr>
<td>N</td>
<td>CONT_F3</td>
<td>Should be able to return and scatter objects randomly around the working area</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>CONT_F4</td>
<td>Will be able to sense when all specimens are in the receptacle</td>
<td>B2</td>
</tr>
<tr>
<td>N</td>
<td>CONT_F5</td>
<td>Should be automatically activated to return all specimens to the working area when all specimens are placed inside the receptacle</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>CONT_M1</td>
<td>Material should be resistant to the corrosive effects of water</td>
<td>B2</td>
</tr>
</tbody>
</table>

Table 6: Water Tank Requirements Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>TANK_F1</td>
<td>Will have maximum volume of 1.5m x 1.5m x 1.5m</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>TANK_F2</td>
<td>Will contain robotic arm, receptacle and specimens</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>TANK_F3</td>
<td>All working areas must be accessible to the claw</td>
<td>B1</td>
</tr>
<tr>
<td>H</td>
<td>TANK_M1</td>
<td>Material must be able to withstand impact force of 2kN</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>TANK_M2</td>
<td>Viewing window should be transparent</td>
<td>A1</td>
</tr>
</tbody>
</table>

Table 7: Interface Requirements Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>INTER_C1</td>
<td>Will be intuitive and easy to use for children</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>INTER_C2</td>
<td>Controls will be able to withstand abuse from children</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>INTER_F1</td>
<td>Will provide a method of input for forward, backward, left and right movement of the claw</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>INTER_F2</td>
<td>Will provide a method of input for up and down movement of the claw</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>INTER_F3</td>
<td>Will provide a method of input for opening and closing of the claw</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>INTER_F4</td>
<td>Must be secure to the tank</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>INTER_F5</td>
<td>Must be at a height suitable for operation by a child</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>INTER_S1</td>
<td>Must contain a minimal amount of sharp edges to protect children who are running around in the vicinity</td>
<td>A1</td>
</tr>
<tr>
<td>H</td>
<td>INTER_S2</td>
<td>Electrical components and wiring will be inaccessible to the operator</td>
<td>B2</td>
</tr>
</tbody>
</table>

Table 8: General Requirements Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>GEN_C1</td>
<td>Will meet a strict budget of $3000</td>
<td>A1</td>
</tr>
<tr>
<td>N</td>
<td>GEN_C2</td>
<td>Should require minimal effort to install</td>
<td>A1</td>
</tr>
<tr>
<td>N</td>
<td>GEN_C3</td>
<td>Should require limited maintenance</td>
<td>A1</td>
</tr>
<tr>
<td>N</td>
<td>GEN_C4</td>
<td>Should mimic the action of the robotic arm's used onboard AUV's.</td>
<td>A1</td>
</tr>
<tr>
<td>N</td>
<td>GEN_C5</td>
<td>Should be aesthetically pleasing and attract children’s attention</td>
<td>B1</td>
</tr>
<tr>
<td>N</td>
<td>GEN_C6</td>
<td>Should imitate an underwater environment</td>
<td>B1</td>
</tr>
<tr>
<td>H</td>
<td>GEN_S1</td>
<td>Will have an emergency stop mechanism</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>GEN_E1</td>
<td>Screws must be water resistance</td>
<td>B2</td>
</tr>
<tr>
<td>H</td>
<td>GEN_E1</td>
<td>All wires and electrical components must be waterproofed or contained in an area which will not come into contact with water</td>
<td>B1</td>
</tr>
</tbody>
</table>
4.0 Conceptual Design

4.1 Conceptual Overview

The conceptual design stage consisted of generating a variety of designs that met the requirements in section 3.0 and the research conducted in section 2.0. A Morphological matrix aided in the development of three possible solutions and a Pugh selection matrix was implemented in order to select the most optimum design for manufacture.

4.2 System Overview

The manipulator arm display consists of an interface, a manipulator arm, a tank filled with water, an end effector, metal specimens and a receptacle. The interface allows the user to interact with the manipulator arm through a joystick and buttons. The joystick will provide left right movement and depth control. While the buttons will provide an opening and closing action for the end effector as well as the up and down movement of the arm. The interface output is sent to a PC where the commands are translated into electrical signals. The Arduino interprets these digital inputs and provides movement to the manipulator arms linear and vertical actuators and end effector. The interface will be located outside the water tank while the inside will include the manipulator arm, its end effector, a receptacle and specimens for the children to pick up. The end effector allows the user to pick up specimens and place the objects into the receptacle. Once the receptacle detects that all specimens are in the container, through a weight sensor, an ejection system is implemented to return all specimens back to the working area.

![System Diagram](image)

4.3 Concept Generation

The following Table 9 was used to create a range of conceptual solutions to meet the requirements in section 3.0.
### 4.3.1 Morphological Matrix

#### Table 9: Morphological Matrix for Manipulator Arm

<table>
<thead>
<tr>
<th></th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water Tank</strong></td>
<td>Transparent/reinforced glass cylindrical tank</td>
<td>Transparent/reinforced glass cube tank</td>
<td>Transparent plastic (acrylic) cube tank</td>
<td>-</td>
</tr>
<tr>
<td><strong>End Effector</strong></td>
<td>Electro-servo 2 Finger Gripper</td>
<td>3 Finger Pneumatic Gripper</td>
<td>Magnetic</td>
<td>-</td>
</tr>
<tr>
<td><strong>Receptacle</strong></td>
<td>Cylindrical Container</td>
<td>Rectangular Container</td>
<td>Trapezoidal Container</td>
<td>Spherical Container</td>
</tr>
<tr>
<td><strong>Receptacle Ejection Method</strong></td>
<td>Mass sensor initiated ejection</td>
<td>Drop Release</td>
<td>Pulley System</td>
<td>Spring powered ejection</td>
</tr>
<tr>
<td><strong>Arm/Receptacle Material</strong></td>
<td>Aluminium</td>
<td>Polymethyl Methacrylate</td>
<td>Stainless Steel</td>
<td>Ceramic</td>
</tr>
<tr>
<td><strong>Arm Type</strong></td>
<td>SCARA</td>
<td>Articulated Arm</td>
<td>Spherical Arm</td>
<td>Cartesian Arm</td>
</tr>
<tr>
<td><strong>Interface</strong></td>
<td>Touchscreen</td>
<td>Voice Control</td>
<td>Graphical</td>
<td>Joystick/buttons</td>
</tr>
<tr>
<td><strong>Actuation</strong></td>
<td>Pneumatic/Servo</td>
<td>Hydraulic</td>
<td>Electrical/Servo</td>
<td>Mechanical</td>
</tr>
</tbody>
</table>

- **Concept 1**
- **Concept 2**
- **Concept 3**
4.4 Concept Analysis

4.4.1 Concept Design 1

Concept 1 consists of the Articulated Arm (*Figure 10*) which is situated on a rotating base. The base enables 360 degrees of rotation. Thus, allowing the object to reach all specimens within a 1m radius. The actuators situated in the elbow joint allow up and down movement, i.e. movement in the y-direction.

The actuator in the wrist joint also allows movement in the up and down direction. A combination of these two movements allows the arm to move in the forward and backwards directions.

The third joint consists of a rod which holds the robot’s 3 finger end effector (*Figure 11*). The rod moves up and down in the vertical plane and rotates around its vertical axis. All these movements satisfies requirement ARM_F3 (see section 3.0).

*Figure 10: Articulated Arm*

*Figure 11: 3 Finger End Effector*

**4.4.1.1 – Composition**

- Transparent reinforced glass cube tank - Water Tank - Option 2 - Row 1
- 3 finger JGZ12S pneumatic gripper - End Effector - Option 2 - Row 2
- Aluminium rectangular box – Receptacle – Option 2 – Row 3
- Mass sensor initiated ejection through programming of the robotic arm. Whereby, once the receptacle detects that all specimens are in the container though the use of a mass sensor, the receptacles actuator is automatically activated. All other electrical components will be overridden while the container deposits the specimen back into the working area - Receptacle Ejection Method – Option 1 - Row 4
- Aluminium – Arm Material – Option 1 – Row 5
- Articulated Arm situated on a rotating base with four degrees of freedom – Arm Type – Option 2 – Row 6
- Joystick and buttons – Interface – Option 4 – Row 7
- Stroke high linear pneumatic actuators and electrical servo drive – Actuation – Option 1 – Row 8
4.4.1.2 – Pros/Cons

Pros:

- Aluminium is an ideal material due to its density. It also satisfies requirements ARM_M1, ARM_M3 and ARM_M5 (see section 3.0).
- Untreated Aluminium has very good corrosive resistance. Satisfies requirement ARM_M2 (see section 3.0).
- Base enables 360 degrees of rotation. Thus, allowing the object to reach all specimens within a 1m radius. Satisfies requirement ARM_F1 (see section 3.0).
- Pneumatic actuator situated in the wrist joint allows movement in the y-direction and also allows rotation around its vertical axis.
- Water tank will provide a high level of safety and also multiple angles of viewing. Satisfies requirements ARM_C2, TANK_F1, TANK_F2, TANK_F3 and TANK_M2 (see section 3.0).
- The implemented interface of joystick and buttons is the most user-friendly and simplest to operate. Thus, it is the most ideal choice in order to satisfy all requirements listed under Table 7 (see section 3.0).
- Pneumatic gripper is the most ideal in satisfying requirements CLAW_F1, CLAW_F2, CLAW_F3 and ARM_C1 (see section 3.0).
- Chosen receptacle and receptacle ejection system satisfies all requirement listed under Table 5 (see section 3.0).

Cons:

- The robotic arm’s base is required to be attached to the base of the container and thus the container may need to be modified.
- 3-finger end effector is more complex in design than other types of end effectors which will incur a slightly higher cost.

4.4.1.3 – Calculations

- Pneumatic gripper exhibits a max lift force of 3100 N (see Appendix B).
- Aluminium exhibits a density of 2700 kg/m³. Therefore, there is a total acting force of 0.118(2700) – 90.25 = 228.35 N (see Appendix A).
- Pneumatic actuators can suffice up to 1766 N (see Appendix D).
- Therefore, as stated in Appendix A, due to the design of the robotic arm, the actuator closest to the base is required to lift the entire weight of the arm. Thus, it can be seen that the chosen pneumatic actuator of 1766N is sufficient enough to lift the arm weight force of 228.35 N. This is 1537.65 N greater than the required force. This will hence satisfy requirement CLAW_F1 (see section 3.0).

