



**UTS**

**UNIVERSITY  
OF TECHNOLOGY  
SYDNEY**



Faculty of Engineering & Information Technology

## **Developing a robotic arm for space applications**

A research submitted for industry representatives in space robotics field

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**UTS**

**UNIVERSITY  
OF TECHNOLOGY  
SYDNEY**

Faculty of Engineering & Information Technology (FEIT)

**Developing a robotic arm for space applications**

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# CERTIFICATE

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This research has been written by me. Any help that I have received in my research work and the preparation of the research itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the research.

Signature of Researcher:

Production Note:

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**Date:** 13 May 2023

# Acknowledgements

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

فَإِنَّ مَعَ الْعُسْرِ يُسْرًا (٥) إِنَّ مَعَ الْعُسْرِ يُسْرًا (٦) (سورة الشرح)

For indeed, with hardship {will be} ease (5). Indeed, with hardship {will be} ease (6).

{Quran, The Soothing/ash-Sharh 94}

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# Abstract

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This industry research describes a robotics control system development with a new techniques for robotic arm in space environment. It will be used by Sperospace company. This technique involves designing a control system for a robotics arm.

Sperospace is developing robotic arms for satellites which enable on orbit servicing. Controlling these six degrees of freedom robotic arms semi-autonomously via sensor feedback is a complex control task. This is especially the case when accuracy and safety must be maximised due to the danger of conducting proximity operations in space.

The software, firmware, control algorithms and skills development needed to conduct these operations will be the focus of this secondment.

**Keywords** — Model-Based Design; Optimal control; Rapid Prototyping; Robotics Arm; Simulation; Space industry;

# Contents

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<b>CERTIFICATE.....</b>	<b>I</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>II</b>
<b>ABSTRACT.....</b>	<b>IV</b>
<b>CONTENTS.....</b>	<b>V</b>
<b>LIST OF FIGURES .....</b>	<b>VII</b>
<b>LIST OF TABLES .....</b>	<b>VIII</b>
<b>ACRONYMS AND ABBREVIATIONS.....</b>	<b>IX</b>
<b>1 INTRODUCTION.....</b>	<b>1</b>
1.1 Statement.....	1
1.2 Objectives .....	1
1.3 Scope.....	3
1.4 Methodology and Approach .....	4
1.5 Outline of the research .....	6
<b>2 LITERATURE REVIEW .....</b>	<b>9</b>
2.1 Overview of existing robotic arms for space applications.....	9
2.1.1 Requirements for Robotic Arms for Space Applications .....	11
2.1.2 Challenges in the Development of Robotic Arm for Space Applications .....	12
2.1.3 Future of Robotic Arms for Space Applications.....	12
2.1.4 Types of Robotic Arms for Space Applications .....	13
2.1.5 Challenges of Using Robotic Arms in Space.....	14
2.2 Australian Space industry .....	14
2.3 Review of relevant research on control systems and electronics for robotic arms ..	15
<b>3 REQUIREMENTS AND DESIGN.....</b>	<b>18</b>
3.1 Whole System Requirements .....	18
3.2 The overall structure of the model .....	19
3.3 Mission.....	20
3.4 Prototype 1 overview .....	21
3.5 Prototype 2 requirements .....	22
3.5.1 Functional Requirements .....	22
3.5.2 Non-Functional Requirements .....	23
3.5.3 Constraints .....	23
3.6 Mechanical Structure .....	24
3.6.1 Assembly.....	24
3.6.2 Functionality .....	26
3.6.3 Actuator.....	27
3.6.4 Motor.....	28
3.6.5 Strain Wave Gear .....	28
3.6.6 Joint structure.....	29
3.6.7 Mechanical manufacturing.....	30
3.7 Mechatronic System Structure .....	31
3.7.1 Drive System.....	31
3.7.2 Control Unit .....	31
3.7.3 Wiring .....	32
3.7.4 Software Design.....	32
3.8 Control unit specifications .....	33
3.9 Chosen Design Architecture .....	34
3.9.1 Block Diagram .....	35

3.10	Robotic arm Software Architecture .....	35
3.10.1	Considerations.....	35
3.10.2	Design Overview .....	36
3.10.3	Application Programming Interface .....	37
3.11	Systems Design processes.....	37
3.12	Motor specifications.....	38
<b>4</b>	<b>CONTROL SYSTEM MODEL DESIGN .....</b>	<b>40</b>
4.1	Control unit interfaces.....	41
4.1.1	Real-time.....	41
4.2	Communications peripherals .....	43
4.3	Inverse Kinematics.....	44
4.4	Conclusion .....	48
<b>5</b>	<b>IMPLEMENTATION AND TESTING .....</b>	<b>49</b>
5.1	Discussion modelling phase.....	50
5.2	Motor vacuum and vibration tests.....	53
5.2.1	Aim .....	53
5.2.2	Method .....	54
5.2.3	Results.....	55
5.2.4	Discussion .....	56
5.3	Challenges or issues encountered .....	58
5.4	Passed test cases.....	60
5.5	Conclusion .....	61
<b>6</b>	<b>RESEARCH CONCLUSIONS .....</b>	<b>63</b>
6.1	Contributions.....	63
6.2	Future research.....	64
6.2.1	Design consideration for the stowed position.....	64
6.2.2	Include sensors and cameras in the chassis design .....	64
6.2.3	Explore second stage/compound gearing.....	65
6.2.4	Arm thermals should be considered.....	65
6.2.5	Explore the design of separating the Harmonic Drive and motor .....	66
Appendix A : URL .....		67
A.1	Research softcopy .....	67
A.2	Presentation.....	67
A.3	Lab videos and photos .....	67
Appendix B : Technical.....		68
B.1	Control unit .....	68
B.2	Vacuum .....	68
Appendix C : Completion Letter .....		70



# List of figures

---

Figure 1-1: System Architecture .....	6
Figure 3-1: Schematic of the robotics arm and payloads integrated on the host satellite.....	20
Figure 3-2: Prototype one .....	22
Figure 3-3: Diagram of Potential TRL6 prototype arm .....	26
Figure 3-4: Exploded view of the actuator .....	27
Figure 3-5: Section view of the arm joint .....	29
Figure 3-6: Joint Architecture .....	30
Figure 3-7: Mechanical structure of robotic arm .....	31
Figure 3-8: Software Architecture .....	33
Figure 3-9: Software design architecture .....	34
Figure 3-10: Block diagram of robotic arm Control System .....	35
Figure 3-11: Control module high-level overview with communication protocols. ....	36
Figure 3-12: Simple block diagram of software architecture for a robotic arm. ....	37
Figure 3-13: Motor Architecture.....	38
Figure 3-14: Tested motor. ....	39
Figure 4-1: Control unit interfaces.....	41
Figure 4-2: Software interfaces.....	42
Figure 4-3: Motors interfaces.....	43
Figure 4-4: Software Flowchart. ....	44
Figure 4-5: Inverse kinematics simulation.....	46
Figure 5-1: Control System Interface. ....	52
Figure 5-2: Testing joint Torque.....	53
Figure 5-3: Accelerometer measurements for peak acceleration tests of motor.....	54
Figure 5-4: Accelerometer measurements for sinusoidal vibration tests of motor .....	54
Figure 5-5: (left) Motor with torque arm positioned in vacuum chamber (right) pressure gauge reading at vacuum. ....	55
Figure 5-6: Torque Current.....	56
Figure 5-7: Space robotic arm.....	60
Figure 6-1: Torque Current. <a href="#">Link</a> .....	66

# List of tables

---

Table 3-1: Prototypes Specifications .....	20
Table 3-2: Functional Requirements.....	22
Table 3-3: Non-Functional Requirements .....	23
Table 3-4: Constraints.....	23
Table 3-5: Control unit Specifications.....	33

# Acronyms and abbreviations

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ACG	Auto code generation
ADC	Analog to digital converter
BLDC	Brushless dc electric motor
CAN	Control area network protocol
DAC	Digital to analog converter
DAI	Data acquisition interface
DCT	Dual-clutch transmissions
DOF	Degree-of-freedom
ECU	Engine control unit
EM	Electric machine
EMC	Energy management controller
HIL	Hardware-in-the-loop
I/O	Digital inputs and outputs
PC	Personal computer
PID	Proportional–integral–derivative
PM	Permanent magnet motor
PMSM	Permanent magnet synchronous motor
PWM	Pulse width modulation
RPM/rpm	Revolutions per minute
RTI	The real-time interface
RTP	Real-time processor unit
SIL	Software-in-the-loop

# 1 Introduction

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Sperospace is developing robotic arms for satellites which enable on-orbit servicing. Controlling these six degrees of freedom robotic arms semi-autonomously via sensor feedback is a complex control task. This is especially the case when accuracy and safety must be maximised due to the danger of conducting proximity operations in space.

The control algorithms and skills development needed to conduct these operations will be the focus of this secondment.

## 1.1 Statement

In the space industry, robotic arms have become an essential tool for a wide range of applications, from assembling and maintaining spacecraft to performing scientific experiments and exploration on celestial bodies. With the increasing demand for satellite servicing and space exploration missions, the development of advanced robotic arms capable of operating in extreme environments has become a key priority for the industry. This report aims to contribute to this effort by presenting the design and development of a robotic arm optimised for space applications, with a focus on its potential to enhance the efficiency and safety of satellite operations.

## 1.2 Objectives

The Sperospace project aims to design and develop a robotic arm optimised for use in the space industry, with a focus on enhancing the efficiency and safety of satellite operations. The main objectives of the project include the development of a control system that enables the reliable and safe operation of the robotic arm in space, incorporating mapping algorithms and coordinate control mechanisms to ensure efficient and accurate movement and positioning of payloads and tools. Another key objective is the implementation of fail-safe mechanisms and anomaly detection systems into the control system to ensure the safety of the robotic arm during

## Introduction

operation. Additionally, the project aims to design the robotic arm to be capable of holding a payload of 2 kg in a 1 G environment and to have a reach of 1m from the base in the Z direction. To achieve these objectives, the project team will also develop suitable locations for mounting internal and external sensors, integrate the controller with different software, and ensure the control system is easy to operate, test, maintain, and modify. Through these objectives, the Sperospace project seeks to make a significant contribution to the development of advanced robotic arms for space applications.

- To design and develop a robotic arm prototype that meets the specified performance criteria for use in the space environment.
- To implement a control system that enables the reliable and safe operation of the robotic arm in space, with suitable options for controlling and monitoring motor drives and integrating with sensors.
- To develop mapping algorithms and coordinate control mechanisms for the robotic arm that enable efficient and accurate movement and positioning of payloads and tools in space.
- To incorporate fail-safe mechanisms and anomaly detection systems into the control system to ensure the safe and reliable operation of the robotic arm.
- To evaluate the performance of the robotic arm and control system through simulations and physical tests, and demonstrate its usefulness for customers in the space industry.
- To document the design, development, and testing processes of the robotic arm and control system in a clear and concise manner, and provide recommendations for future improvements and modifications.

This report will specifically examine the supervisor control unit of the robotic arm, particularly the electronics part of the mechatronics system. The main objectives of this research include the development of a high-performance integrated controller that executes real-time

## Introduction

applications and task control, communication with peripherals, and monitoring and control of motor drive power consumption. The control system must also include fail-safe mechanisms and anomaly detection systems to ensure the safe and reliable operation of the robotic arm. Additionally, the research will focus on integrating the controller with different software, such as C, C++, and Simulink Embedded Coder Control, and designing the control system software to be easy to maintain and modify. Through these objectives, this research seeks to make a significant contribution to the development of a supervisor control unit for advanced robotic arms optimised for space applications.

The outcomes of this industry research includes:

- Upskilling: Dr Mohamed will upskill two mechatronics engineers in the software and programming skills needed to develop a control system for Sperospace's robotic arm.
- Completion of a TRL6 level control system that includes positional and speed control of all 6 actuators on the robotic arm.
- Completion of software required for sensor integration and automated feedback to the control system.

### 1.3 Scope

This industry research is focused on developing an industry control prototyping for a robotic arm that can function in the space environment. The requirements are as follows:

- Demonstratable and useful results for customers.
- Suitable control options for robotic operations in space
- The robotic arm must have suitable locations to mount internal and external sensors.
- The robotic arm must be able to hold a payload of 2 kg in a 1 G environment.
- The robotic arm must have a reach of 1m from the base in the Z direction.

## Introduction

- The control system should be used mapping algorithms.
- The control system should include fail-safe mechanisms and anomaly detection systems.
- The control system should accept spatial coordinates to control all motor drives.
- Containing a processor that executes Real-Time applications and task control, and communication with peripherals.
- The control system should be able to monitor and control motor drive power consumption during operation.
- The control system shall be easy to operate and test.
- The control system shall integrate the controller with different software (C, C++, and Simulink Embedded coder control).
- The control system software shall be easy to maintain and modify.
- The control system shall utilise a high-performance integrated controller

## 1.4 Methodology and Approach

This research will follow a design-build-test methodology to develop a prototype of a robotic arm suitable for space applications. The approach will include the following steps:

- **Requirements Analysis:** We will define the requirements and specifications for the robotic arm based on the needs of potential customers and relevant industry standards.
- **Design:** We will use a mechatronic design approach to develop the mechanical and electronic components of the robotic arm. This will include selecting suitable materials, motors, sensors, and controllers, and designing the system to meet the requirements.
- **Control System Design:** We will develop a control system for the robotic arm that incorporates mapping algorithms, fail-safe mechanisms, and anomaly detection

## Introduction

systems. We will use software tools such as C, C++, and Simulink Embedded Coder to implement the control system.