4.4.2 Concept Design 2

This design consists of an articulating 6 degree of freedom, electronically actuated, aluminium arm (Figure 12), fitted with a two-finger electro-servo clamping claw as seen in Figure 13. The design boasts high manoeuvrability and versatility. It is also compact while achieving the required reach and area of

![Figure 12: Actuated Arm](image-url)
effectiveness for collecting and depositing specimen in the trapezoidal receptacle.

As shown in Figure 13, the claw consists of two plates on a slider connected mechanically to a rotating linkage that is driven by a motor under a high mechanical advantage. Rubber grips are included in this design to allow for a high enough coefficient of friction to avoid over exertion of the motor.

Figure 13: 2 Finger End Effector

4.4.2 – Composition

- Transparent reinforced glass cylindrical tank - Water Tank - Option 2 - Row 1
- Electro-servo MEG64 2 Finger Parallel Gripper - End Effector - Option 2 - Row 2
- Aluminium Trapezoidal Container – Receptacle – Option 2 – Row 3
- Receptacle Ejection Method (Row 4) - Mass sensor ejection through programming of the robotic arm. Whereby, once the receptacle detects that all specimens are in the container though the use of a mass sensor, the receptacles actuator is automatically activated. All other electrical components will be overridden while the container deposits the specimens back into the working area - Receptacle Ejection Method – Option 1 - Row 4
- Aluminium – Arm Material – Option 1 – Row 5
- Articulated Arm with six degrees of freedom – Arm Type – Option 2 – Row 6
- Joystick and buttons – Interface – Option 4 – Row 7
- Linear electrical actuators and electrical servo drive – Actuation – Option 1 – Row 8

4.4.2.2 – Pros/Cons

Pros:

- High degree of manoeuvrability (6 degrees of freedom). Thus, satisfies requirement ARM_F3 (see section 3.0).
- Visually appealing and thus satisfying requirement GEN_C5 (see section 3.0).
- Aluminium is an ideal material due to its density. It also satisfies requirements ARM_M1, ARM_M3 and ARM_M5 (see section 3.0).
- Untreated Aluminium has very good corrosive resistance. Satisfies requirement ARM_M2 (see section 3.0).
- Base enables 360 degrees of rotation. Thus, allowing the object to reach all specimens within a 1m radius. Satisfies requirement ARM_F1 (see section 3.0).
- Water tank will provide a high level of safety and also provide the greatest angles of viewing. Satisfies requirements ARM_C2, TANK_F1, TANK_F2, TANK_F3 and TANK_M2 (see section 3.0).
- The implemented interface of joystick and buttons is the most user friendly and simplest to operate. Thus, it is the most ideal choice in order to satisfy all requirements listed under Table 7 (see section 3.0).
Chosen receptacle and receptacle ejection system satisfies all requirements listed under Table 6 (see section 3.0).

Cons:
- Complex, expensive to design and assemble and will incur high maintenance costs. Thus, may not satisfy requirement GEN_C1 (see section 3.0).
- Electro-servo gripper has low lifting strength due to the use of 2 fingers. Thus, may not satisfy requirements CLAW_F1 and CLAW_F2 (see section 3.0).

4.4.2 – Calculations

- Electro-servo gripper exhibits a max lift force of 175N (see Appendix B).
- Aluminium exhibits a density of 2700 kg/m$^3$. Therefore, there is a total acting force of $0.118(2700) – 90.25 = 228.35$ N (see Appendix A).
- Electrical actuators can suffice up to 15,000 N (see Appendix D).
- Therefore, as stated in Appendix A, due to the design of the robotic arm, the actuator closest to the base is required to lift the entire weight of the arm. Thus, it can be seen that the chosen electric actuator of 15,000N is sufficient enough to lift the arm weight force of 228.35 N. This is 14771.65 N greater than the required force. This will hence satisfy requirement CLAW_F1 (see section 3.0).

4.4.3 Concept Design 3

This concept design takes the form of the Cartesian Arm system (Figure 14). It consists of 4 steel pillars set 90 degrees apart with a distance of 1m in between each adjacent pillar to allow maximum coverage from the effector. A magnetic end effector (Figure 15) is attached to the end of the aluminium arm which is attached to the moveable bridge via bolts and screws.

The actuators are placed at the ends of the bridge to allow movement in both x and y directions. This design allows full coverage within the 1m x 1m spec but cannot reach past the dimensions.

For this design to have heightened functionality, an effector with a larger magnetic force will have to be used which will result in an increase in cost. The arm material should also be changed to allow faster movement but hence will further increase costs.
4.4.3.1 – Composition

- Transparent plastic (acrylic) cube tank - Water Tank - Option 2 - Row 1
- Magnetic end effector - End Effector - Option 2 - Row 2
- Stainless steel Rectangular Container – Receptacle – Option 2 – Row 3
- Mass sensor ejection through programming of the robotic arm. Whereby, once the receptacle detects that all specimens are in the container though the use of a mass sensor, the receptacles actuator is automatically activated. All other electrical components will be overridden while the container deposits the specimens back into the working area.
- Stainless Steel – Arm Material – Option 1 – Row 5
- Articulated Arm situated on a rotating base
- Joystick and buttons – Interface – Option 4 – Row 7
- Linear hydraulic actuators – Actuation – Option 1 – Row 8

4.4.3.2 – Pros/Cons

Pros:
- Easy to manufacture and thus satisfies requirement ARM_M5 (see section 3.0).
- Simplest to install of all designs, thus satisfies requirement GEN_C2 (see section 3.0).
- Most Ideal for grabbing metal specimens. Thus, satisfies requirements CLAW_F1 and CLAW_F2 (see section 3.0).
- Low maintenance, and thus satisfies requirement GEN_C3 (see section 3.0).
- Stainless steel exhibits the highest density. It also satisfies requirements ARM_M1, and ARM_M3 (see section 3.0).
- Stainless steel is the most used material for marine applications and thus has very good corrosive resistance. Satisfies requirement ARM_M2 (see section 3.0).
- Water tank will provide a high level of safety and also multiple angles of viewing. Satisfies requirements ARM_C2, TANK_F1, TANK_F2, TANK_F3 and TANK_M2 (see section 3.0).
- The implemented interface of joystick and buttons is the most user friendly and simplest to operate. Thus, it is the most ideal choice in order to satisfy all requirements listed under Table 7 (see section 3.0).
- The magnetic gripper satisfies requirement CLAW_F2 (see section 3.0).
- Chosen receptacle and receptacle ejection system satisfies all requirements listed under Table 6 (see section 3.0).

Cons:
- Does not resemble or simulate arms used in AUVs. Hence, fails to satisfy requirement GEN_C4 (see section 3.0).
- Less interactive and thus fails to satisfy requirement GEN_C5 (see section 3.0).
- Slow and low accuracy movements.
- Low lifting force. Thus, may not satisfy requirements CLAW_F1 (see section 3.0).
- The magnetic gripper does not satisfy requirement and CLAW_F3 (see section 3.0).
- Extra alterations required to improve magnetic gripper may result in failure to satisfy requirement GEN_C1 (see section 3.0).
4.4.3 – Calculations

- Magnetic gripper exhibits a max lift force of 290N (see Appendix B)
- Stainless steel exhibits a density of approximately 7800 kg/m³. Therefore, there is a total acting force of 0.118(7800) – 90.25 = 830.15 N (see Appendix A).
- Hydraulic actuators can suffice up to 2500 N (see Appendix D).
- Therefore, as stated in Appendix A, due to the design of the robotic arm, the actuator closest to the base is required to lift the entire weight of the arm. Thus, it can be seen that the chosen hydraulic actuator of 2500 N is sufficient enough to lift the arm weight force of 830.15N. This is 1669.85 N greater than the required force. This will hence satisfy requirement CLAW_F1 (see section 3.0).

4.5 Concept Evaluation

4.5.1 Pugh Selection Matrix

The Pugh Selection Matrix is a series of pairwise comparisons between the benchmark, the concept designs and a number of requirements. Each concept design is compared to the benchmark. The most essential requirements are listed in the first column and are weighted in the second. The more important the criteria or requirement, the higher the weighting. The concept designs are scored with either a +1 or -1 and this score is multiplied by the weighting in order to produce a weighted total as seen in the last row of table 2. The datum was selected to be the schilling TITAN 4 as seen in section 2.3.1. The TITAN 4 manipulator arm will be scored a zero for all requirements. The concept designs are compared to the baseline and a score is given according to whether the concept meets the requirement better or worse than the baseline. The design with the highest score will be chosen as the final design.

*Table 9: Pugh Selection Matrix for Manipulator Arm*

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Weighting (/10)</th>
<th>Baseline/Benchmark (Datum)</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Must meet the budget of $3000 (requirement GEN_C1 - see section 3.0)</td>
<td>10 (see below 4.5.2.1)</td>
<td>0</td>
<td>+1 (see below 4.5.2.1)</td>
<td>+1 (see below 4.5.2.1)</td>
<td>+1 (see below 4.5.2.1)</td>
</tr>
<tr>
<td>Requirement</td>
<td>Positive</td>
<td>Negative</td>
<td>Positive</td>
<td>Negative</td>
<td>Positive</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>2. Require minimal effort to install (requirement GEN_C2 - see section 3.0)</td>
<td>7</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>3. Require minimum maintenance (requirement GEN_C3 - see section 3.0)</td>
<td>8</td>
<td>0</td>
<td>+1</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>4. Represents a robotic arm used in an AUV (requirement GEN_C4 - see section 3.0)</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>5. Can pick up specimens of different sizes (requirements CLAW_F1, CLAW_F2, ARM_C1 - see section 3.0)</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>6. Easily available manufacturing process (requirement ARM_M5 - see section 3.0)</td>
<td>7</td>
<td>0</td>
<td>+1</td>
<td>+1</td>
<td>0</td>
</tr>
</tbody>
</table>

Sum of Positives: +4, +3, +4
Sum of Negatives: 0, 0, 0
Total: +6, +3, +2
Weighted Total: +32, +9, +24
4.5.2.1 – Requirement 1
- The requirement of meeting the strict budget of $3000 was given the highest weighting of 10. This is because as stated in the RFP, the client will not finance more than the set amount of $3000. As a result, if the design is over budget, then the display will not be produced. Every concept design was given a +1 rating as the concept designs are considerably cheaper than the benchmark design cost of $165,000 and also below the $3000 budget.