- **Implementation:** We will build a prototype of the robotic arm and control system, and integrate the different components. We will use industry-standard techniques for assembling and testing the system.
- **Testing:** We will perform a series of tests on the robotic arm and control system to verify that they meet the requirements and perform as expected. This will include testing the performance of the arm under different loads and environmental conditions.
- **Analysis and Evaluation:** We will analyse the test results to evaluate the performance of the robotic arm and control system. We will also compare our results to existing solutions in the industry.
- **Documentation and Reporting:** We will document the design, implementation, and testing of the robotic arm and control system, and prepare a report that presents the results and conclusions of the research.



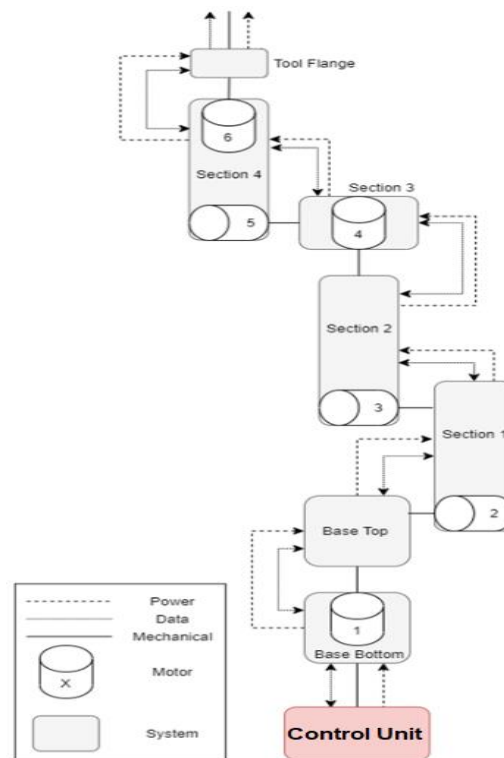


Figure 1-1: System Architecture

## 1.5 Outline of the research

Detailed modelling and analysis methods in this research are introduced to sufficiently represent the control unit and component dynamics to aid the reader in their understanding of the procedures applied and provide clarity and continuity of research. This research is divided into chapters. The contents of the chapters are subdivided into subsections to maintain the flow of the chapters. The main topics of each chapter are introduced in the following sections.

### Chapter 2

In the case of developing a robotic arm for space applications, the literature review should cover topics such as the history and development of robotic arms, the current state-of-the-art technology, and the challenges and limitations of operating a robotic arm in space. It should also examine the various types of control systems used in robotic arms, including feedback control, trajectory planning, and force control. Additionally, the literature review will explore

## Introduction

the use of sensors in robotic arm and how they are used to control the arm's movement and actions.

- Overview of existing robotic arm for space applications
- Review of relevant research on control systems and electronics for robotic arm
- Discussion of relevant standards and regulations for space applications

## Chapter 3

This chapter provides the framework for the research of this research. Initially, it provides an introduction to the problem in addition to background information. This is followed by a detailed system architecture

- A detailed description of the robotic arm design
- Discussion of the requirements and specifications for the robotic arm
- Discussion of the design choices made to meet the requirements.

## Chapter 4

This chapter will define the control system design

- Overview of the control system design approach
- Discussion of the mapping algorithms used in the control system
- Discussion of the fail-safe mechanisms and anomaly detection systems used
- Description of the integration of different software (C, C++, and Simulink Embedded coder control) in the control system
- Discussion of the real-time task control, communication with peripherals, and motor drive power consumption monitoring and control

## Chapter 5

## Introduction

The overview of the development is discussed. The power flow management under various drive conditions is explained in this chapter.

- Description of the implementation of the robotic arm and control system
- Discussion of the testing approach and results
- Discussion of any challenges or issues encountered during implementation and testing

## Chapter 6

The concluding chapter reviews and summarises this research with a general summary of the contributions of each of the previous chapters, presenting significant and novel results of this research as well as identifying the important areas for further research.

- Summary of the project objectives and scope
- Discussion of the contributions of the research
- Evaluation of the success of the project
- Suggestions for future research and improvements

## 2 Literature Review

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In the context of developing a robotic arm for space applications, the literature review plays an essential role in understanding the current state-of-the-art technology, challenges, and limitations of operating a robotic arm in space. The literature review should cover topics such as the history and development of robotic arms, the various types of control systems used in robotic arms, including feedback control, trajectory planning, and force control, and the use of sensors in robotic arm.

### 2.1 Overview of existing robotic arms for space applications

Robotic arms have been used in space applications for decades. They are used for a variety of tasks, including assembly and construction of space structures, repair and maintenance of satellites and other spacecraft, sample retrieval from space objects, extravehicular activity (EVA) support, and scientific research.

There are a number of robotic arms that are currently in use for space applications. These arms are used for a variety of tasks, including:

- Assembly and construction of space structures.
- Repair and maintenance of satellites and other spacecraft.
- Sample retrieval from space objects.
- Extravehicular activity (EVA) support.
- Scientific research.

Some of the most well-known robotic arms for space applications include:

- The Space Shuttle Remote Manipulator System (SSRMS).
- The European Robotic Arm (ERA).
- The Japanese Experiment Module Remote Manipulator System (JEMRMS).
- The Canadarm2.

## Literature Review

- The Robonaut.

The SSRMS is the most powerful and versatile robotic arm in space. It is used for a wide range of tasks on the International Space Station (ISS), including:

- Assembly of the ISS.
- Repair and maintenance of the ISS.
- Sample retrieval from space objects.
- EVA support.
- Scientific research.

The ERA is a robotic arm that was developed by the European Space Agency (ESA). It is used on the ISS for a variety of tasks, including:

- Assembly of the ISS.
- Repair and maintenance of the ISS.
- Sample retrieval from space objects.
- EVA support.
- Scientific research.

The JEMRMS is a robotic arm that was developed by the Japanese Aerospace Exploration Agency (JAXA). It is used on the ISS for a variety of tasks, including:

- Assembly of the ISS.
- Repair and maintenance of the ISS.
- Sample retrieval from space objects.
- EVA support.
- Scientific research.

The Canadarm2 is a robotic arm that was developed by the Canadian Space Agency (CSA). It is used on the ISS for a variety of tasks, including:

## Literature Review

- Assembly of the ISS.
- Repair and maintenance of the ISS.
- Sample retrieval from space objects.
- EVA support.
- Scientific research.

The Robonaut is a humanoid robot that was developed by NASA. It is designed to assist astronauts with EVA tasks, such as repairing and maintaining the ISS. The Robonaut is still under development, but it has already been used on the ISS to perform a variety of tasks, including:

- Cleaning and inspecting the ISS.
- Moving objects around the ISS.
- Assisting astronauts with EVA tasks.

These are just a few of the robotic arms that are currently in use for space applications. As technology continues to advance, we can expect to see even more sophisticated and capable robotic arms being developed in the future.

### **2.1.1 Requirements for Robotic Arms for Space Applications**

Robotic arms for space applications must meet a number of stringent requirements. These requirements include:

- The ability to operate in a vacuum.
- The ability to withstand extreme temperatures.
- The ability to operate in a hostile environment.
- The ability to be remotely controlled.
- The ability to perform a variety of tasks.

### **2.1.2 Challenges in the Development of Robotic Arm for Space Applications**

There are a number of challenges in the development of robotic arms for space applications.

These challenges include:

- The high cost of development and deployment.
- The complexity of design and operation.
- The risk of failure in a critical situation.
- The need for international cooperation.

### **2.1.3 Future of Robotic Arms for Space Applications**

The future of robotic arms for space applications is bright. As technology continues to advance, we can expect to see even more sophisticated and capable robotic arms being developed in the future. These arms will play an increasingly important role in space exploration and development.

Some of the potential future applications of robotic arms in space include:

- Construction of large space structures, such as space telescopes and space stations.
- Repair and maintenance of satellites and other spacecraft.
- Sample retrieval from space objects.
- Extravehicular activity (EVA) support.
- Scientific research.

Robotic arms have the potential to revolutionize space exploration and development. They can help us to explore new worlds, build new structures, and conduct scientific research in ways that were previously impossible. As technology continues to advance, we can expect to see even more amazing things being accomplished with robotic arms in space.

## Literature Review

The control system design of a space robotic arm is critical for achieving precise and reliable operation in various space applications. Space robotic arms are used to perform a range of tasks, such as repairing and servicing spacecraft, capturing and manipulating payloads, and deploying and maintaining space infrastructure. The design of a control system for a space robotic arm involves integrating different components, such as sensors, actuators, and controllers, to achieve the desired performance.

### **2.1.4 Types of Robotic Arms for Space Applications**

There are two main types of robotic arms for space applications:

- Teleoperated robotic arms are controlled by astronauts on Earth.
- Autonomous robotic arms can operate without human intervention.

Teleoperated robotic arms are the most common type of robotic arm used in space. They are used for a variety of tasks, including assembly and construction of space structures, repair and maintenance of satellites and other spacecraft, sample retrieval from space objects, and extravehicular activity (EVA) support.

Autonomous robotic arms are becoming increasingly common in space applications. They are used for a variety of tasks, including inspection and maintenance of space structures, sample retrieval from space objects, and scientific research.

#### Benefits of Using robotic arms in Space

There are a number of benefits to using robotic arms in space. These benefits include:

- Increased safety. Robotic arms can perform tasks that are too dangerous or difficult for astronauts to do themselves.



## Literature Review

- Increased efficiency. Robotic arms can perform tasks more quickly and efficiently than astronauts can.
- Reduced cost. Robotic arms can reduce the cost of space missions by eliminating the need to send astronauts on EVAs.

### **2.1.5 Challenges of Using Robotic Arms in Space**

There are a number of challenges to using robotic arms in space. These challenges include:

- The harsh environment. Space is a harsh environment that can damage robotic arms.
- The lack of gravity. The lack of gravity can make it difficult to control robotic arms.
- The need for precision. Robotic arms must be very precise in order to perform tasks in space.

## **2.2 Australian Space industry**

The Australian space industry is growing rapidly and is expected to be worth A\$12 billion per annum by 2030. The sector is already contributing significantly to the Australian economy, generating A\$5.7 billion in revenue in 2020 and supporting 15,234 jobs.

The Australian space industry is competitive and innovative, with a strong track record of success. Australian companies are involved in a wide range of space activities, including satellite manufacturing, launch services, ground station operations, and space data analytics.

The Australian government is supportive of the space industry and has a number of initiatives in place to help it grow. These initiatives include the Space Infrastructure Fund, the International Space Investment – Expand Capability Grants, and the Australian Space Agency.

The Australian space industry is well-positioned to continue to grow in the coming years. The sector is benefiting from a number of positive trends, including the falling cost of launch, the increasing demand for space-based services, and the growing importance of space data.

## Literature Review

Here are some of the key developments that are driving the growth of the Australian space industry:

- **Falling launch costs:** The cost of launching satellites into space has been declining in recent years, making it more affordable for businesses and governments to access space-based services.
- **Increasing demand for space-based services:** The demand for space-based services is growing, as businesses and governments look to space to provide solutions for a range of challenges, such as climate change, disaster management, and resource exploration.
- **The growing importance of space data:** Space data is becoming increasingly important for a range of applications, such as agriculture, environmental monitoring, and urban planning.

The Australian space industry is well-positioned to capitalize on these trends and continue to grow in the coming years. The sector has a strong track record of innovation and is supported by a number of government initiatives. As the global space industry continues to grow, Australia is well-placed to become a leading player in this exciting and rapidly growing field.

### **2.3 Review of relevant research on control systems and electronics for robotic arms**

The control system is responsible for moving the robotic arm to the desired position and orientation. There are two main types of control systems used in robotic arms: open-loop and closed-loop.

Open-loop control systems do not use feedback to adjust the motion of the arm. This type of control system is simple and inexpensive, but it is not very accurate. Closed-loop control systems use feedback to adjust the motion of the arm. This type of control system is more accurate and complex, but it is also more expensive.

## Literature Review

The most common type of closed-loop control system used in robotic arms is the proportional-integral-derivative (PID) controller. The PID controller uses three terms to calculate the error between the desired position and the actual position of the arm:

- Proportional term: This term is proportional to the error. The larger the error, the larger the proportional term.
- Integral term: This term is proportional to the integral of the error. The integral term helps to reduce steady-state errors.
- Derivative term: This term is proportional to the derivative of the error. The derivative term helps to reduce oscillations.
- Electronics

The electronics for a robotic arm are responsible for powering the arm and controlling the motors. The most common type of motor used in robotic arms is the DC motor. DC motors are relatively inexpensive and easy to control.

The electronics for a robotic arm also include sensors. Sensors are used to measure the position, velocity, and acceleration of the arm. This information is used by the control system to move the arm to the desired position and orientation.

Some of the most common sensors used in robotic arms include:

- Position sensors: These sensors measure the position of the arm.
- Velocity sensors: These sensors measure the velocity of the arm.
- Acceleration sensors: These sensors measure the acceleration of the arm.

The control system and electronics for a robotic arm are essential for the arm to function properly. The control system allows the arm to move to the desired position and orientation, and the electronics provide the power and control for the motors.

## Literature Review

In addition to the control system and electronics, there are a number of other factors that need to be considered when designing a robotic arm for space applications. These factors include:

- **Weight:** The weight of the arm must be minimised to reduce the amount of fuel required to launch the arm into space.
- **Durability:** The arm must be able to withstand the harsh environment of space, including extreme temperatures, radiation, and microgravity.
- **Reliability:** The arm must be reliable and able to perform its tasks without failure.

The design of a robotic arm for space applications is a complex challenge. However, by carefully considering the factors mentioned above, it is possible to design an arm that is capable of performing its tasks in the harsh environment of space.

## 3 Requirements and Design

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When developing a system architecture that is cheap to manufacture with elevated levels of customisation, several options must be considered, and the cost-effectiveness must be balanced against the performance criteria required.

The robot arm and control system were developed separately in distinct teams, the mechanical team (robot arm) and the mechatronics team (control system). There was constant communication between these two teams as requirements often overlapped, and neither system could progress far without understanding the state of the other.