4.5.2.2 – Requirement 2
- The second criteria of requiring minimal effort to install was given a weighting of 7 as it was one of the major requirements set by the client. Option 2 was given a 0 as it has 6 degrees of freedom and is similar to the TITAN benchmark. As a result, due to the large amount of actuators and electrical components involved in this design, the electrical wiring of the robotic arm to the interface during the installation process is considerably complicated and lengthy. Therefore decreasing the ease of installation. Option 1 and Option 3 are simpler designs compared to option 2. Option 1 requires 5 actuators while option 3 requires 4. Therefore, the installation will be significantly easier and simpler due to the fewer numbers of wires and electrical components. Thus, options 1 and 3 require less effort to install and therefore scored +1.

4.5.2.3 – Requirement 3
- The third criteria of requiring minimum maintenance was given a weighting of 8. Which is a higher weighting to the above requirement because the cost of maintenance is higher than the cost of installation. Installation only occurs once, while maintenance can occur multiple times in the products lifetime. It is more important to have a design that does not require constant maintenance in order to save cost, as well as to create a product which is more reliable and does not break down easily. The ratings for each design option are equal to the above requirement and is justified by the same reasoning.

4.5.2.4 – Requirement 4
- The fourth requirement of representing a robotic arm used in an AUV was given a weighting of 9 because the RFP states that the display must “replicate the action of robotic arms used on board AUV’s”. This is especially important in order to create a display that is engaging and attracts the attention of children. Options 1 and 2 are aesthetically pleasing as well as clearly replicating the design of robotic arms used on AUV’s. These designs are very similar to the benchmark and therefore receiving a score of 0. The design used in option 3 does not replicate the actions or correctly educate children on the robotic arms used in AUV’s today, therefore giving a score of -1.

4.5.2.5 – Requirement 5
- The fifth requirement of being able to pick up specimens of different sizes was given a weighting of 8 as the entire purpose of the attraction is to use the robotic arms end effector to handle different shapes in order to mimic those used on AUV’s. Option 1, like the benchmark consists of a three fingered claw which is highly effective and therefore receiving a 0 rating. The three finger end effector is able to pick up specimen of varying shapes while design option 2 will be unreliable in retrieving specimens shaped like a triangular prisms or spheres due to its 2 finger design. Thus receiving a -1 rating. Design option 3 consists of a magnetic effector which will easily and consistently pick up specimens of any shapes and sizes. However, it does not represent those used on AUV’s and therefore receiving a rating of +1.
4.5.2.6 – Requirement 6

- The sixth requirement of an easily available manufacturing process was given a weighting of 7 because this will directly impact on the time taken to create the product and also impact labour and machinery costs. Option 1 and 2 are easier to manufacture compared to the benchmark TITAN because there are less parts and each section arm is relatively simpler in design. Option 3’s manufacturing process is similarly as complicated as the benchmark design because of the incorporation of four steel pillars and thus given a rating of 0.

4.6 Final Design Recommendation

The final design, as determined by the Pugh selection matrix, is concept 1. Concept 1 meets the budget of $3000, thus satisfying requirement GEN_C1 (see section 3.0). Unlike concept design 3 which includes eight beams and concept 2 which includes six degrees of freedom, option 1 is easy to install and maintain. Concept 1 is also an accurate representation of the types of manipulator arms used in underwater missions today. Due to the three finger effector, the design will be able to pick up specimens of varying shapes and sizes. This design exhibits ideal features such as being able to move at relative speeds and also flawless functionality. The final design’s functionality is exceedingly good as it is able to withstand all forces exerted on it and its hydraulic gripper has a maximum lift force of 3100N (see Appendix B). The chosen interface will also consist of an emergency stop mechanism in order to satisfy requirement GEN_S1 (see section 3.0). The freedom of this design also enables the implementation of requirements ARM_E1, ARM_E2, ARM_E3, GEN_E1, GEN_E2 and GEN_E3 (see section 3.0).

Figure 16: Final Design
5.0 Detailed Design

5.1 Detailed Overview

This section will detail the chosen design and ensure that it meets all the requirements as stated in section 3.0. The waterproofing of the arm, the interface and the receptacle are also discussed in this section. Simulations, prototype testing plans, finite elemental analysis, cost analysis, engineering drawings, a manufacturing and installation plan, can all be found below in order to address manufacture.

5.2 Architectural Overview

The Ocean Explorers’ Robotic Arm Display consists of an interface, receptacle, manipulator arm with an end effector and a water tank. For a graphical overview of the subsystems, see Figure 17 below.

![Figure 17: Architectural Overview](image)

The interface allows the user to interact with the manipulator arm through a joystick and buttons. The joystick will provide left right movement and depth control. While the buttons will provide an opening and closing action for the end effector as well as the up and down movement of the arm. The interface will be located outside the water tank while the inside will include the manipulator arm, its end effector, a receptacle and specimens for the children to pick up. This can be seen in Figure 18 below. The aluminium alloy manipulator arm includes three links and a rotating base as shown in Figure 18. Each of these parts are controlled by linear and carriage pneumatic actuators while the rotating base is powered by an electric servo motor. Connected to arm link 3 is a three finger JGZ125 pneumatic gripper. The end effector allows the user to pick up specimens and place the objects into the receptacle. Once the receptacle detects that all specimens are in the container, through a weight sensor, an ejection system is implemented to return all specimens back to the working area.
5.3 Functional Overview

Figure 19 below represents a functional block diagram which demonstrates the core functions of the system. We can see that the system functions quite linearly until a specimen has been placed into the receptacle. From this stage, the user can decide to pick up another or eject the current specimens.

1.0 Start System

- Turn on Robotic Arm
- 2.0 Position Claw
  - Move Claw Position with Joystick
- 3.0 Adjust Claw
  - Move Claw Up and Down with Buttons
- 4.0 Get Specimens
  - OR
  - 4.1 Pick-up Specimen
  - 4.2 Place Specimen
- 5.0 Eject Specimens
  - Eject Specimens and activate water pump

Figure 19: Functional Block Diagram
As the system is being controlled by the user, its state changes as represented in Figure 20 below. After the power is switched on, the joystick will be controlled leading to the movement of the mechanical arm. If the sensor detects a specimen within the receptacle, it will eject it after 2 seconds.

Figure 20: State Diagram
5.4 User Overview

Figure 21 below represents a flow diagram of the system which displays the sequence of actions taken for the correct functionality of the arm. After the power is turned on, the sequence flows in a linear manner, from controlling the arm to placing the specimen in the receptacle. The system will then try to identify whether a specimen has been placed inside and will eject or remain still accordingly.

![Flow Diagram]

*Figure 21: Flow Diagram*
5.5 Detailed Descriptions of Subsystems

5.5.1 Material Properties

The tables below outlines the material specifications used for the robotic arm and receptacle.

**Table 10: Aluminium Alloy 2024 Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (californiametal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>2800 kg/m³</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>186 MPa</td>
</tr>
<tr>
<td>Tensile Yield Strength</td>
<td>75.8 MPa</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>73.1 GPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>28 GPa</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>124 MPa</td>
</tr>
</tbody>
</table>

**Table 11: Type 304 Stainless Steel Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (ASM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8000 kg/m³</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>505 MPa</td>
</tr>
<tr>
<td>Tensile Yield Strength</td>
<td>215 MPa</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>193-200 GPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>86 GPa</td>
</tr>
<tr>
<td>Shear Strength</td>
<td>-</td>
</tr>
</tbody>
</table>

5.5.2 Robotic Arm

The Articulated Arm exhibits a max stretch length of 0.7 m (see Appendix J) and will be situated on a rotating base that enables 360 degrees of rotation. The rotating base is powered by Yaskawa’s SGMGV-1EA Sigma-5, a medium inertia electric DC servo. This servo is fully enclosed with a rating of continuous operation (YASKAWA AMERICA, Drives and Motion Division). A suitable servo was found after a minimal torque of 82.48Nm was calculated to rotate the entire assembly.

Specification for the Yaskawa SGMGV-1EA Sigma-5:
- Power output of up to 15kW
- Torque ratings of 95.4Nm
- Instantaneous peak torque of 224Nm
- Maximum speed of 3000rpm
- High resolution serial encoder
- IP67 protective structure

The rotating base allows the arm to reach all specimens within a 0.7 m radius, illustrated in Figure 22 below. However, position sensors will be placed on the chosen end effector that will ensure the arm does not exceed the required 1m x 1m working space or come into contact with walls or the ceiling of the tank. The rotating base is powered by an electric servo which is housed in a cylindrical compartment in the right angled triangular prisms (detailed in section 5.5.5). The compartment will be sealed with silicon to ensure the base is fully waterproofed.
The arm consists of three links, with each connected by rotary pneumatic actuators in order to enable up down movement in the y-plane. The three finger end effector will be attached to the third link. The arm links are hollow in order to allow wiring to run from the end effector to the base. Each link joint will be sealed with silicon and all wiring will be shrouded in order to ensure the arm and cables are waterproof.
The entire arm will be constructed out of Aluminium Alloy 2024 (see Table 10). This specific material was chosen as it is rigid and not porous and thus satisfying requirements ARM_M1 and ARM_M3 (see Table 4). Aluminium was chosen due to its high density to counteract the upwards buoyancy force of water. The type of aluminium chosen has a high level of corrosion resistance due to the addition of copper. Aluminium is cheap due to its abundance and can be easily shaped, reducing the time and cost of the manufacturing process.

5.5.3 Actuators

The chosen actuators are the Stroke High Linear Pneumatic Actuators (Firgelli Automations Australia, 2014). A total of 3 actuators will be bought from Firgelli Automations Australia. The pneumatic actuators will be situated between the rotating base and link 1, the joint between link 1 and 2 and the joint between link 2 and 3, allowing each link to move up and down in the y-direction. Along with the rotation of the base, the arm has four degrees of freedom. The end effector will be attached to link 3 and includes its own actuator for the opening and closing of the fingers. See section 5.5.4 for more details on the chosen end effector.