The choice for separate teams allowed for faster and higher quality development, as even during the mechanical design stage of the robotic arm, the mechatronics team could determine crucial factors and requirements to be covered by the mechanical system, an example of this is the choice to go to a 7-degree-of-freedom robot arm with continuous rotation at each joint, which requires the design and integration of more parts and components.

Once the mechanical structure had been fully manufactured and preliminary testing has been conducted, the control systems that had been developed could start integration. Integration took a couple of weeks, and it resulted in a mostly articulable robot arm.

### 3.1 Whole System Requirements

The project aims to develop a robotic arm for satellite servicing, with the system demonstrated via the Robotics Satellite Demonstration Mission.

The system consists of five subsystems.

- Robotic arm: 6 degrees of freedom and 1 m of reach
- End Effector: parallel gripper
- Control System: Computer and microcontrollers

## Requirements and Design

- Dummy Satellite: deployable 2U CubeSat with tether and magnetorquer
- Self-Service Payload: 1U CubeSat with testable fasteners
- Host Satellite: 200 kg deployment vehicle

For convenience, the project refers to the grouping of the robotic arm and End Effector subsystems. Test Payloads refer to the grouping of the Dummy Satellite and Self Service Payload subsystems.

The Host Satellite will be launched into low earth orbit (LEO) of less than 350 km to limit the risk of space debris risk. At an agreed time after launch and early orbit phase (LEOP) activities and other external duties are complete, the robotics arm will demonstrate the following capabilities:

- Maintenance - by tightening and loosening fasteners on the Self Service Payload
- Docking - by tracking, grabbing and manipulating the deployed, floating Dummy Satellite

The mass budget is 19.98 kg, allowing a 50 % margin on the current system mass. Autonomous tasks with manual stop-go commands will address limited power and data periods during the 90-minute orbit.

### **3.2 The overall structure of the model**

In addition to this, the lightweight and simple structure, as well as the easy and cheap availability of parts in Australia made this robotic choice appropriate as a basis for the later development of the physical prototype. It was expected to be substantially simpler to modify it.

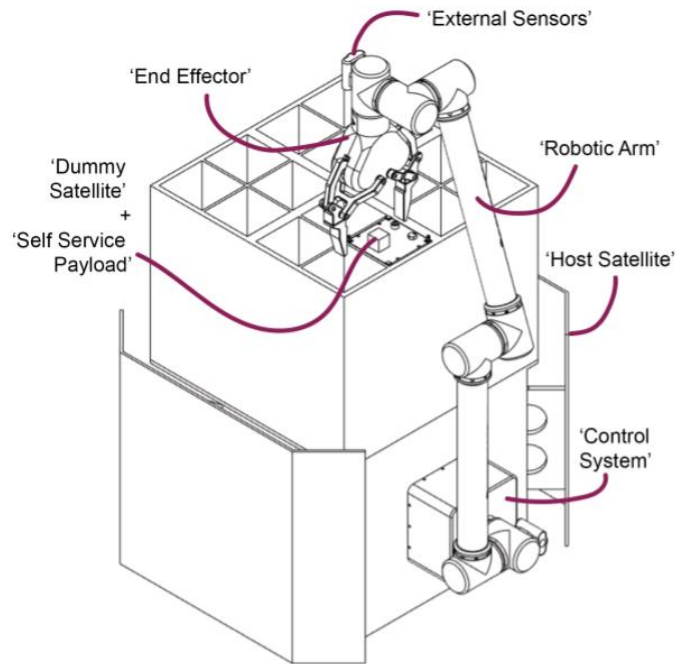


Figure 3-1: Schematic of the robotics arm and payloads integrated on the host satellite

The robotic arm is required to move the end effector to a position where it can connect with the payload from the satellite. The end effector is required to grab the service payload and dummy satellite. The service payload fulfils the role of demonstrating satellite serviceability. The dummy satellite is required the for demonstration of arm capture capability in the Low Earth Orbit environment.

### 3.3 Mission

This research focuses on a robotic arm. Sperspace has the plan to implement three generations of robotic arms discussed in the following table. Prototype 2 “second generation” is the main target of this research.

Table 3-1: Prototypes Specifications

	Pre-Secondment	Secondment	Post-Secondment
Prototype Name	Prototype 1	Prototype 2	Prototype 3
Chassis:	Plastic	Aluminum	Aluminum
Gearing	30:1	100:1 (Harmonic)	160:1 (Harmonic)
DOF:	3 (1 functional)	6 motors	7 motors
Power (Power per Motor)	260 W (86.66 W)	210 W (30 W)	?
Encoder	Relative	Relative	Absolute

## Requirements and Design

<i>Brake</i>	No	No	Yes
<i>Sensors:</i>	No	Camera	Camera, Thermosensors, etc
<i>Communication:</i>	CAN	RS-485	RS-485
<i>Motion Planning:</i>	No	Inverse-Kinematics, Basic path-planning	Complex path planning, collision avoidance,
<i>Shaker Table Test:</i>	No	Yes	Yes
<i>Thermal Testing:</i>	No	No	Yes
<i>Time:</i>	4 months	9 months	?

- Each Joint has a 20 Nm Torque & 15 Nm of Back drivability force.
- Each joint can rotate infinitely and continuously.
- Meter reach.
- 7 Degrees of Freedom. Allows for more theoretical poses than 6 DOF and adds kinematic and dynamic redundancy.
- Has a parallel gripper, with 115mm of stroke. Allowing for a 7.5mm error when grabbing a 100mm object.

### 3.4 Prototype 1 overview

The robotic arm has 6 degrees of freedom and 1.1 meters of reach. The arm uses an on-axis architecture to reduce loads on joints and enable the use of rapid additive manufacturing. The end effector used a parallel gripper arrangement with a grip force of 12.8 N.

The following tests demonstrated the technology readiness level:

- **Experiment 1 - Robotic arm operation:** actuation demonstrated by the movement of 3 DOF arm in a 1G environment using coordinate control with software developed in-house.
- **Experiment 2 – End effector operation:** Gripper actuation demonstrated by full opening and closing, and measuring finger gripping force of 1.3 kg shown analytically to be sufficient for dummy satellite manipulation.
- **Experiment 3 – Motor in simulated space environment:** Measured valid torque curve for motor actuator component after exposure to low vacuum (24 Torr) (defined in Appendix B.2), sinusoidal vibration (~1 G 6 Hz and ~1 G 12 Hz) and peak acceleration (>7g in x, y and z), emulating orbit and launch environments.





Figure 3-2: Prototype one

Where 1) Base, 2) Shoulder joint, 3) Arm linkage, 4) Lower elbow joint, 5) Upper elbow joint, 6) Forearm linkage, 7) Lower wrist joint, 8) Upper wrist joint

### 3.5 Prototype 2 requirements

#### 3.5.1 Functional Requirements

Table 3-2: Functional Requirements

ID	Description
ARM-FR-1	The system must have a reach of 1m with a standard 7DOF configuration
ARM-FR-2	The system must have a reach of 2m with the addition of two telescoping joints in place of a standard joint.
ARM-FR-3	The system must be able to reach, attach, hold and detach securely to a payload.
ARM-FR-4	The system must have the option of teleoperation. Controlled remotely using sensors for feedback.
ARM-FR-5	The system must have the option of conducting basic automated motions for placement and stowage.
ARM-FR-6	The system must be able to identify the locations of each joint to an accuracy of 3mm.

## Requirements and Design

ARM-FR-7	The system must be able to integrate with different end effectors.
ARM-FR-8	The system must be mechanically stable under launch forces of up to 9G
ARM-FR-9	The system must be able to handle payloads of 1 kg under 1G conditions and 500 kg under 0G conditions.
ARM-FR-10	The system must have an expected operational lifespan of 5 years in LEO
ARM-FR-11	The system must have a redundant control unit set
ARM-FR-12	The system must be able to operate on the RS485 protocol for motor driver firmware
ARM-FR-13	The system must have the option of communicating with the host satellite using several protocols including USB, CAN-Bus, Ethernet, and Modbus
ARM-FR-14	The system must be able to visually verify the arm and end effector's operations

### 3.5.2 Non-Functional Requirements

*Table 3-3: Non-Functional Requirements*

ID	Description
ARM-NFR-1	The system shall be modular and easy to reduce or increase the number of DOF based on customer requirements
ARM-NFR-2	The system shall be easy to test and identify failures
ARM-NFR-3	The system shall appear aesthetically clean and professional
ARM-NFR-4	The system shall where possible use COTS, CNC and 3D-printed components

### 3.5.3 Constraints

*Table 3-4: Constraints*

ID	Description
ARM-C-1	The system must weigh less than 20 kg with a standard configuration. This is inclusive of the arm, end effector, and control unit.
ARM-C-2	The system must have a peak power usage of 60 Watt.
ARM-C-3	The system must be able to operate at 24 V.
ARM-C-4	The system must have an operational internal temperature between -10 C and +60 C.
ARM-C-5	The system must be able to operate in a high-vacuum environment

## Requirements and Design

ARM-C-6	The system must be able to operate in an LEO radiation environment excluding the South Atlantic Anomaly and polar regions
ARM-C-7	The system must be able to survive a high-vibration environment during the launch
ARM-C-8	The arm and end effector must be able to fit inside a stowage space of 400 mm x 300 mm x 200mm
ARM-C-9	The control unit must be stored inside the satellite and be smaller than 60x100x100 mm

This industry research will be focused on the Control unit of prototype 2, but the following sections will give a brief about the whole robotic arm.

### 3.6 Mechanical Structure

It is a 7-DOF robotic arm consisting of a base, five elbow joints, two links, a flange adaptor and a tool flange. The links of the robotic arm are connected by joints with a harmonic drive to allow rotational motion with zero backlash. The tool flange, also connected to the joint through a harmonic drive, is used to connect the robotic arm with the gripper end effector. The motor drive system to power and control the system is housed in the elbow joints.

Articulated Robot Architecture: This prototype robotic arm uses a fully articulated robotic architecture, which uses revolute joints to achieve movements in all three dimensions. Due to there being 7 degrees of freedom, there are two joints for each axis of movement and a remaining joint that is there for redundancy. This allows the prototype to reach all points in space within a 1m radius semi-sphere.

#### 3.6.1 Assembly

The arm is comprised of:

- 3x Male Joints
- 4x Female Joints
- 2x Linkages

## Requirements and Design

- 1x Gripper
- 1x Base

Male joints are ones whose base has a protrusion, allowing the linkages to be attached to the base of the joint. The female joints have a bore, allowing the couplers of other joints to connect to the base of this joint. These components are assembled in the following procedure:

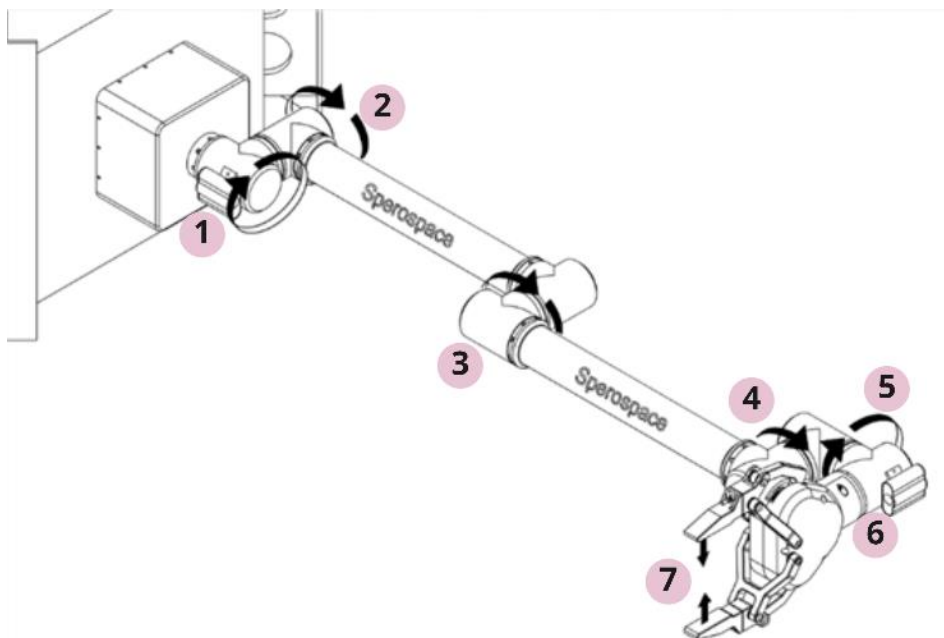
1. First, the output of a female joint (Joint1) is connected to the arm base using its ‘Universal’ coupler and 8x M3 bolts. The cables coming from the joint must be attached be routed through the bore hole in the base before it is mechanically attached. The cylindrical component of the arm base is the structural component and bares all forces produced by the arm. The rectangular housing around the base is simply a cover for all of the electronic componentry underneath it.
2. The second operation connects the output wires from a male joint (Joint 2) to the first joint and then attaches mechanically using a universal couple and 8x M3 bolts. This forms the second axis of rotation.
3. A linkage (Linkage 1) can now be attached to the base of the male joint using 8x M3 bolts. A long cable should be routed through the linkage, to connect the second joint to the rest of the arm.
4. The input of a male joint (Joint 3) should now be electrically and mechanically attached to the other end of the linkage, using 8x M3 bolts. This joint must be following the same direction and axis as joint 2.
5. The base of another female joint (Joint 4) can now be connected to the output of joint 3 using 8x M3 bolts. Compared to a normal 6DOF robot, this joint would be considered a redundant joint.
6. Now the second linkage (Linkage 2) using 8x M3 bolts, can be attached to output joint 4. This joint will actuate this entire linkage and all following joints.

## Requirements and Design

7. The final male joint (Joint 5) can be attached to the other end of the linkage with 8x M3 bolts.
8. A female joint (Joint 6) will now be attached to the output of joint 5 with 8x M3 bolts.
9. The final female joint (Joint 7) is attached to the output of joint 6 using 8x M3 bolts.  
This is the final joint and is responsible for rotating the gripper.
10. The gripper is attached to the output of joint 7 using 8x M3 bolts.

### 3.6.2 Functionality

**Degrees of freedom** - The arm was designed to be a fully articulating 7 DOF arm, capable of complex manipulability and movement. This was done as it was decided that the robot should have the ability to reach as many places as possible, as this will make it more versatile and useful when in a space environment. 7 DOF is the lowest number of joints needed to make this possible, to put it very simply there is a joint for each X, Y, Z, Pitch, Roll & Yaw movement in 3D space.



*Figure 3-3: Diagram of Potential TRL6 prototype arm*

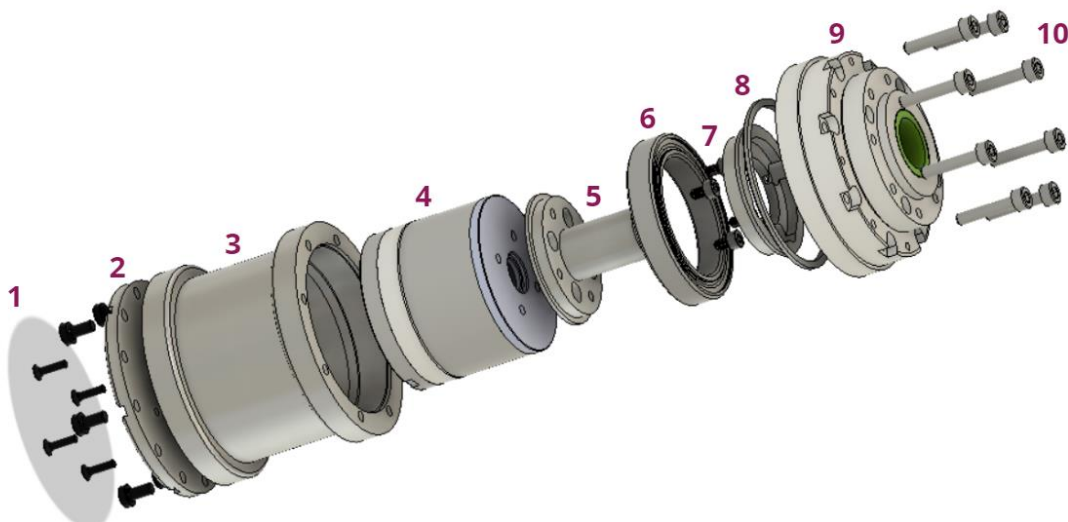
1)Base Joint, 2) Shoulder Joint, 3) Elbow Joint, 4) Elbow-Twist Joint, 5) Wrist Joint, 6) Wrist-Twist Joint

## Requirements and Design

Fusion is the platform of choice for prototyping the CAD models to be used in this project. This is also the platform from which these models can be structurally verified by running preliminary simulation tests before prototyping. Fusion teams enable a collaborative workspace between members for review.

### 3.6.3 Actuator

The Actuator is the system within the robot arm responsible for actuating/rotating the robotic joints. It is composed of a motor, gear reducer (to increase torque) and housing components which when combined produce the necessary force to reliably move the arm and its potential payload.



*Figure 3-4: Exploded view of the actuator*

1. Fasteners
2. Actuator Housing Cap
3. Actuator Housing
4. Motor
5. Motor Shaft
6. Bearing
7. Fasteners

## Requirements and Design

8. Bearing Constrainers
9. Strain Wave Reducer (Gear)
10. Fasteners

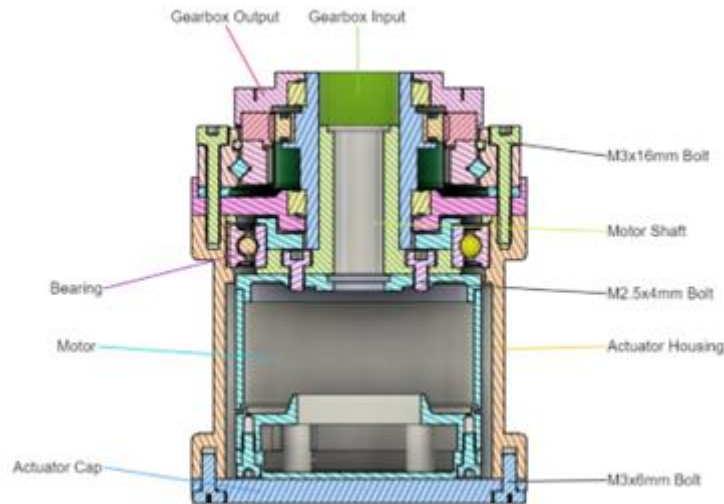
### **3.6.4 Motor**

The motor is a small, out-runner BLDC (Brushless Direct Current) motor with a through bore hole. This motor type was selected because:

- Having a hollow centre allows cables to pass through the actuator and is simply capable of routing.
- Brushless motors are more reliable and last longer than brushed motors, which is beneficial for the unforgiving space environment.
- This motor came with a motor controller integrated into the motor chassis. This allowed for not only simpler mechanical design but also allowed for far quicker integration and testing of the arm.

### **3.6.5 Strain Wave Gear**

A strain wave gear is a type of “gearbox” or “reducer”, which means its purpose is to slow down the speed but increase the torque of its output compared to its input. It is a very specialised design and it provides some amazing benefits to the design of the prototype. Because of the nature of the mechanism, we can achieve a remarkably high torque output in a compact form factor and crucially with a hollow centre. By having a part such as this, it can be paired with the motor above to form a small yet powerful robotic actuator for us to use in the joints of the prototype.



*Figure 3-5: Section view of the arm joint*

### 3.6.6 Joint structure

Joints are the components that house all the components necessary for actuation. They attach to each other and the linkages of the arm via a ‘universal’ coupler. The base-satellite interface is needed to create power, data, and mechanical connections to the host satellite. Camera 2 is required to track the end effector and provide visual feedback for control and semi-autonomous command confirmation.

The coupler is necessary to connect the joint to the linkages in the robotic arm. The strain wave reducer provides torque multiplication from the motor to the joint output to provide sufficient torque to operate the arm. An encoder is necessary to track the location of the robotic joint and feed the information back into a control loop for the whole arm. A temperature sensor tracks the internal motor temperature to ensure it is within a safe operating range. The actuator housing mechanically holds all internal components and creates a seal to prevent external debris from entering the robotic joint. The motor provides rotational mechanical power to the system.



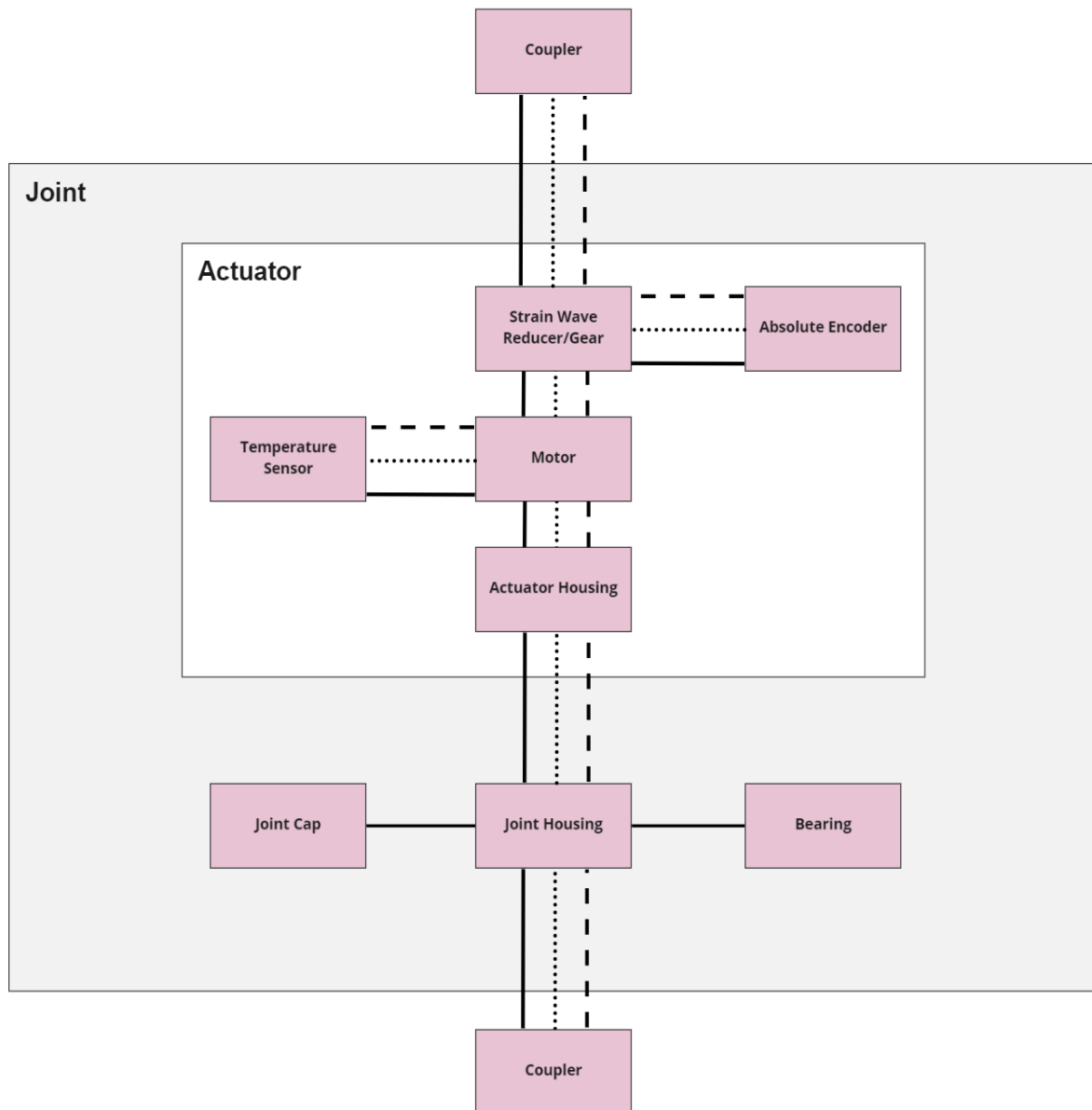
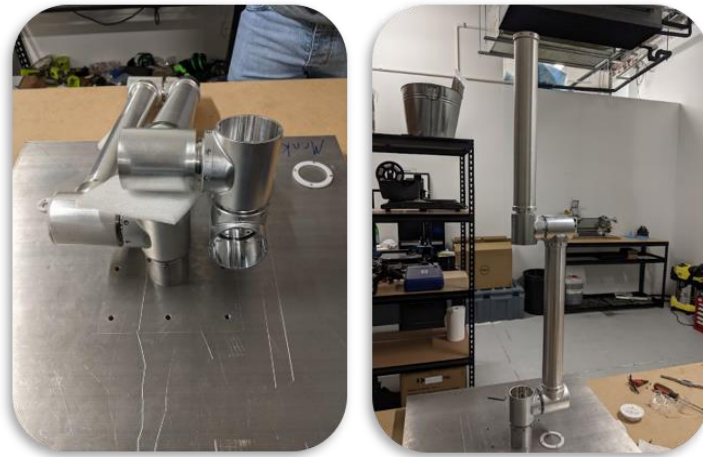


Figure 3-6: Joint Architecture

### 3.6.7 Mechanical manufacturing

The section describes the manufacturing of the robotic arm. As shown in the following Figure.

The arm is a 7-degree-of-freedom serial-link robot manufactured using off-the-shelf components and additive manufacturing processes. The robotic arm weighs 9 kg.



*Figure 3-7: Mechanical structure of robotic arm*

## **3.7 Mechatronic System Structure**

### **3.7.1 Drive System**

The drive system consists of a motor, gearhead, encoder and driver. A motor was the optimal choice for the motor because of its high power-to-weight ratio. It also had the added advantage of having a high torque density and compact footprint. Relative magnetic encoders are used for home positioning and feedback control. A 4-Q speed and current controller are used for the motor. Also, it is a positioning controller with a higher-level master, which takes care of process control and sends individual commands to the positioning controller and other slave modules in the system via the bus system.

### **3.7.2 Control Unit**

Multi-axis motion controllers are freely programmable controllers that make it possible to easily synchronise coordinated movements of several axes. It is a PID controller that additionally uses a feed-forward that is proportional to speed and acceleration to compensate for friction and inertia with optimum system adjustment.

Feedback/Sensors

## Requirements and Design

- Digital encoders are located with each motor and provide relative and absolute position control.
- The LIDAR sensor implemented into the gripper provides the vital distancing parameters for the coding to interpret accordingly. This is because the sensor measures the distance between its placement and the nearest surface directly in front of its orientation. This ensures that the gripper has a level of understanding of its distance from the payload, its location on the track, and its progression through the path it needs to take. Additionally, this sensor works in conjunction with the PID to ensure the correct distance is executed at the appropriate time.
- The controller measures the force and can control deceleration.
- Camera: It will be the vision system and will be used for visual verification of arm operations.

### **3.7.3 Wiring**

All wires/cables will be shielded and will be integrated internally into the system. It will be efficient in a space environment. It will provide bidirectional, speed data transmission with minimal crosstalk, signal attenuation and low skew. Additionally, it meets stringent electrical and mechanical requirements such as non-flammable and solderability.

### **3.7.4 Software Design**

The robots are supplied with attributes that make it possible to program them, such as a control unit, and software. The system-controlled protocol defined by us as frame messages “commands”, which are sent from the main control unit of a satellite or by a GUI software is a graphical interface that makes programming easy and accessible. It is a full solution easy-to-use software interface that allows for quick programming. The following figure represents the main software layers between the firmware of the arm control unit and the software on the PC.