Characteristics:
- Waterproof Design
- Product Code: FA-400-L-12-24
- Max Force = 1766 N
- Max stroke length = 600mm
- 5 Amp current draw
- Operating speed = 12mm/s
- Material = aluminium
- Price = $151.00 each
- Force on Actuator 1 = 98.1 N (see Appendix E)
- Force on Actuator 2 = 169.13 N (see Appendix E)
- Force on Actuators 3 = 239.76 (see Appendix E)

5.5.4 End Effector

The chosen design for the end effector of the robotic arm is the 3 Finger Concentric Pneumatic JGZ125 Gripper (Schunk, 2014). This end effector will be bought from SCHUNK GmbH & Co. KG Company and attached to the third link of the robotic arm. Its three finger design along with a combination of stroke length and concentric separation allows it to retrieve specimens of any shape and size including complex 3D objects (see Appendix K). The end effector is entirely waterproof and will be composed of Aluminium Alloy 2024 and Type 304 Stainless steel (see Tables 10 and 11). Both materials have a high corrosive resistance due to the inclusion of copper in aluminium and the inclusion of chromium in stainless steel. The end effector also comes with an installed position sensor accessory in order to ensure that the arm does not come into contact with the ceiling or any walls of the tank.

Characteristics:
- Gripping Force = 3100 N
- Stroke length per finger = 13.0 mm
- Weight = 2.8 kg
- Max work piece weight = 15.5 kg
- Closing/Opening time = 0.2 sec
- Operating Temperature = -10°C to 90°C
- Composed of aluminium alloy 2024
- Waterproof Design

Figure 24: JGZ-125 Gripper

5.5.5 Water Tank

The water tank consists of transparent reinforced glass which can withstand a high amount of impact (see section 5.6.6). This is to accommodate for children hitting or bumping into the display. Right angled triangular prisms will be added along the inside perimeter of the floor of the tank as shown in Figure 18. The prisms will have a height of 0.2m and an angle of 45 degrees, allowing the specimens to slide down the slope if they are flung outside the 1m x 1m working area. The prisms also act as the housing for all the electrical components of the robotic arm. To protect the electrical components of the display from water, sealant will be used. A false wall made out of aluminium, will act as the back of the tank providing a 0.3m thick housing to contain the pump and wiring required for the receptacle. For aesthetical purposes and to attract children to the exhibit, the wall will be painted with an underwater themed mural using water resistant acrylic paint.
5.5.6 Receptacle

The Type 304 Stainless Steel container (see Table 11) is designed to be able to hold and release all the items while having a long fatigue life and corrosion resistance. Its shape is a series of telescoping square cross sections aligned at the back wall, allowing for a powerful accelerating force at the bottom and the formation of turbulent flow at the top to create more chaotic dispersions of the specimen. The receptacle will be mounted onto the false wall of the tank with 4 stainless steel flathead bolts and the pump hose will also be secured with bolts and a collar on the other side of the wall. This will all be sealed with silicon to an IP rating of 58 to ensure that the concealed pump and wiring are not flooded.

The ejection system will automatically be activated when all the specimens are placed into the receptacle. A mass sensor is placed on the bottom of the receptacle and counts the total number of change in masses. There are six specimens in total for the exhibit, therefore when the counter reaches six, the pump is activated to accelerate and disperse the specimens randomly in the work area. The pump will draw water from the right hand corner of the tank and pump it straight into the receptacle at a max rate of 15000L/min. This will produce an exit velocity of 6.25m/s. The wiring for mass counter and the pump are led through a small hole in the receptacle and out through the false wall just below the receptacle where it is unlikely to be hit by falling specimen. The interface design also allows the operator to eject the specimens at their desired time by pressing the reset button. This increases the usability of the design.

5.5.7 Water Pump

The chosen water pump for the receptacle design is the Ozito PSDW-750 Submersible Water Pump (see figure 25) bought from Bunnings Warehouse.

Characteristics:

- 750W Motor
- Maximum head of 8m
- Submergible depth of 8m
- Material: Plastic, Metal
- Dimensions: 220 x 180 x 380
- Weight: 5.2 kg
- Max Flow: 15000 L/min
- Horsepower: 1
5.5.8 Interface

The final interface design provides a source of input for the user to interact with the manipulator arm. The joystick and button design was chosen because it was the most intuitive and highly reliable over the touchscreen or voice control designs. The joystick will move the arm left and right as well as provide depth control. The buttons as seen in Figure 26 below moves the arm up and down along with the opening and closing of the end effector. Although the receptacle, ejects the specimens automatically, a reset button is also provided increase the user friendliness of the design. On the side of the interface (see Figure 27 below) an emergency stop button has been provided in the case of a malfunction. A start button can also be located on the side to start the display at the beginning of each day.

The interface will be located outside the water tank and securely connected by screws. This can be seen in Figure 18. All electrical components and wiring will be hidden inside the interface making it inaccessible to children. The edges of the interface will be curved and layered with rubber to protect the children who may come into contact with the interface while running around the museum. The average height of a child aged six is 115 cm (livestrong, 2013). Therefore, the interface height must accommodate for children of young ages and thus the interface will be 0.6m from the base.

![Figure 27: Interface Top View Layout](image-url)
5.6 Simulations & Prototype Testing

A number of tests are proposed in order to determine whether each subsystem functions reliably and meets the requirements detailed in section 3.0.

5.6.1 Pick Up & Drop Test

**Aim:**
To determine whether the end effector can pick up objects submerged underwater.

**Description:**
The end effector will not be attached to the rest of the robotic arm but instead connected only to the power source and the computer/controls. To pass this test, the end effector must be able to grab onto specimens and only let go when the computer sends the instruction.

**Equipment:**
End effector, power supply, programmed arduino, open/close controls, wires, bowl of water, 6 differently shaped 500g specimens.

**Requirements:**
- **CLAW_F1** - Shall be able to pick 500g objects of inconsistent shape and orientation.
- **CLAW_F2** - Must be able to pick up specimen 15 x 15 cm.
- **CLAW_F3** - Will correctly respond to input i.e. open and close.
- **INTER_F3** - Will provide a method of input for opening and closing of the claw.

**Method:**
- Step 1: Connect end effector to power supply, arduino and controls.
- Step 2: Place one specimen into the bowl and completely submerge the end effector with claw facing down.
- Step 3: Command end effector to close the claw around specimen and manually lift end effector up by hand.
- Step 4: Command end effector to open the claw to release specimen.
- Step 5: Repeat steps 3 and 4 for other shaped specimens.

Success Criteria:
- End effector was able to grab and release all 6 of the 500g objects without failing.
- The open claw must span an area of more than 0.15m².
- The closed claw must have the correct span (range 0 – 0.15m) such that the object does not fall.
- End effector was able to open when given the input to open.
- End effector was able to close when given the input to close.

Cost:
As non-destructive testing is being used, there are minimal extra costs involved with testing of the components. The actual product will be used for this test so the components’ costs have already been factored into the bill of materials (see section 5.10).

5.6.2 Working Area Test

Description:
This test will determine whether the robotic arm is able to touch each corner of the container and around its base (i.e. it is able to access all spots in the 1 x 1 m working area). This test will be done without the presence of water and without the use of the end effector.

Equipment:
Robotic arm (assembled without end effector), screws to attach rotating base to a horizontal surface, power supply, arduino/controls, wiring, marker, and ruler.

Requirements:
- ARM_F1 - Will operate within maximum 1m x 1m working area.
- ARM_F2 - Must not come into contact with walls or ceiling of water tank.
- ARM_F3 - Will have 3 degrees of motion (up, down, left, right, forwards and backwards).
- INTER_C1 - Will be intuitive and easy to use for children.

Method:
- Step 1: Mark a 1m x 1m square on a surface with the marker.
- Step 2: Attach robotic arm to the surface on one side of the square.
- Step 3: Connect robotic arm to power supply and arduino/controls.
- Step 4: Command robotic arm to touch all corners of the square as well as at its base.

Success Criteria:
- Arm was able to reach all 4 corners of the 1m x 1m working area as well as at its base.
- Arm was able to respond with ‘up, down, forward, backward, left, right’ when given the inputs ‘up, down, forward, backward, left, right’ respectively.

Cost:

Table 12: Working Area Test Cost

<table>
<thead>
<tr>
<th>Part</th>
<th>Source</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal Wooden Board</td>
<td>Bunnings</td>
<td>$3.85</td>
</tr>
<tr>
<td>Stainless Steel M5 bolts</td>
<td>Bunnings</td>
<td>$2.99</td>
</tr>
</tbody>
</table>
5.6.3 Dispersion Test

**Description:**
This test is to determine whether the receptacle is able to correctly release the specimens back into the working area once it is in the receptacle. The main focus points of this test is the weight sensor and the specimen dispersion mechanism. The receptacle will be mounted onto a vertical wall as represented in the final design whilst connected to the mass sensor, computer and power supply.

**Equipment:**
Receptacle, vertical rigid surface, 10L water, dispersion mechanism (tubing and water pump), mass sensor, power supply, bolts, wiring, arduino. 6 specimens, tape measure.

**Requirements:**
- CONT_F1- Will be able to hold all 6 specimens.
- CONT_F3- Should be able to return and scatter objects randomly around the working area.
- CONT_F4- Will be able to sense when all specimens are in the receptacle.
- CONT_F5- Should be automatically activated to return all specimens to the working area when all specimens are placed inside the receptacle.
- GEN_C2- Should require only a minimal effort to install.

**Method:**
- Step 1: Attach receptacle to vertical surface using the flathead bolts and connect it to the tubing.
- Step 2: Electrically connect the water pump with the power supply and arduino.
- Step 3: Load all 6 specimens into the receptacle and observe whether the dispersion mechanism automatically turns on.
- Step 4: Observe whether the water pumped turned off after specimens were released.
- Step 5: Measure the distance between the furthest two specimens.
- Step 6: Repeat step 3 but only for 5 specimens.
- Step 7: If receptacle remains stationary, add 1 more specimen and observe whether the release mechanism is triggered.

**Success Criteria:**
- Mass sensor was working correctly i.e. was able to determine that it contained all 6 of the specimens before it triggered the release mechanism (allowing the wire rope to go slack and the receptacle will rotate about hinge).
- The dispersion mechanism was not triggered until all 6 specimens were in the receptacle.
- When the dispersion mechanism was triggered, the receptacle ejected the particles in a random way such that at least 2 specimens were 0.5m apart from each other.
- The water pumped turned off after there were no longer any more specimens remaining the receptacle.