## Requirements and Design

During system running the software can detect position, speed, force, and feedback in real-time. The interface between the two control units will be USB or Ethernet protocol.

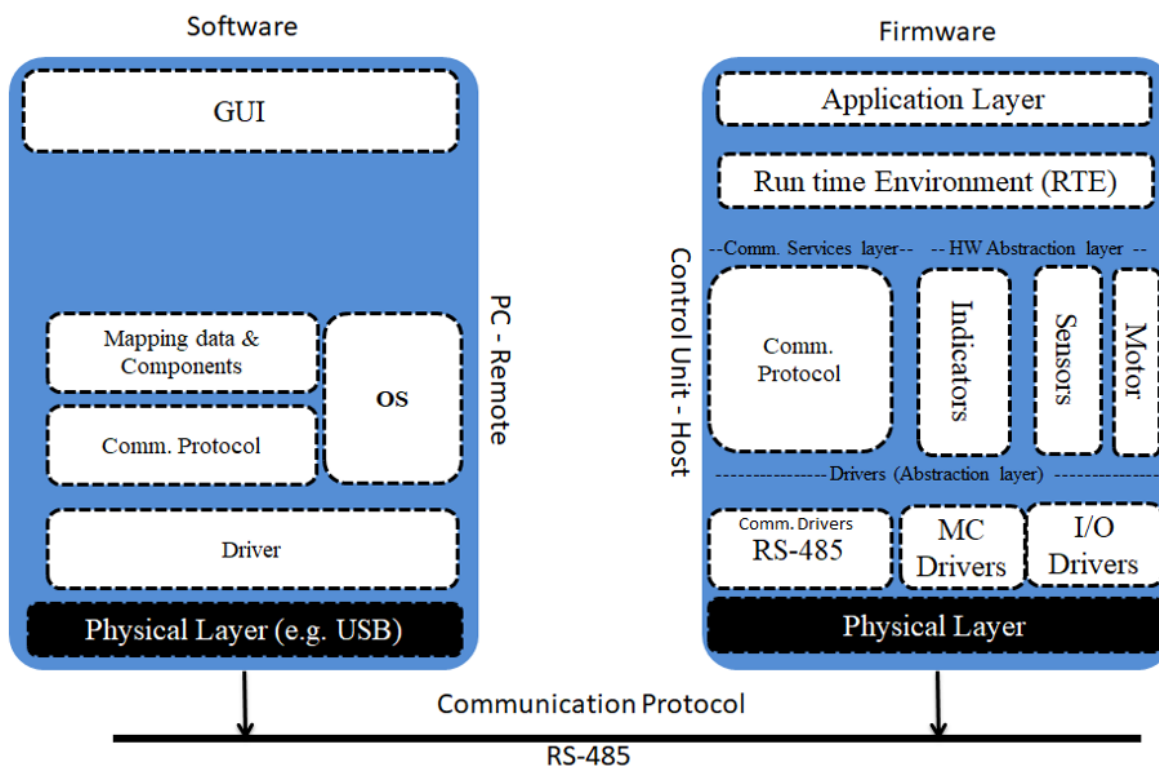


Figure 3-8: Software Architecture

## 3.8 Control unit specifications

Table 3-5: Control unit Specifications

Quality	Description
Processing Time	Processing time is important to consider when developing the control structure as this determines how efficiently the control unit operates. This is intricately linked to the time complexity of the program.
Power consumption	The amount of power needed for the control unit to operate and process data.
Robustness	The ability of the control unit to handle errors and extreme cases and its impact on functionality.
Closed loop capability	The ability of the unit to deal with errors using sensor information and real-time analysis.
Compatibility with camera/sensors	The unit's compatibility with sensors and camera units.
Comm Bus compatibility	The unit's compatibility with the Bus communication protocol.

### 3.9 Chosen Design Architecture

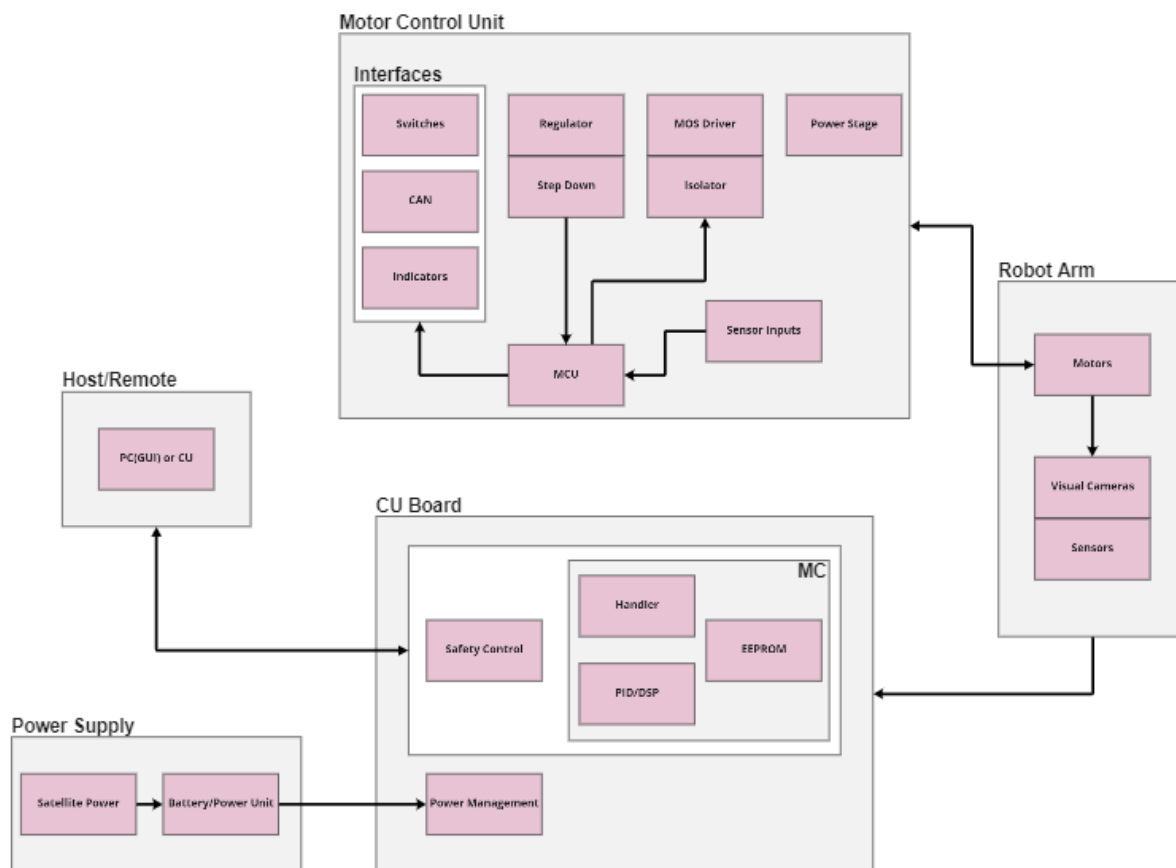


Figure 3-9: Software design architecture

The control system architecture shown in the above figure provides a detailed overview of each of the modules that are responsible for each section of the Project and its individual components. The motor control module controls the signals that are being sent to the motors for trajectory planning. The robot arm module handles the motor actuator as well as the vision system.

### 3.9.1 Block Diagram

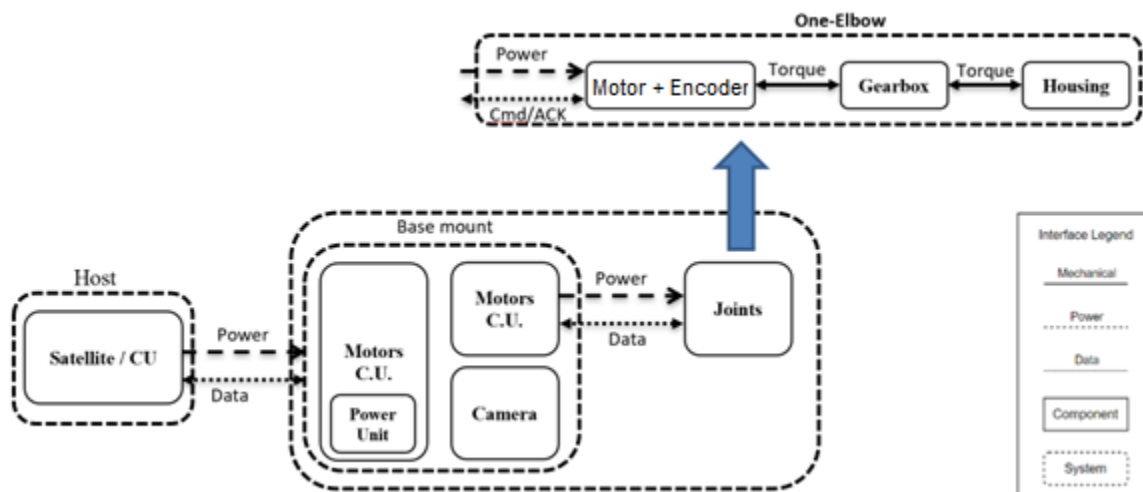


Figure 3-10: Block diagram of robotic arm Control System

### 3.10 Robotic arm Software Architecture

The purpose of the robotic arm software architecture (RASA) is to:

- Define an API for the end-user.
- Plan implementation by defining internal interfaces.
- Create a motion planning library for the robotic arm.

The control system shall be a complete System on Module (SOM) including CPU, GPU, memory, power management, high-speed interfaces, and more.

The control system shall have physical capacity for future component upgrades.

The control system shall integrate the controller with different software (C, C++ and Simulink Embedded coder control).

#### 3.10.1 Considerations

- Software Principles

## Requirements and Design

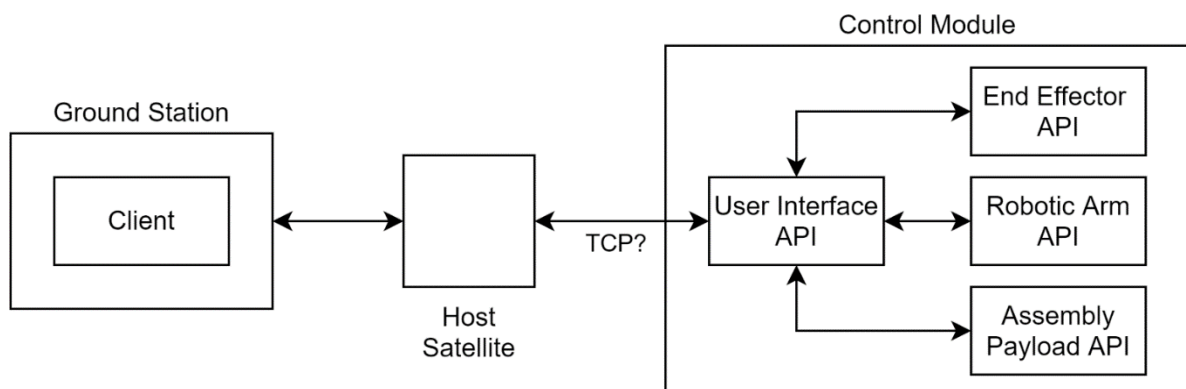
From the above-prioritised requirements and considerations, the identified software principles which will be significant in the software architectural design process are:

- Correctness
- Maintainability
- Usability
- Hardware

A small computer will be used to compute closed-loop kinematic, kinetic, and mapping algorithms, process and encode video, and log data.

- Language
- MATLAB will be used for engineering analysis.
- C and MATLAB Embedded Coder will be used for firmware and multi-core analysis.
- C++ will be used for GUIs and high-level interfaces.
- Libraries and Frameworks

### 3.10.2 Design Overview



*Figure 3-11: Control module high-level overview with communication protocols.*

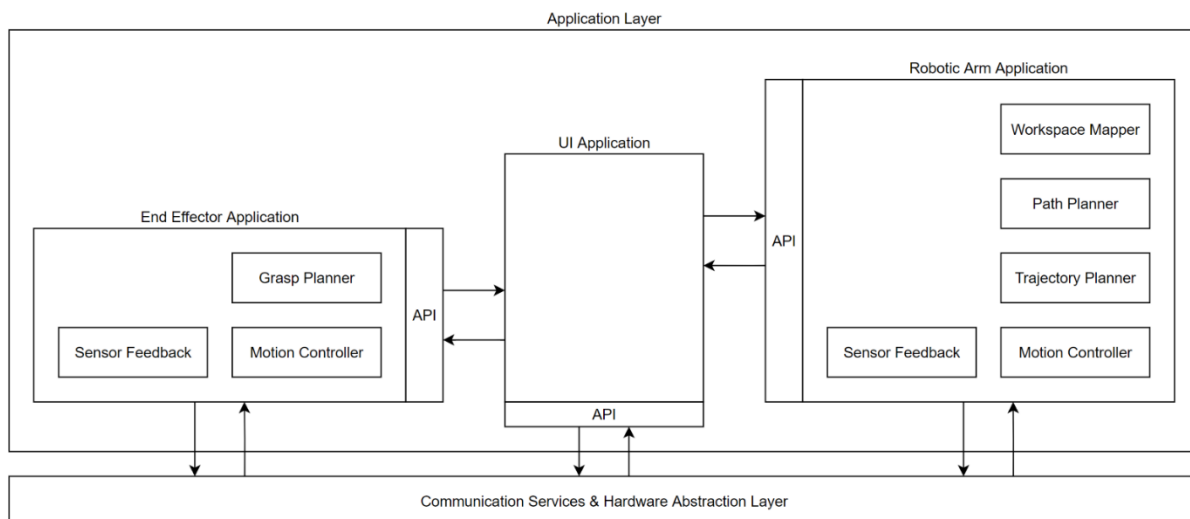


Figure 3-12: Simple block diagram of software architecture for a robotic arm.

### 3.10.3 Application Programming Interface

## 3.11 Systems Design processes

The stakeholders of the RSD mission involved Spersospace and its suppliers. Thus, the baseline stakeholder expectation of the RSD mission is to have a successful demonstration of the robotic arm in orbit. This requirement is used to derive the technical performance criteria for the robotic arm and the host satellite. These criteria are then broken down into lower-level product specifications, with the involvement of stakeholders.

During the systems design phase, responsibilities and authority of performing planned processes shall be assigned using a skills matrix. Upon assignment, training will be given through seminars and induction sessions as needed. In addition, individuals will be provided adequate nonhuman resources that include software such as MATLAB/Simulink, C++ compilers, and Fusion 360 CAD as well as hardware components as required. Designated software/hardware products shall be placed at appropriate levels of configuration management as defined by the configuration management plan.



### 3.12 Motor specifications

The robotic arm was designed with a power draw in mind, it was powered by smaller more power-efficient motors, paired with a harmonic gear pair that increases their strength 100x. This allowed for a significantly smaller profile and overall power draw of the arm (260 -> 210 W max), despite the jump from 3 to 7 motors (83 -> 30 W).

The robotic arm also made use of a closed loop control system, which modulates incoming power to maintain constant torque, Speed or position, this combined with the code discussed above allowed for the arm to precisely control the position of its entire arm, within its range of motion. The arm also makes use of an internal slip ring that allows for internal routing of cables while allowing for an infinite range of motion, without risk of snagging.

**Motors selection** – A brushless DC motor was selected from *MyActuator*. The motor had internal gearing for increased torque and RS485 for communication.

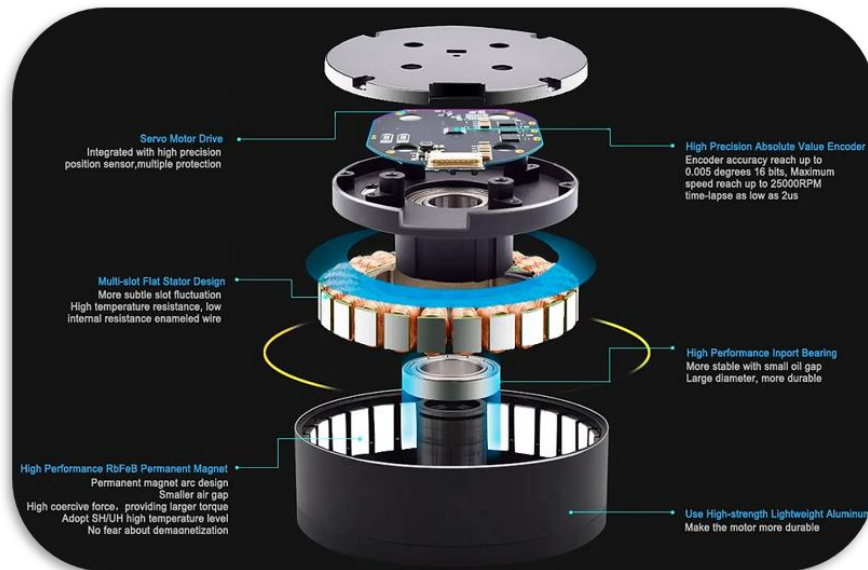


Figure 3-13: Motor Architecture.

## Requirements and Design



*Figure 3-14: Tested motor.*

## 4 Control system model design

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Due to the nature of the relationship and dynamic interaction between system components, it becomes difficult to emulate varying environments for different robotics. Accuracy and repeatability are vital aspects of ensuring the most appropriate simulation for any given system. This is also without consideration to result in validity, playing an essential role in selecting an appropriate simulation platform. These attributes are characterised and embodied in the simulation software platform. This chapter describes the overall structure of the arm model and its components in detail.

In this chapter, we present a control system design for a robotic arm that can perform complex tasks with high precision and accuracy in a space environment. The proposed control system is based on a feedback control strategy that uses encoder feedback to continuously adjust the arm's position and orientation. The control system includes a motor controller, which controls the robot's actuators, and a microcontroller, which processes sensor data and sends commands to the motor controller. This chapter will also present key points gained from the development of this arm, and what changes will be made moving on to the next prototype of the arm.

## 4.1 Control unit interfaces

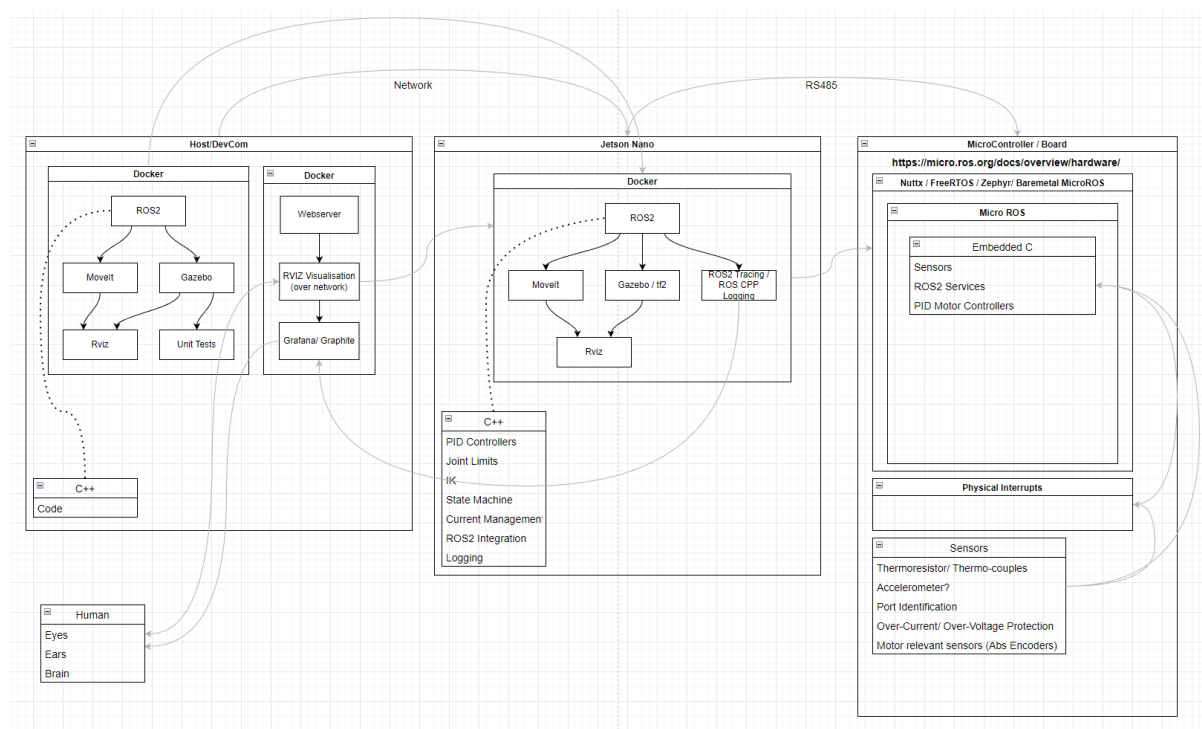


Figure 4-1: Control unit interfaces.

### 4.1.1 Real-time

The control unit uses a real-time control is defined as a reference model architecture where the issue of real-time computing is a requirement to be solved.

The libraries used in this iteration of the robotic arm are specialised for each of the three modules that are present on the arm which are the Software communication module “UART”, the Inverse Kinematics module and the Camera Sensing module.

The following flow diagram shows how each of the modules interacts to create the message queue that is sent to each of the motors.

For a system to be considered as being capable of real-time control, the system must be able to gather data and process them in a tight window to update the system's current state. the arm was able to achieve this requirement of real-time control to move to the targeted position within a reasonable time window.

## Control system model design

The camera sensing module handles the vision component of the arm to detect markers in the grippers' perspective via an attached camera. This module uses the OpenCV library to implement the vision system. It uses the functionality of detecting aruco markers to accurately locate its position in 3d space with respect to the origin of the arm. This information is then passed over to the kinematics module to generate solutions for the inverse kinematics problem. The camera module will not be included in this research.

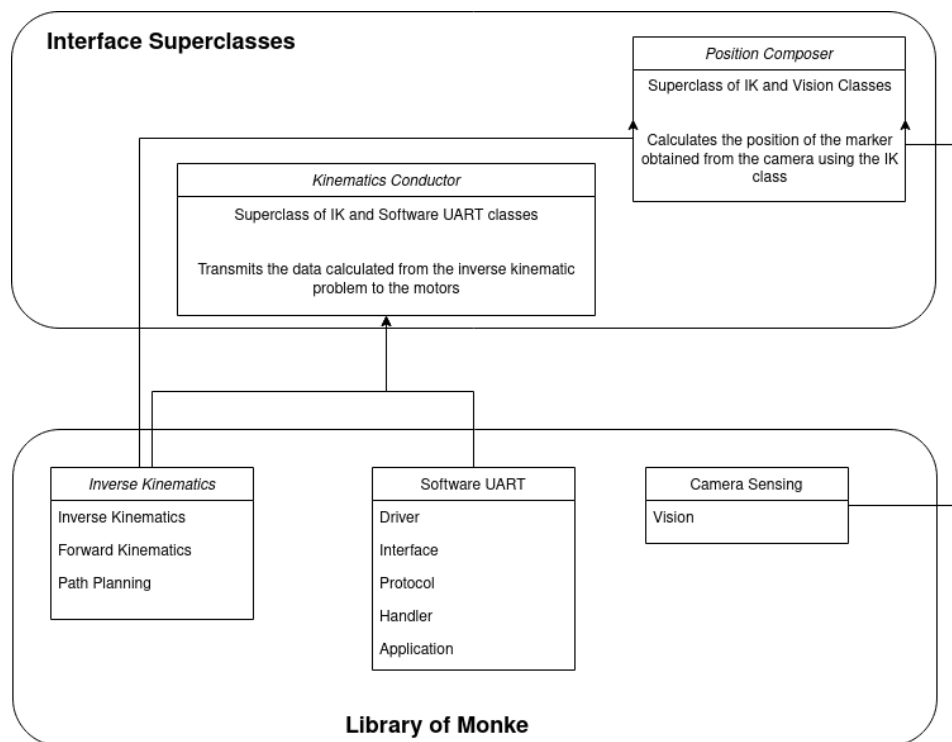


Figure 4-2: Software interfaces.

## 4.2 Communications peripherals

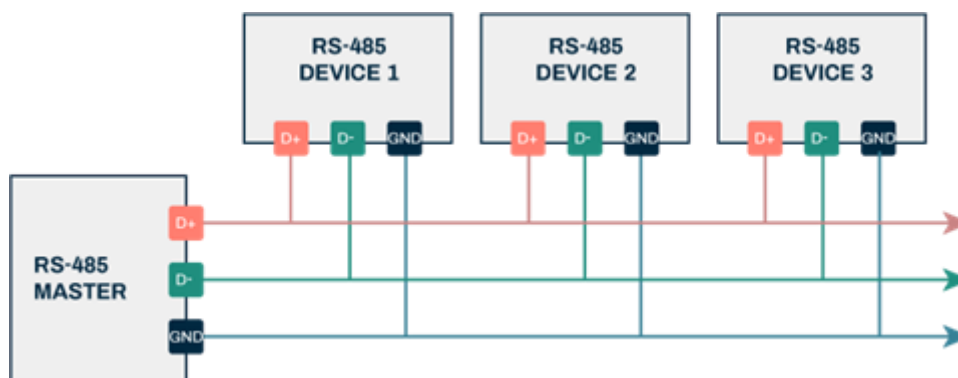


Figure 4-3: Motors interfaces.

Communication to the arm was done via the RS-485 line running at 115200 baud. RS-485 is a differential signal method, reliant on two data lines terminated at both ends with a  $\sim 100$  ohm resistor. This was chosen as RS-485 supports fast data transfer at relatively long distances (up to 1.2km), it also supports a high number of devices on the same line (up to 32) which results in it being a highly flexible communication solution, comparable to CAN. The disadvantage of RS-485 however was that it is by default half-duplex, meaning that only a single device can speak at the same time, this however was mitigated by the fact that the chosen motors act as slave devices, only sending messages in response. This solution allowed us to both power and communicate bi-directionally with all 8 motors simultaneously on just four lines (two data two power). These benefits aided in overcoming the physical constraints of the arm. Overall we found that communication was more lightweight and usable compared to CAN used on the next version. [Link](#), [Link](#)

The software UART module handles the communications between the main control unit and each of the 8 motors situated throughout the arm. For the Software UART module, we used an external state machine library to handle the different states that the arm undergoes. This library was open source and can be found ([Link](#)). An external serial library was also used to establish a connection between the serial port and the arm since a USB to RS485 converter was used. ([Link](#)). This module also handles any errors that may occur during the operation of the arm by

## Control system model design

stopping motion should there be a surge in current and verifying the data packets being received through a checksum.

### 1) Flowchart for software and integration of different software

The flowchart underneath shows the dependency graph of the Software UART and its placement in the higher-level hierarchy.

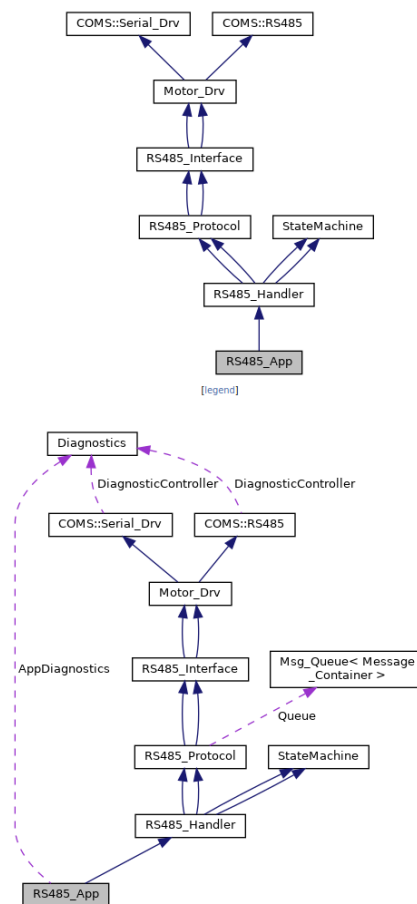


Figure 4-4: Software Flowchart.