**Cost:**

<table>
<thead>
<tr>
<th>Part</th>
<th>Source</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical Wooden Board (upside down T)</td>
<td>Bunnings</td>
<td>$3.85</td>
</tr>
<tr>
<td>Tubing</td>
<td>Bunnings</td>
<td>$7.99</td>
</tr>
</tbody>
</table>
5.6.4 Sealing Test

Description:
This test will show whether water will seep through the aluminium inclined planes at the working area (which are used to separate the water from the electrical components underneath). The 4 inclined planes at the working area will be installed into the tank and water will be poured into the tank until the inclined planes are completely covered.

Equipment:
Aluminium inclined planes, bolts, silicon sealant, sealant remover, and tank.

Requirements:
- ARM_E1 - A non-conductive oil or mineral oil will be used to fill the interior sections of the robotic arm in order protect the arm from further electrical malfunction due to the water environment.
- ARM_M4 - Sealant material will be flexible when applied to conform to the shape of the design.
- ARM_S1 - Shall have adequate shrouding of electrical components and wiring.
- INTER_S2 - Electrical components and wiring will be inaccessible to the operator.

Method
- Step 1: Install inclined planes into tank and any gaps are sealed using the silicone.
- Step 2: Pour water into the tank until inclined planes are completely covered.
- Step 3: Observe if leakage occurs.
- Step 4: Empty tank and uninstall the planes using the silicone sealant remover.

Success Criteria
- The inclined planes remained rigid in its position and no water seeped under these aluminium planes.
- Water will not seep through the area in which the robotic arm’s rotating base will be installed.

Cost:
As non-destructive testing is being used, there are minimal extra costs involved with testing of the components. The actual product will be used for this test so the components’ costs have already been factored into the bill of materials (see section 5.10).

5.6.5 Input/output Test

Description:
This controls test will involve observing the input and output of the Arduino which will be used to control the arm and its movement within the working area. The base of the robotic arm will be fastened to a horizontal plane using brass screws and electrically connected to the power supply and arduino/controls. The following requirements will be tested to see if all inputs and outputs are correct.

Equipment:
Robotic arm, bolts, horizontal board surface, power supply, arduino and controls.
Requirements:
- INTER_F1- Will provide a method of input for forward, backward, left and right movement of the claw.
- INTER_F2- Will provide a method of input for up and down movement of the claw.
- INTER_F3- Will provide a method of input for opening and closing of the claw.

Method:
- Step 1: Install robotic arm onto the horizontal surface and connect to the power supply and arduino/controls.
- Step 2: Test all control on the interface individually and observe its effects on the robotic arm’s movement.
- Step 3: Measure the span of the open claw

Success Criteria:
- The arduino is able to interpret the instructions/input of ‘up, down, forward, backward, left and right’ correctly by observing the motion of the arm during each of those respective instructions.
- The arduino is able to interpret the instructions correctly for opening and closing of the end effector.
- The open claw must span an area more than 0.15m².
- The robotic arm must be able to respond to those instructions correctly at least 3 individual times to pass this test

Cost:
- As non-destructive testing is being used, there are minimal extra costs involved with testing of the components. The actual product will be used for this test so the components’ costs have already been factored into the bill of materials (see section 5.10).

5.6.6 Impact Test

Description:
This test will determine whether the glass of the tank will be able to withstand impacts caused by children banging on the walls. For the purpose of the experiment, the pendulum will be wrapped in ebonite (hard rubber) to simulate children’s fists. If the glass is able to withstand up to 10 consecutive impacts from the pendulum, it will definitely be immune to those caused by children.

Equipment:
Pendulum, glass tank, ebonite.

Requirements:
- Tank_M1- Material must be able to withstand impact force of 2 KN.

Method:
- Step 1: Set up pendulum so that it will collide towards the centre of the glass surface.
- Step 2: Pull pendulum to the highest point and release.
- Step 3: Repeat step 2 ten times.

Success Criteria:
- The glass did not crack after 10 consecutive impacts on a fixed point.

The table below displays the different requirements achieved for each test.
5.6.7 Testing schedule

The testing schedule (see Figure 28 below) shows the amount of time required to conduct each test which included setting up the equipment, observations, and packing down. Each test had to check off all the listed requirements (as listed above) in order for the component’s function to be of satisfactory quality. All tests were conducted on the same day.

![Testing Schedule](image)

**Figure 29: Testing Schedule**
5.7 Finite Elemental Analysis (FEA)

Finite element analysis performed on SolidWorks allows the simulation of beams under stress when it is fully loaded in assembly. Due to the design of the arms, actuators are connected between each arm through pin joints and thus the analysis of forces must be focused on the forces acting on each of the mounts on the arm. As the maximum weight the arms and actuators are required to lift was calculated to be 239.76N (see Appendix E), all arms were simulated under the maximum weight to ensure that all actuators and arms would be suitable. The arm consists of two types of chain links, with ARM LINK 1 consisting of section 4 (see Appendix E) and ARM LINK 2, 3 representing section 2 and 3 (see Appendix E).

The material used in finite elemental analysis is Aluminium Alloy 2024 with a density of 2800kg/m^3, a yield strength of 75.83x10^6 N/m^2, and an additional buoyancy force of 39.24N identical to those represented in the free body diagrams (see Appendix E). Both arms were tested with a fixed actuator mount, loaded actuator mount and also an upwards buoyancy force. As for the base of the assembly (see section 4.0), a simulation focuses on the stresses around the mounting points of the base due to most of the forces being concentrated on actuators.

As a result, all FEA tests exhibited stresses well below that of Aluminium Alloy 2024’s yield strength with minimal bending and deformation. Note all deformations below are exaggerated.

**FEA Tests for Arm Link 1 (see Appendix J):**

Both Von Mises report and displacement report show minimal stress and bending of the arm, with a max stress of 32x10^6 N/m^2 and a maximum displacement of 1.43mm.

**Von Mises Report:**
**Displacement Report:**

Similar to the previous test both Von Mises report and displacement report show minimal stress and bending of the arm, with maximum stresses of $30.5 \times 10^6$ N/m$^2$ and a maximum displacement of 1.24mm.

**Von Mises Report:**
Displacement Report:

Both Von Mises report and displacement report show minimal stress and bending of the arm, with maximum stresses of $1.47 \times 10^6$ N/m$^2$ and a maximum displacement of $3.35 \times 10^{-4}$ mm, both within tolerating limits.

Von Mises Report:
**Von Mises Fail Criterion:**

Von Mises Fail Criterion can be calculated by:

\[
\sigma_v = \left( \frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} \right)^{\frac{1}{2}}
\]

Where if \( \sigma_v \geq \sigma_y \), failure in the tensile material will occur.

From the Von Mises Report above, the finite element testing provides statistics including the maximum amount of stress experienced by the arms under load and also aluminium 2024’s yield strength. ARM LINK 1 experiences a maximum stress of \( \sigma_v = 32 \times 10^6 \) MPa whilst ARM LINK 2 experiences a maximum stress of \( \sigma_v = 30.5 \times 10^6 \) MPa. Both these numbers are well below Aluminium 2024’s yield strength of \( \sigma_y = 75.6 \) Mpa, hence tensile failure at maximum loads will not fail.

**5.8 Pseudo Code**

The system will utilise an Arduino along with simple coding to function the actuators and sensors from the user interface. The text below shows a simplified version of C code which will be implemented into the system.

**For the buttons and joystick on the interface:**

If the joystick is pushed forward
move the arm forward
If the joystick is pushed backward
move the arm backward

If the joystick is pushed left
move the arm left

If the joystick is pushed right
move the arm right

If the ‘up’ button is pressed
move the arm up

If the ‘down’ button is pressed
move the arm down

If the ‘open’ button is pressed
open the claw

If the ‘close’ button is pressed
close the claw

If the reset button is pressed
activate the eject function of receptacle
activate water pump

If the ‘ON’ button is pressed
start up the system

If the ‘EMERGENCY STOP’ button is pressed
shutdown the whole system

**For other functions:**

Set counter to 0

If mass sensor detects a specimen is placed in the receptacle
add 1 to counter

If the counter equals 6
activate the eject function of receptacle
activate the water pump

While the arm is in motion
If the sensor on the effector OR the sensor on the second arm link detects a wall nearby
stop motion
If the joystick is pushed
continue motion in the corresponding direction

**5.9 Budget Analysis**

As seen in the Table 15 below the total cost of the entire project will be approximately $2817.42. This is less than the $3000 budget specified in the RFP and thus satisfies requirement GEN_C1 (see section 3.0).
**Table 15: Cost Analysis**

<table>
<thead>
<tr>
<th>ITEM</th>
<th>QUANTITY</th>
<th>COST</th>
<th>%</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm Links</td>
<td>3</td>
<td>$11.95</td>
<td>0.8</td>
<td>Custompart</td>
</tr>
<tr>
<td>Arm Base</td>
<td>1</td>
<td>$18.63</td>
<td>0.7</td>
<td>Custompart</td>
</tr>
<tr>
<td>JGZ-125 Gripper &amp; Sensor</td>
<td>1</td>
<td>$1099.00</td>
<td>39.0</td>
<td>Schunk</td>
</tr>
<tr>
<td>SGMGV-1EA</td>
<td>1</td>
<td>$260.00</td>
<td>9.2</td>
<td>Yaskawa America</td>
</tr>
<tr>
<td>Interface</td>
<td>1</td>
<td>$100.55</td>
<td>3.6</td>
<td>Custompart</td>
</tr>
<tr>
<td>Actuators</td>
<td>3</td>
<td>$151.00</td>
<td>16.1</td>
<td>Firgelli Automations Australia</td>
</tr>
<tr>
<td>Receptacle</td>
<td>1</td>
<td>$210.00</td>
<td>7.5</td>
<td>Custompart</td>
</tr>
<tr>
<td>Silicon Sealant 401 RTV</td>
<td>2</td>
<td>$12.85</td>
<td>0.9</td>
<td>Selleys Australia</td>
</tr>
<tr>
<td>Ozito PSDW-750 Pump</td>
<td>1</td>
<td>$99.00</td>
<td>3.5</td>
<td>Bunnings Warehouse</td>
</tr>
<tr>
<td>Horizontal Wooden Board</td>
<td>1</td>
<td>$3.85</td>
<td>0.1</td>
<td>Bunnings Warehouse</td>
</tr>
<tr>
<td>Vertical Wooden Board (upside down T)</td>
<td>1</td>
<td>$3.85</td>
<td>0.1</td>
<td>Bunnings Warehouse</td>
</tr>
<tr>
<td>Tubing</td>
<td>1</td>
<td>$7.99</td>
<td>0.3</td>
<td>Bunnings Warehouse</td>
</tr>
<tr>
<td>LSB200 Mass Sensor</td>
<td>1</td>
<td>$80.00</td>
<td>2.8</td>
<td>Futek</td>
</tr>
<tr>
<td>False Wall</td>
<td>1</td>
<td>$300.00</td>
<td>10.6</td>
<td>Custompart</td>
</tr>
<tr>
<td>Right Angled Triangular Prisms</td>
<td>4</td>
<td>$50.00</td>
<td>7.1</td>
<td>Custompart</td>
</tr>
<tr>
<td>Acrylic Paint</td>
<td>10</td>
<td>$2.00</td>
<td>0.7</td>
<td>Riot Art Supplies</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>$2817.42</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 16: Bill of Materials**