## 4.3 Inverse Kinematics

In this section, we proposed a control system design for a robotic arm that employs a mapping algorithm to convert desired end-effector positions and orientations into motor commands. The mapping algorithm plays a critical role in the control system's ability to execute tasks

## Control system model design

accurately and efficiently. In this section, we discuss the mapping algorithm in detail, including its implementation and performance.

The mapping algorithm used in our control system is based on the inverse kinematics of the robotic arm. The inverse kinematics problem involves computing the joint angles required to achieve a desired end-effector position and orientation. The solution to the inverse kinematics problem is not unique, and there can be multiple solutions for a given end-effector position and orientation. In our control system, we employed a closed-form solution to the inverse kinematics problem, which allows us to calculate the joint angles directly from the desired end-effector position and orientation. The algorithm used to generate the solutions is based on a Jacobian method.

The inverse kinematics module handles the path generation of the arm and all adjacent operations related to the movement of the arm. Such operations are a generation of values needed to achieve an inverse kinematics problem as well as providing solutions for the forward kinematics scenario. The library used in this module is the Robotics Library [Link](#). This module sends the generated values obtained via the algorithm implemented in the library and propagates this message over the data line to be received by the motors.

The mapping algorithm takes the desired end-effector position and orientation as input and computes the joint angles required to achieve that position and orientation. The joint angles are then converted into motor commands using a motor controller. The motor controller sends the motor commands to the robotic arm's actuators, which move the arm to the desired position and orientation.

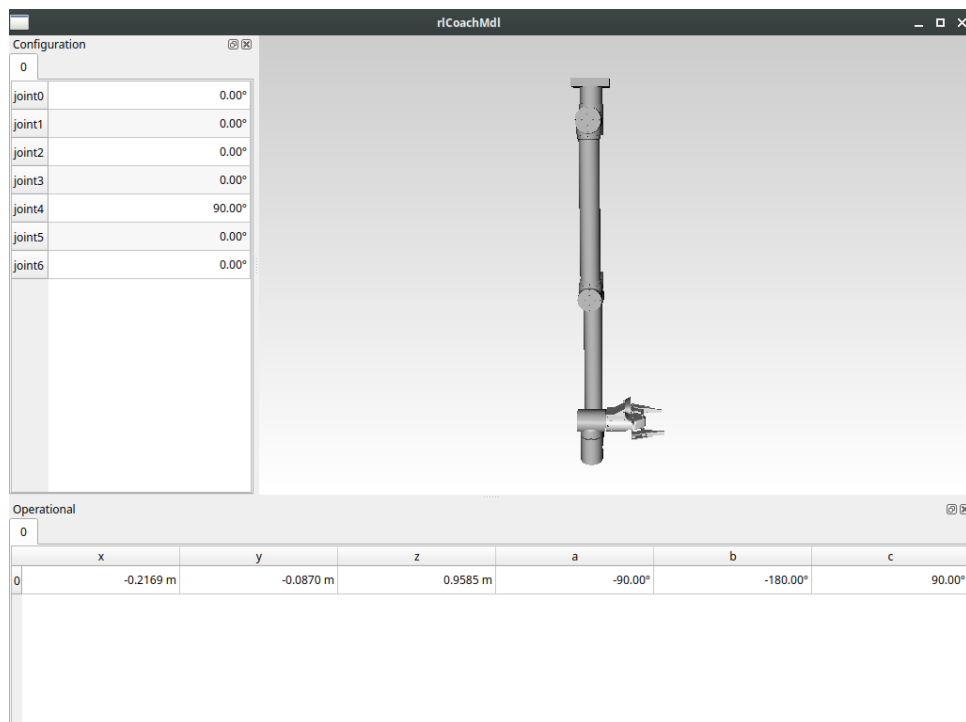
The performance of the mapping algorithm was evaluated through simulations and experiments. The simulations involved testing the control system's ability to perform various tasks, such as reaching a desired position and orientation and following a trajectory. The



## Control system model design

experimental evaluation involved testing the control system's performance on a physical robotic arm.

The results of the simulations and experiments demonstrated that the mapping algorithm was able to achieve high levels of accuracy and efficiency in executing tasks. The control system was able to reach desired positions and orientations with sub millimetre accuracy and follow trajectories with minimal error.



*Figure 4-5: Inverse kinematics simulation.*

The screenshot above shows the arm in the simulation environment used in this current iteration. In the left panel it displays the joint angles of the arm and the panel on the bottom displays the position and rotational components of the end effector with respect to the arm's origin. This origin point is located at the square base at the top of the arm. Through simulations the arm was able to be verified, showing the feasibility of achieving the required positions given by the marker.

An IK Handler class was created as a wrapper for the Robotics Library. Further functions were written as part of a wrapper class in our implementation. These functions include:

## Control system model design

- **Trajectory generation:** This function conducts path planning according to the planner parameters which are the goal joints vectors in radians and the maximum number of steps between start and endpoints. Upon completion, it would mark out the complete trajectory the robotic arm will follow to achieve the required configuration.
- **Collision avoidance:** This function uses the camera's detection of an aruco tag to determine an object of interest within the workspace. A trajectory in the 3D world space is then designed to avoid the obstacle found while still achieving the desired end-effector position and orientation. The collision-free trajectory is then generated by the trajectory generation function.
- **A visualiser for the simulator:** This function is used to mimic the movements of the arm in simulation. With this function, testing can be more rigorous as orientations, positions and trajectories can be trialled in software before moving into real-world integration and testing.

However, the Robotics Library was shown to be insufficient for advanced path planning and collision avoidance, its visualiser was not extensive enough to meet the high requirements such as being able to interact with the arm. As a result, for the next iteration development of the arm will be using ROS2 as the main library for control.

The main achievement was demonstrating that control of a 7 DOF arm was feasible and will only continue to improve as the arm gets iterated over the development process. The reliability of the arm will noticeably improve as development shifts over to using ROS2 to handle the path generation and control of the arm as opposed to the Robotics Library used in the current arm. This is because ROS2 offers specialised packages suitable for the control of robotic systems such as Moveit2 and Rviz.

## Control system model design

This was a big improvement moving from the prototype one of the arm to the current arm. The previous arm in comparison to the current prototype was unable to meet the real-time control requirement and did not follow this architecture which led to a litany of integration issues once each subsystem was verified. Moving on to the third prototype, a similar architecture will be implemented albeit more complicated since ROS2 will be used.

## 4.4 Conclusion

In this chapter, we presented an overview of the electrical, mechatronic, firmware and software components of a space robotic arm. We discussed the design considerations and challenges involved in developing a space robotic arm, including the harsh environmental conditions, the need for high reliability, and the limited power and resources available.

We began by discussing the electrical components of the space robotic arm, which include the power management system, the sensors, the actuators, and the communications system. We highlighted the importance of designing these components to be lightweight and compact to ensure the arm's reliability and functionality in space environments.

We then discussed the mechatronic aspects of the space robotic arm, including the arm's mechanical design, its joint actuation and control, and its end-effector design. We emphasised the need for the arm to be designed to handle the significant forces and torques encountered during operation while remaining lightweight and precise.

## 5 Implementation and Testing

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This section outlines the test activities that will be used to evaluate end products. This list aims to give an overview of the test activities but is not an exhaustive list. The evaluations will be utilised for end products where they are relevant to the subsystem requirements.

- Component Performance testing

The component testing will test the function of individual components in particular the motor, and sensors. The components will be connected to a microcontroller in a breadboard configuration. It will look to find the actual output of each component and allow the development of software to operate each component. In addition, low vacuum testing will be conducted to test the operation of each component in a vacuum with respect to overheating and outgassing.

- Control System Simulation

Control system simulation will tune the system so that the components limits (e.g. current) aren't exceeded and also ensure that the system completes requirements in a timely manner. The control system will also test how the system behaves in the presence of external disturbances too.

- FEA Studies

For end products and integrated systems, mechanical analysis will need to be completed. This ensures that the system complies with any mechanical requirements specified for operation or launch outlined by the host satellite provider.

- Component Vacuum testing

The component vacuum testing will test the ability of each component to function in a vacuum. The components will be weighed and placed in a low-vacuum chamber. After, they will be weighed again, and their performance will be tested again in a breadboard configuration.

- Vibration testing

## Implementation and Testing

Vibration testing will aim to ensure that the payload will be able to withstand the vibrations experienced during launch. The system will be attached to a Shaker table and vibration loads will be applied based on the requirements specified by the host satellite provider.

- The following tests are not included in this prototype
- Thermal functionality testing
- Radiation Testing

The performance of the control system is evaluated through simulations and experiments, and the results demonstrate the system's ability to achieve high levels of accuracy and efficiency in space applications. In this chapter, we provide an overview of the space robotic arm's hardware and its kinematic model, we describe the proposed control system design in detail, including the various control techniques employed and we present the simulation and experimental result.

### **5.1 Discussion modelling phase**

Due to the power supply limitations of satellites, it is not likely that the prototype will be able to operate with more than three motors at any one time.

- Power

The arm was powered at 24 V and its peak was pulling 4 A while driving all motors. This would give the arm a power draw of 96 W at peak, which would have been much higher if the motors were under more load or in a different position. Regardless this number would be lower in a space environment because of microgravity, and thus the load/force on the arm is dramatically lower. High power draw can also be addressed by simply reducing the number of motors running at any one time.

- Positioning

## Implementation and Testing

Due to the motors that were selected, the position of each motor can be tracked and communicated with the use of internal encoders. This is a necessity for the control systems behind the arm which make it move, as we know the position of the joints at any one time, we can combine this data with the known geometry and dimensions of the arm to calculate the exact position of the end effector for any given movement. To ensure accuracy and reliability, absolute encoders will be included outside of the motors, so that the absolute position is always known and can be compared with the theoretical position to ensure the end effector is in fact where it is calculated to be.

- Control System

MyActuator motors use a proprietary control board to handle both motor driving and motor control. Pre-defined command bytes are sent to the motor to utilise control and feedback commands. These commands include writing new values to PID variables, setting desired position, speed, and torque values, and reading information from the motor such as encoder position, temperature, and torque values. The motors then handle updating the control of the motor and then driving the motor.

The motors are communicated using the RS485 protocol. For this application, an RS485 USB Adaptor was utilised so the motors could be communicated with, directly from a computer. The real-time programming language Simulink was used so updates to speed, position and encoder position could be updated in real-time and responded to. MATLAB Simulink contains a tool interface that is utilised for RS485 communication within the model. Below is a snapshot of the control panel of the model.

MATLAB and Simulink are both used for the development and validation of the control system. The communication model would be verified using MATLAB where it is developed using Simulink and utilising the prototype micro-controller. Simulink is used to create a

## Implementation and Testing

graphical interface and represent message frames in a readable format. As stated previously, designs created would be stored on GitHub where they can be reviewed by other members and iterated upon.

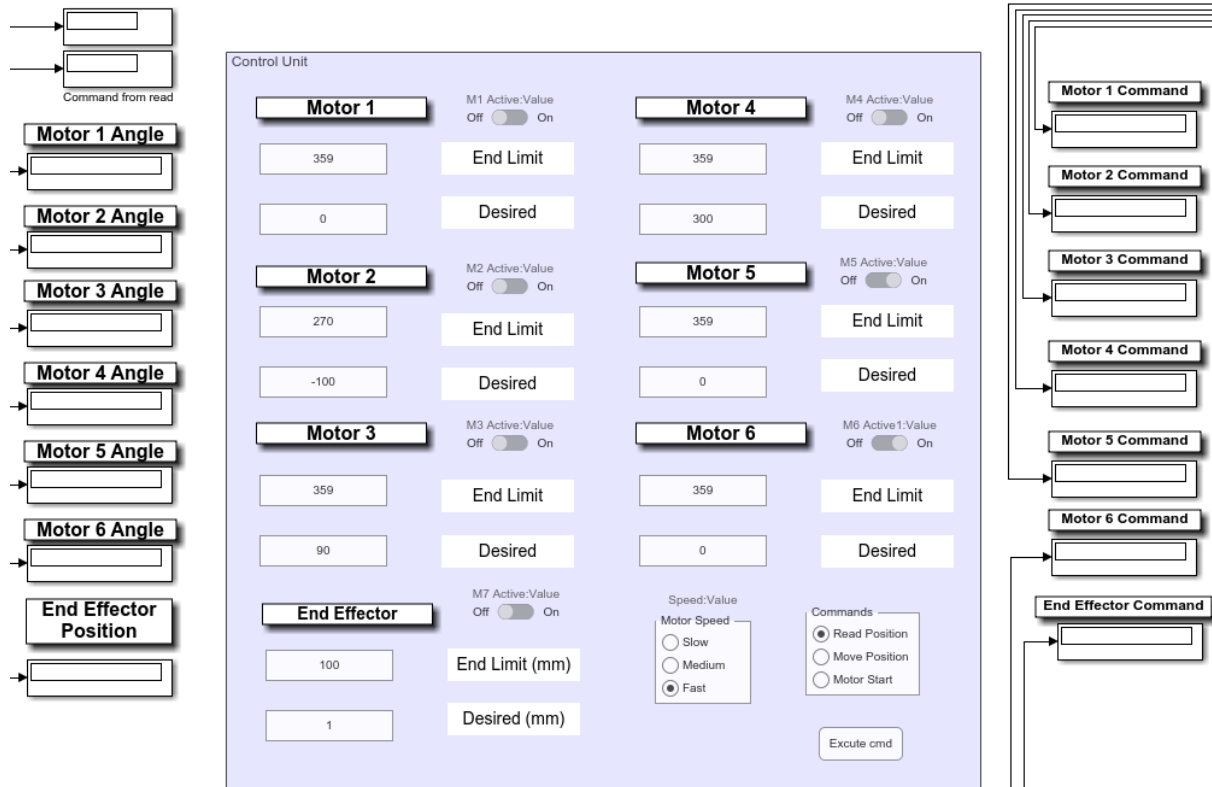


Figure 5-1: Control System Interface.