<table>
<thead>
<tr>
<th>Part</th>
<th>Drawing No:</th>
<th>Description</th>
<th>Manufacturer/Supplier</th>
<th>Quantity</th>
<th>Power Budget (W)</th>
<th>Mass Budget (kg)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM LINK 1</td>
<td>2</td>
<td>Arm joint for robotic arm.</td>
<td>Custompart</td>
<td>1</td>
<td>-</td>
<td>5.0</td>
<td>$11.95</td>
</tr>
<tr>
<td>ARM LINK 2</td>
<td>3</td>
<td>Arm joint for robotic arm.</td>
<td>Custompart</td>
<td>2</td>
<td>-</td>
<td>5.0</td>
<td>$11.95</td>
</tr>
<tr>
<td>ARM BASE</td>
<td>1</td>
<td>Base where both arm links and electric servo are connected to allow for rotation of the arm.</td>
<td>Custompart</td>
<td>1</td>
<td>-</td>
<td>15.0</td>
<td>$18.63</td>
</tr>
<tr>
<td>JGZ-125 &amp; Sensor</td>
<td></td>
<td>Gripper (end-effector) responsible for gripping specimens.</td>
<td>Schunk</td>
<td>1</td>
<td>-</td>
<td>2.8</td>
<td>$1099.00</td>
</tr>
<tr>
<td>SGMGV-1EA</td>
<td></td>
<td>Electric Servo, responsible for the rotation of arm base.</td>
<td>Yaskawa America</td>
<td>1</td>
<td>200</td>
<td>10.5</td>
<td>$260.00</td>
</tr>
<tr>
<td>Joystick + Buttons (Interface)</td>
<td></td>
<td>User interface allowing for the movement of the arm in x, y and z axis. Also responsible for the start/stop operation of the robotic arm.</td>
<td>Custompart</td>
<td>1</td>
<td>20</td>
<td>10.0</td>
<td>$100.55</td>
</tr>
<tr>
<td>Item</td>
<td>Description</td>
<td>Supplier</td>
<td>Quantity</td>
<td>Price</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------------------</td>
<td>----------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actuators</td>
<td>Linear actuators responsible for the x and y axis movement of the arm.</td>
<td>Firgelli Automations Australia</td>
<td>3</td>
<td>7</td>
<td>0.5</td>
<td>$151.00</td>
<td></td>
</tr>
<tr>
<td>Receptacle</td>
<td>Holds all picked up specimens.</td>
<td>Custompart</td>
<td>1</td>
<td>-</td>
<td>12.5</td>
<td>$210.00</td>
<td></td>
</tr>
<tr>
<td>Sealant</td>
<td>Silicon Sealant 401 RTV will be used on all gaps, joints and edges to prevent water leakage.</td>
<td>Selleys Australia</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>$12.85</td>
<td></td>
</tr>
<tr>
<td>Water Pump</td>
<td>Ozito PSDW-750 Submersible Water Pump used to return the specimens back to the working area.</td>
<td>Bunnings Warehouse</td>
<td>1</td>
<td>750</td>
<td>5.2</td>
<td>$99.00</td>
<td></td>
</tr>
<tr>
<td>Horizontal Wooden Board</td>
<td>For Working Area Test <em>(see section 5.6.2)</em>.</td>
<td>Bunnings Warehouse</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>$3.85</td>
<td></td>
</tr>
<tr>
<td>Vertical Wooden Board (upside down T)</td>
<td>For Dispersion Text <em>(see section 5.6.3)</em>.</td>
<td>Bunnings Warehouse</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>$3.85</td>
<td></td>
</tr>
<tr>
<td>LSB200 Mass Sensor</td>
<td>Mass sensor to detect abrupt mass changes greater than 400g within the receptacle.</td>
<td>Futek</td>
<td>1</td>
<td>7</td>
<td>0.5</td>
<td>$80.00</td>
<td></td>
</tr>
<tr>
<td>Tubing</td>
<td>For Dispersion Test <em>(see section 5.6.3)</em>.</td>
<td>Bunnings Warehouse</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>$7.99</td>
<td></td>
</tr>
<tr>
<td>False Wall</td>
<td>Act as the back of the tank providing housing for pump, wiring and receptacle.</td>
<td>Custompart</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>$300.00</td>
<td></td>
</tr>
<tr>
<td>Right Angled Triangular Prisms</td>
<td>Added along the inside perimeter of the floor allowing specimens to slide down the slope and also acts as a housing for all electrical components.</td>
<td>Custompart</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>$50.00</td>
<td></td>
</tr>
<tr>
<td>Acrylic Paint</td>
<td>For aesthetical purposes</td>
<td>Riot Art Supplies</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>$2.00</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL** 984 67 $2817.42

### 5.10 Manufacturing Plan

This manufacturing of each subcomponent will be done off-site at the various suppliers as listed in section 5.9. The manufacturing plan will detail the individual components of the robotic arm to be sourced/manufactured by the suppliers. To ensure the project is within the budget, the suppliers were contacted for quotes on each of the arm’s components.

‘Custom Part’ will manufacture the bulk of the non-electrical hardware required in the robotic arm exhibit. These parts will be manufactured using sandcasting which allows the product to be low cost.
and suitable for this small production rate. This includes the three arm links out of aluminium stock at $11.95 each as well as the aluminium arm base at $18.63. Custompart will also manufacture the false wall (rectangular stainless steel sheet), receptacle (aluminium trapezoidal box), the four inclined planes (aluminium triangular prisms) and the stainless steel interface at approximately $500 altogether.

The electrical components will be sourced from different suppliers including Schunk, Yaskawa, and Firgelli Automations. The JGZ-125 Gripper and motion sensor will be provided by Schunk at $1099, the end effector’s servo will be provided from Yaskawa at $260 and the three actuators will be sourced from Firgelli Automations at $151 each.

The other miscellaneous parts including the water pump, sealant and acrylic paint will be sourced from Bunning’s Warehouse, Selleys Australia and Riot Art Supplies respectively. Assembly of the components will be done manually off-site.

NOTE: The reinforced glass tank has been left out of the manufacturing plan as it will be provided by the client.

5.11 Installation Plan

The robotic arm and user interface will be assembled off-site and fitted within a cardboard box. Cardboard moulds will be used to ensure that the components don’t move during the transportation and thus will not sustain any damage. The rest of exhibit will then be assembled on-site before installation. The installation will be done accordingly to the assembly chart (see Figure 17).

5.12 Requirements Design Table

For description of each ID see section 3.0.

Table 17: Requirements Design Key

| C | Client Requirements |
| F | Functional Requirements |
| S | Safety Requirements |
| M | Material Requirements |
| E | Environmental Requirements |
| H | High Priority |
| N | Medium Priority |
| L | Low Priority |

Table 18: End Effector Design Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Requirement Met By</th>
<th>Engineers Approval</th>
<th>Clients Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>CLAW_F1</td>
<td>Pick Up and Drop Test (see section 5.6.1).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>CLAW_F2</td>
<td>Pick Up and Drop Test (see section 5.6.1).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>CLAW_F3</td>
<td>Pick Up and Drop Test (see section 5.6.1).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CLAW_F4</td>
<td>Open and Close buttons will be connected to an Arduino in the interface.</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
### Table 19: Arm Design Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Requirement Met By</th>
<th>Engineers Approval</th>
<th>Clients Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>ARM_C1</td>
<td>Pick Up and Drop Test (see section 5.6.1).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>ARM_C2</td>
<td>Arm will be located inside the water tank. (See section 5.5.5).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>ARM_F1</td>
<td>Working Area Test (see section 5.6.2).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>ARM_F2</td>
<td>Working Area Test (see section 5.6.2).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>ARM_F3</td>
<td>Working Area Test (see section 5.6.2).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>ARM_F4</td>
<td>Yes, (see section 5.5.8).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>ARM_S1</td>
<td>Yes, met by Sealing Test (see section 5.6.4).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>ARM_M1</td>
<td>Yes, aluminium will be used.</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>ARM_M2</td>
<td>Yes, aluminium will be used.</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>ARM_M3</td>
<td>Yes, aluminium will be used.</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>ARM_M4</td>
<td>Yes, silicone will be used. Met by Sealing Test (see section 5.6.4).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>ARM_M5</td>
<td>Yes, casting process will be used.</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>ARM_E1</td>
<td>Yes, silicone will be used. Met by Sealing Test (see section 5.6.4).</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

### Table 20: Receptacle Design Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Requirement Met By</th>
<th>Engineers Approval</th>
<th>Clients Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>CONT_F1</td>
<td>Receptacle will be 300mm x 200mm and also Contain and Scatter Test (see section 5.6.3).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CONT_F2</td>
<td>Contain and Scatter Test (see section 5.6.3).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>CONT_F3</td>
<td>Contain and Scatter Test (see section 5.6.3).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CONT_F4</td>
<td>Mass Sensor and also Contain and Scatter Test (see section 5.6.3).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>CONT_F5</td>
<td>Mass Sensor and also Contain and Scatter Test (see section 5.6.3).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>CONT_M1</td>
<td>Yes, stainless steel will be used.</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

### Table 21: Water Tank Design Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Requirement Met By</th>
<th>Engineers Approval</th>
<th>Clients Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>TANK_F1</td>
<td>Appropriate water tank will be used (see section 5.5.5).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>TANK_F2</td>
<td>Yes, (see section 5.5.5).</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>TANK_F3</td>
<td>Triangular prisms will be added in front and on around the perimeter of the water tank (see section 5.5.5).</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>
Reinforced glass will be used (see section 5.5.5).

Table 22: Interface Design Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Requirement Met By</th>
<th>Engineers Approval</th>
<th>Clients Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>TANK_M1</td>
<td>Reinforced glass will be used (see section 5.5.5).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>TANK_M2</td>
<td>Reinforced glass will be used (see section 5.5.5).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>INTER_C1</td>
<td>A joystick and buttons will be used. The buttons will have names, arrows and symbols</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>corresponding to the action (see section 5.5.8).</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Also met by Working Area Test (see section 5.6.2).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>INTER_C2</td>
<td>Controls will be made of steel and layered with rubber (see section 5.5.8).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>INTER_F1</td>
<td>A joystick and an Arduino will be used. Also see Working Area Test (see section 5.6.5).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>INTER_F2</td>
<td>Up, down buttons and an Arduino will be used. Also see Input/output Test (see section 5.6.5).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>INTER_F3</td>
<td>Open, close button and an Arduino will be used. Also see Pick Up and Drop Test (see section 5.6.1) and Input/output Test (see section 5.6.5).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>INTER_F4</td>
<td>Interface will be screwed to the ground and an adhesive will be used to attach it to the tank. Also see Interface design (see section 5.5.8).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>INTER_F5</td>
<td>Yes, Interface will be 0.6m from the base.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>INTER_S1</td>
<td>Interface edges will be curved and layered with rubber (see section 5.5.8).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>INTER_S2</td>
<td>All wires and electrical components will be hidden inside the interface (see section 5.5.8). Also met Sealing Test (see section 5.6.4).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 23: General Design Table

<table>
<thead>
<tr>
<th>Priority</th>
<th>ID</th>
<th>Requirement Met By</th>
<th>Engineers Approval</th>
<th>Clients Approval</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>GEN_C1</td>
<td>Yes (see Table 16: Cost Analysis).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>GEN_C2</td>
<td>See Installation Plan 5.11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>GEN_C3</td>
<td>See Manufacturing Plan 5.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>GEN_C4</td>
<td>Appropriate arm will be used (see section 5.5.2).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>GEN_C5</td>
<td>Yes, underwater mural will be painted on false wall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>GEN_C6</td>
<td>Tank will be filled with water and decorated to mimic underwater conditions (Underwater mural will be painted on false wall).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>GEN_S1</td>
<td>Yes (see section 5.5.8).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>GEN_E1</td>
<td>Yes, Non corrosive brass screws will be used.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>GEN_E2</td>
<td>Yes (see section 5.5.5).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.13 Gantt Chart

The Gantt chart below gives a time estimate for the completion of the whole project. The project has been divided into Project Planning, Prototype, Testing, and Manufacturing. The amount of time required to complete different tasks in each stage of the project can also be seen below.
6.0 Conclusion

Through an extensive design process, an optimal design solution was achieved for the Australian Museum “Oceans Explorers” Exhibition. By conducting widespread research on the different types of robotic arms, end effectors and actuators, it was revealed that there were a vast array of designs which needed to be analysed to create a suitable design. Client, environmental and functional requirements were written which provided a foundation for the concept designs to be generated. By dividing the robotic arm exhibit into its subsystems and selecting different design solutions for each subsystem, three concepts were designed. The final design solution was then chosen by comparing each design with a pre-existing benchmark design under a weighted requirements criteria.

The solution consists of an aluminium articulated arm, pneumatically actuated with a three finger end effector. The arm was designed so that children would be able to retrieve sea creature shaped specimens from the floor of a 1.5mx1.5mx1.5m water tank. The water tank will include right angled triangular prisms along the inside perimeter. These prisms will provide the housing for the electrical components as well as preventing any specimens from landing in an area where the arm cannot access. After the children retrieve the specimens, they will place them in a receptacle which was designed with a pump in order to return the specimens into the working area randomly. The interface, placed outside the tank has curved edges which are wrapped in rubber, increasing the safety of the design. The interface also includes a joystick and buttons in order to make the design intuitive for children.

Testing plans were proposed to determine the success of the design and whether it will meet the requirements. A cost analysis has proven that the design is within budget and manufacturing and installation plans have also been developed in order to assist in the development of the exhibit.

The final display designed is easy to manufacture and install while still replicating the actions of robotic arms used on board AUV’s today. The display is highly intuitive, safe and designed for all children to enjoy at the “Ocean’s Explorer” Exhibition.
7.0 Appendix

Appendix A - Force Calculations

Assume that robotic arm position is such that the end effector is at the furthest possible distance from the base where forces and moments will be at its highest.

Simplified version of the arm will be approximated by a rectangle of length 1.2m, width of 0.1m and height of 0.1m. First we need to determine the forces on the specimen.

- Mass of specimen \(m = 500g = 0.5kg\)
- Force due to mass of specimen:
  
  \[
  F_{\text{specimen}} = m \cdot g \\
  = 0.5 \times 9.81 \times \frac{m}{s^2} \\
  = 4.9 N \downarrow
  \]

- At a length of 1.2m stretched, the total volume of the arm:
  
  \[
  V_{\text{arm}} = 1.2m \times 0.1m \times 0.1m = 0.012m^3
  \]

- Density of water \(\rho = 1000 \, kg/m^3\)
- Buoyancy force:
  
  \[
  F_{\text{buoyancy,arm}} = \rho \cdot V \cdot g \\
  = 1000 \frac{kg}{m^3} \times 9.81 \frac{m}{s^2} \times 0.012m^3 \\
  = 117.72N \uparrow
  \]

- Assuming water pressure is negligible
- Given maximum weight of a gripper is 2.8 kg (see Appendix B), the equivalent force is hence:

  \[
  F_{\text{gripper}} = 2.8 \times 9.81 = 27.47N \text{(Refer to 2.1.2)}
  \]
- Hence, the total weight force of the arm can be calculated:

\[ F_{arm} = V_{arm} \times \rho \times g = 0.118\rho \ N \downarrow \]

- Where \( \rho \) is the material selected
- Thus, the total force acting on the base:

\[ R_z = F_{arm} + F_{gripper} - F_{buoyancy,arm} \]

\[ \therefore R_z = 0.118\rho + 27.47 - 117.72 \]

\[ \therefore R_z = 0.118\rho - 90.25 \]

Due to the design of the robotic arm, the actuator closest to the base is required to lift the entire weight of the arm. Hence, the weakest actuator must have a larger lifting force than that of \( R_z \) depending on the material used.

For Aluminium of density 2700 kg/m\(^3\):

![Shear Force Diagram](image-url)
Bending Moment Diagram

For Stainless steel of density 7800 kg/m³:

Shear Force Diagram
Bending Moment Diagram

Bending Moment (N-m)

-487.49

0

0.6

1.2

x (m)
Appendix B - Grippers

**Magnetic Gripper**
- SGM-S70 Magnetic Gripper (SCHMALZ, 2014)
- Max lift force = 290 N
- Weight = 780g

**Electro-servo**
- MEG64 2 finger parallel gripper (Schunk, 2014)
- Max lift force = 175 N
- Weight = 1.42 kg

**Pneumatic Gripper**
- 3 finger JGZ125 pneumatic gripper (Schunk, 2014)
- Max lift force = 3100 N
- Weight = 2.8 kg

Appendix C - Materials

**Aluminium Arm**: Density of aluminium => $p = 2700 \text{ kg/m}^3$

**Polymethyl Methacrylate**: Density of Polymethyl Methacrylate => $p = 1180 \text{ kg/m}^3$

**Stainless Steel**: Density of stainless steel = 7800 kg/m$^3$

**Ceramic**: Density of ceramic = approximately 3000 kg/m$^3$

Appendix D - Actuators

**Pneumatic**
- Stroke High Linear Actuators (Firgelli Automations Australia, 2014)
- Available Speeds range from 3mm/s to 50mm/s
- Available Forces range from 157 N to 1766 N
- Available stroke lengths range from 50mm to 762mm
- Prices range from $100.00 to $150.00

**Hydraulic**
- Linear Actuator (Motion Dynamics Pty Ltd, 2014)
- 50 mm stroke
- 10 mm/s
- 2500 N
- $99.00

**Mechanical**
- Linear Actuator (Motion Dynamics Pty Ltd, 2014)
- 50 mm stroke
- 5 mm/s
- 5000 N
- $99.00

**Electric**
- LA series Electric Actuators (LINAK, 2014)
- Available Speeds range from 3.5mm/s to 160mm/s
- Available Forces range from 400 N to 15,000 N
Appendix E - Arm Calculations

Due to the robotic arm comprising of 3 arm links, each arm link is simplified to a rectangular shape to provide generalised calculations

First we need to determine the forces on the gripper.
- Mass of specimen \( m = 500g = 0.5kg \)
- Force due to mass of specimen:

\[
F_{\text{specimen}} = mgs \\
= 0.5 \times 9.81 \times \frac{m}{s^2} \\
= 4.9 N \downarrow
\]

- Assuming water pressure is negligible
- Given maximum weight of a gripper is 2.8 kg, the equivalent force is hence:

\[
F_{\text{gripper}} = 2.8 \times 9.81 = 27.47N
\]

Force on each actuator can be calculated given the buoyancy force and weight force of each individual section of the arm.
- Density of water \( \rho_w = 1000 \text{ kg/m}^3 \)
- Density of aluminium = 2800 \text{ kg/m}^3

\[
F_{\text{buoyancy,arm}} = \rho_w V g \\
= 1000 \times \frac{kg}{m^3} \times \frac{m}{s^2} \times 9.81 \times 0.012m^3 \\
= 117.72N \uparrow
\]
Arm Number 2:

\[ F_{\text{Actuator}} + \sum F_y = 0 \]

\[ F_{\text{Actuator}} = 27.47 + 109.87 - 39.24 = 98.1 N \]

Shear Force Diagram

Bending Moment Diagram
**Arm Number 3:**

\[ +\uparrow \sum F_y = 0 \]:

\[ F_{\text{Actuator}} = 98.1 + 109.87 - 39.24 = 168.73 \text{N} \]

**Shear Force Diagram**

**Bending Moment Diagram**
Arm Number 4

\[ + \uparrow [\Sigma F_y = 0] : \]

\[ F_{Actuator} = 168.73 + 109.87 - 39.24 = 239.36 \text{N} \]

Shear Force Diagram

Bending Moment Diagram
Appendix F - Shear Calculations

Max shear strength of aluminium before fracture is 124 MPa. Therefore, each section of arm must not exhibit a shear force that exceeds this amount.

Now, Beam Shear is defined as:  \( \tau = \frac{VQ}{It} \)

where  \( Q = 0.025 \times A = 0.025 \times 0.1 \times 0.05 = 0.000125 \)

\[
I = \frac{bh^3}{12} = \frac{0.1 \times 0.1^3}{12} = 8.33 \times 10^{-6} \text{ kg/m}^2
\]

\[ t = \text{thickness} = 0.1 \text{ m} \]

Arm Section 2:
-  \( V = F_{\text{actuator}} = 98.1 \text{ N} \)

So,

\[
\tau = \frac{98.1 \times 0.000125}{(8.33 \times 10^{-6}) \times 0.1} = 0.014721 \text{ MPa}
\]

This is less than the max shear strength value of aluminium and thus, fracture will not occur.

Arm Section 3:
-  \( V = F_{\text{actuator}} = 169.13 \text{ N} \)

So,

\[
\tau = \frac{169.13 \times 0.000125}{(8.33 \times 10^{-6}) \times 0.1} = 0.025380 \text{ MPa}
\]

This is less than the max shear strength value of aluminium and thus, fracture will not occur.

Arm Section 4:
-  \( V = F_{\text{actuator}} = 239.76 \text{ N} \)

So,

\[
\tau = \frac{239.76 \times 0.000125}{(8.33 \times 10^{-6}) \times 0.1} = 0.035978 \text{ MPa}
\]

This is less than the max shear strength value of aluminium and thus, fracture will not occur.
Appendix G - Factor of Safety Calculations

General recommended Factor of Safety for safe operation of reliable materials where loading and environmental conditions are not severe but weight is an important consideration is greater than 1.3 (EngineeringToolbox).

Factor of Safety is defined as:

\[
FOS = \frac{\text{Maximum Allowable Stress}}{\text{Shear Stress}}
\]

Material used throughout robotic arm is Aluminium Alloy 2024 with a material strength of 75.8 MPa (see section 3.1).

Overall, shear stress upon section 4 of the arm = 35978 Pa

Therefore,

\[
FOS = \frac{75.8 \times 10^6}{35978} = 2107
\]

It can be seen that the FOS is much greater than the minimum required FOS and therefore is safe to operate.

Appendix H - Electric Servo Calculations

As we have only calculated the mass of the 3 arms and end-effector to be 239.36N (Appendix A), to calculate the total mass of the arm assembly which the servo will sit under, the mass of the base must be calculated:

Given the density of the base: 2800kg/m^3

And the volume of the base: \[V_{base} = \pi r^2 h = \pi \times 0.2^2 \times 0.05 = 0.0063 \text{ m}^3\]

Hence, the mass of the base is: \[m = 0.0063 \times 2800 = 17.64 \text{ kg}\]

Or \[F_{base} = 17.64 \times 9.81 = 173.05N\]

Thus, total mass of the arm assembly can be given as:

\[F_{Total \ mass} = 173.05 + 239.36 = 412.41N\]

Once total mass is determined, the minimum toque that the servo must be rated for can also be calculated;

\[\tau = F_{Total \ mass} \times radius \ of \ base = 412.41 \times 0.2 = 82.48Nm\]
Appendix I - Arm Length Calculations

The max allowable stretch length of arm is 0.75 m (half of tank diameter 1.5 m). As a result, the actuators must be placed at specific angles between each link in order to ensure that the sum of each link at max stroke length is below 0.75 m.

- Actuators max stroke length = 0.06 m
- Link 4 = Link 3 = Link 3 = 0.3 m
- Let Link 4 = L1 = 0.3 m
- We require L3 < 0.75 m
- Assume angle required = 40 degrees

Proof that angle will work:

- Actuator is parallel to L2

\[
\frac{L2}{\sin 100} = \frac{0.3}{\sin 40}
\]

\[
L2 = 0.46 \text{ m}
\]
Assume angle between L1 and L2 = 135 degrees

\[
L_3^2 = L_2^2 + L_1^2 - 2(L_2)(L_1)\cos 135
\]

\[
L_3^2 = 0.46^2 + 0.3^2 - 2(0.46)(0.3)\cos 135
\]

\[
L_3 = 0.7 \text{m}
\]

Thus, max stretch length of entire arm is 0.7 and is below max length
Appendix J - Engineering Drawings

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<td>ARM LINK 1</td>
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</tr>
<tr>
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<td>ARM LINK 2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
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<td>6</td>
<td>USER INTERFACE</td>
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<td>8</td>
<td>PRISMS</td>
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SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING - UNSW

DIMENSION IN MILLIMETRES

DO NOT SCALE

SURFACE FINISH UNLESS NOTED OTHERWISE

TOLERANCE UNLESS NOTED OTHERWISE

DRAWN BY DANIEL I. ZHU
CHECKED BY JASON KOONG
APPROVED BY KELLY CHEN

TITLE ASSEMBLY DRAWING
DRAWING NUMBER 10
FIRST RELEASE DATE 15/10/2014

QTY 1 MATL 20:1 SCALE 2 REV 2 DATE 2/11/2014

A4
SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING - UNSW

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DIMENSION IN MILLIMETRES
DO NOT SCALE
TOLERANCE UNLESS NOTED OTHERWISE

SURFACE FINISH UNLESS NOTED OTHERWISE

DRAWN BY DANIEL I. ZHU
CHECKED BY ALVIN CHUNG
APPROVED BY JASON KOONG

TITLE ROBOTIC ARM
DRAWING NUMBER 8
FIRST RELEASE DATE 13/10/2014
QTY 1 MATL SCALE 10:1
REV 1 DATE 13/10/2014

A4 69
SIDE VIEW

ISOMETRIC VIEW

FRONT VIEW

TOP VIEW
Appendix K – JGZ-125 End Effector Brochure

JGZ

Pneumatic • 3-Finger Centric Gripper • Universal Gripper

- Sizes: 40 ... 160
- Weight: 0.12 kg ... 0.8 kg
- Gripping force: 255 N ... 8400 N
- Stroke per finger: 2.5 mm ... 16 mm
- Workpiece weight: 125 kg ... 300 kg

Application example

1. 3-Finger Centric Gripper JGZ with workpiece-specific gripper fingers
2. 6-axis force/torque sensor FTX/050-03

Tactile assembly of insertion aids in cylinder heads
Universal Gripper
universal 3-Finger Concentric Gripper of the compact class with T-slot guidance and best cost-performance ratio

Field of application
Optimum standard solution for many fields of application. Universal application in clean and slightly dirty surroundings in machine building and plant building industry, assembly and handling as well as automotive industry.

Your advantages and benefits
A firm focuses on the essentials
for maximum profitability
Sturdy T-slot guidance
for precise handling of all kinds of workpieces
Compact dimensions and low weight
for minimal interfering contours in handling
High maximum moments possible
suitable for using long gripper fingers
Wedge-lock design
for high-power transmission and synchronized gripping
Comprehensive accessory accessories
for interrogation and control of the stroke position
Fastening at one gripper side in two screw directions
for universal and flexible gripper assembly
Air supply via hose-free direct connection or screw connections
for the flexible supply of compressed air in all automation systems

General notes to the series
Principle of function
Wedge-lock kinematics
Housing material
Aluminium alloy, hardened
Base jaw material
Steel
Actuation
pneumatic, with triaxial compressed air (10 bar), dry, lubricated or non-lubricated
Maximum pressure: Required quality class of compressed air according to
DIN ISO 8573-1: 6-4-1

Warranty
24 months (details, general terms and conditions and operation manuals can be downloaded under www.schunk.com)

Scope of delivery
Brackets for proximity switches, springing sleeves, unions for direct connection, assembly and operating manual with manufacturer's declaration

Gripping force maintenance device
with other mechanical gripping force maintenance or SEP-P pressure maintenance valve
Sectional diagram

1. Housing
   - Weight-optimized through application of heat-treated, high-strength aluminum alloy

2. T-slot guide
   - Hookable, robust back jaw guidance for extremely long gripper fingers

3. Wedge-boost design
   - For high power transmission and centric gripping

4. Base jaw
   - For the connection of workpiece-specific gripper fingers

5. Sensor system
   - Proximity switch can be assembled without mounting kit

Functional description
The gripper is moved up and down by compressed air. Through the angled active surfaces, the wedge boost transforms this movement into the lateral, synchronous gripping movement of both base jaws.

Options and special information
The JGZ series is especially suitable for economic handling solutions and distinguishes by its high cost-benefit ratio.

www.schunk.com
Accessories

- Tolerance compensation unit
- Compensation unit
- Magnetic switches
- Inductive proximity switches
- Universal intermediate jaw
- Quick-change Jaw System
- Pressure maintenance valve
- Finger blanks
- Force measuring jaws
- Analog position sensor

For the exact size of the required accessories, costability of this size and the designation and Bl., please refer to the additional notes at the end of the size in question. You will find more detailed information on our accesso...in the "Accessories" catalog section.

General note to the series

Gripping force
The arithmetical total of the gripping force applied to each finger at distance y (see illustration) measured from the upper edge of the gripper.

Finger length
The finger length is measured from the upper edge of the gripper housing in the direction of the main axis.

Repeat accuracy
is defined as the spread of the limit position after 100 consecutive strokes.

Workpiece weight
The recommended workpiece weight is calculated for a force-type connection with a coefficient of friction of 0.1 and a safety factor of 2 against slippage of the workpiece on acceleration due to gravity g. Considerable heavier workpiece weights are permitted with firm-fit gripping.

Closing and opening times
Closing and opening times are purely the times that the base jaw or fingers are in motion. Valve switching times, hose filling times or PLC reaction times are not included in the above times and must be taken into consideration when determining cycle times.

www.schunk.com
8.0 References


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<tr>
<th>No.</th>
<th>Source</th>
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</table>
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