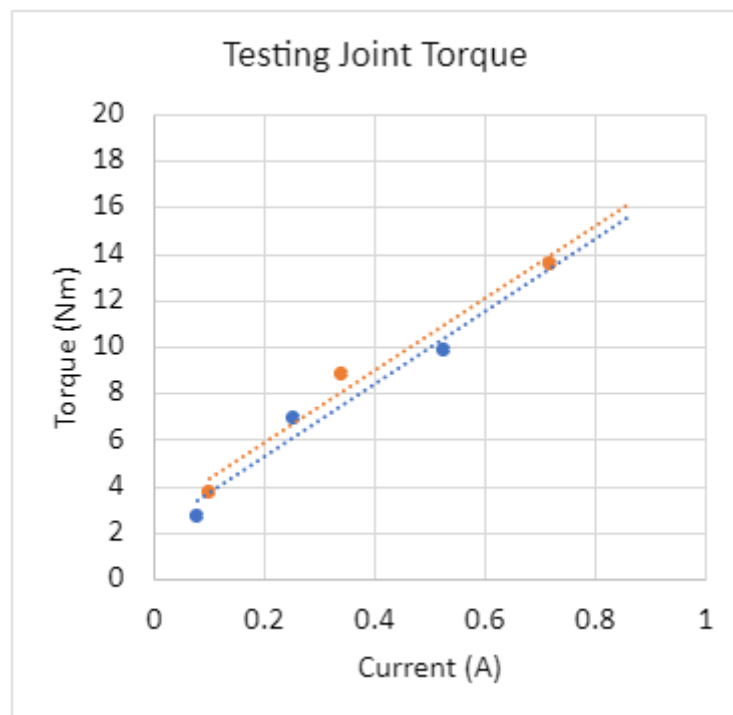
The above model allows for position control of all motors within the prototype robot arm. Additionally, end limits have been added to limit the position range the motors can operate within to ensure overextending the motors that could damage joints. Further, the speed can be changed of the speed of the motors.

An additional Simulink model was created to calculate the inverse kinematics of the arm, so the corresponding angles between points in space can be moved between. This model also allowed for the design of complex motion models. An interface between the inverse kinematic model and the control model was created so that the arm would be able to operate simply. However, due to the failure of some motors in the system, the inverse kinematic model was not utilised due to it needing substantial modification to work with the reduction in motors.

## Implementation and Testing

- Torque

To validate the operating ability of the robot arm, the torque of this prototype must be determined to be suitable for PROTOTYPE's application in space. Running the arm one motor at a time with the power specification of a constant 24 V and up to 2 A being supplied, would result in a max torque output of 4.18 Nm. and a no-load speed of 215 rpm as calculated from the motor specifications. This speed will decrease linearly as a load is applied; it reaches 0 at the stall torque of 21 Nm. and thus, at the torque of 4.18 Nm. it will have a max speed of 172 rpm. These values will be sufficient to actuator the 13 kg arm in a zero-gravity environment.



*Figure 5-2: Testing joint Torque.*

## 5.2 Motor vacuum and vibration tests

### 5.2.1 Aim

To demonstrate that the motor component used in the robotic arm can survive a simulated space environment to demonstrate TRL5.



## 5.2.2 Method

1. Subject motor to low vacuum
- Subject motor to vibration
3. Subject motor to peak acceleration vibration
4. Measure motor torque outputs at multiple currents and compares them to nominal values provides in the technical datasheet

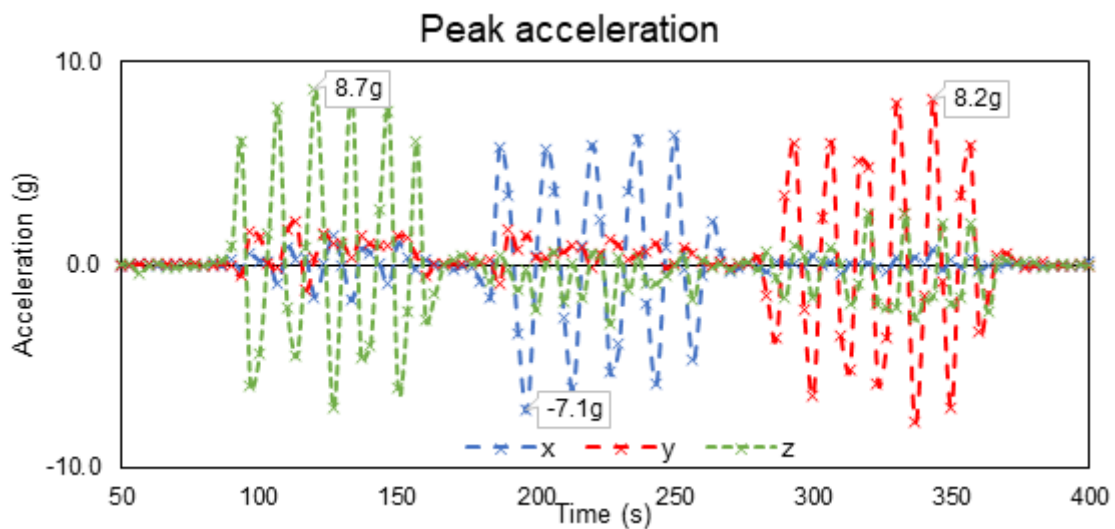


Figure 5-3: Accelerometer measurements for peak acceleration tests of motor.

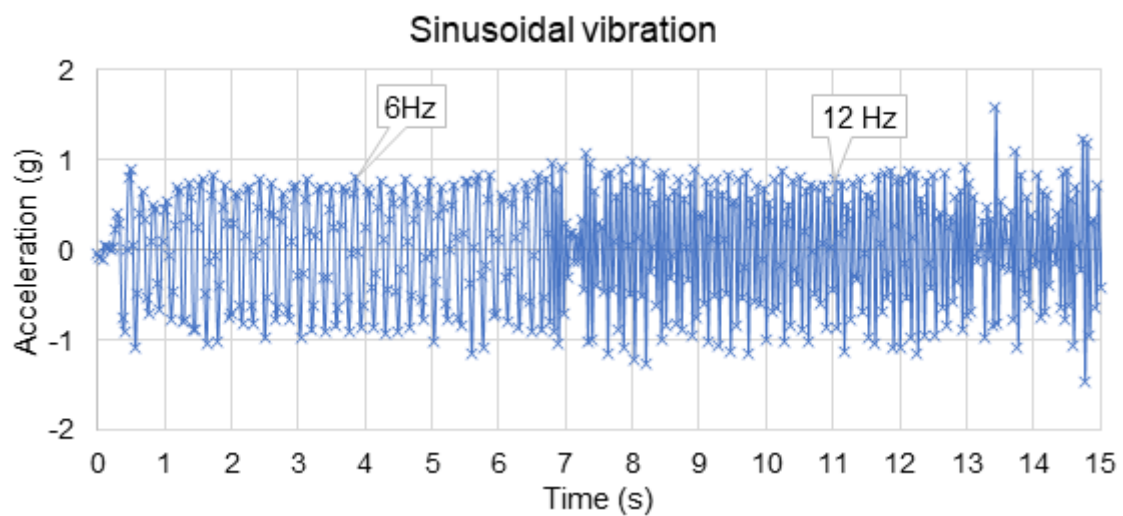
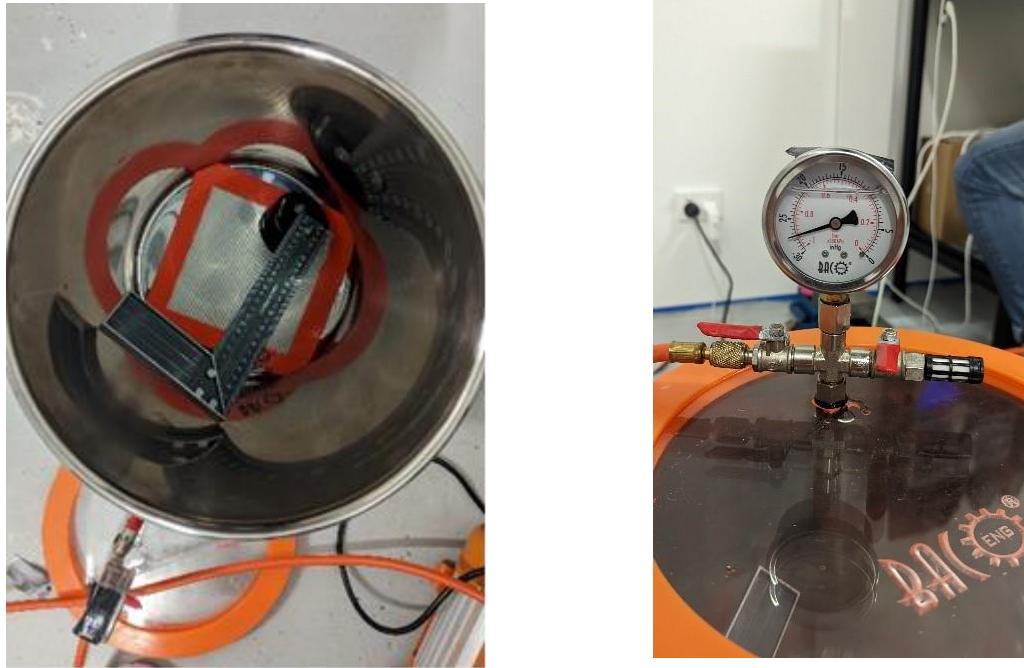


Figure 5-4: Accelerometer measurements for sinusoidal vibration tests of motor

## Implementation and Testing



*Figure 5-5: (left) Motor with torque arm positioned in vacuum chamber (right) pressure gauge reading at vacuum.*

### 5.2.3 Results

The measured torque curve of the motor after the vacuum experiment was found to be marginally above the nominal torque, hence proving that the vacuum chamber did not affect the performance of the motor.

## Implementation and Testing

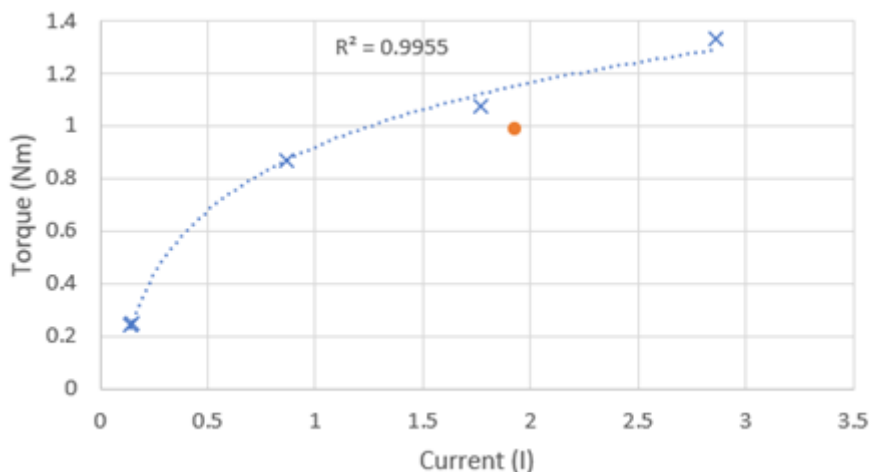


Figure 5-6: Torque Current.

Blue markers showed measured motor torque values while the dotted blue line is the best fit.

The orange marker is the torque value listed on the technical data sheet.

### 5.2.4 Discussion

#### 5.2.4.1 Vacuum

The purpose of the vacuum test is to quantify the resistance of the selected actuators, control systems and mechanical components to vacuum pressures they would typically experience in orbit. Although this experimental setup is not suitable to simulate high-vacuum environments, it still provides valuable insight into the quality and durability of the tested components. Information from this experiment will influence future design iterations and product selection based on their performance during the experiment.

The atmospheric pressure at the time of testing was 0.992 bar, and the chamber decreased the pressure inside by 0.96 bar, so the absolute pressure inside the pressure is 0.032 Bar. The motor was subject to this pressure for 15mins. The time taken to reach the desired pressure took 5 minutes. Outgassing was not deemed to be present as the pressure reached was not low enough. The low pressure was maintained throughout the duration of the experiment, with no leaks or outgassing present and the chamber was kept at constant room temperature.

## Implementation and Testing

A potential improvement to this experimental procedure would be to add interfacing ability with the motor whilst it is within the vacuum chamber to test its ability under a vacuum. Due to the simplistic set-up of the vacuum chamber used for the experiment, this was not possible, and likely a new chamber would be needed to allow for this functionality. However, external vacuum facilities will be used for future experiments, so modification to the current equipment is unnecessary.

### 5.2.4.2 Motor

Pressure testing was conducted on the MyActuator L-70 45T motor that was used in the prototype robot arm. Before being placed in the vacuum chamber, the motor was tested at different current levels to determine the corresponding max torque performance. This process was repeated after the vacuum test provide a comparison to pre-experiment, and hence determine whether the performance of the motor was affected by the vacuum.

Additionally, a consistent torque experimental set-up is required to maintain consistency over torque testing due to inaccuracies in alignment leading to fluctuations in the data gathered. This could be a simple setup with a static motor mount and a lever arm interacting with a point at a consistent distance. However, due to the rudimentary setup used for measuring the torque for this setup, alternations in the positioning of the motor led to discrepancies in the magnitude of torque generated. Additionally, using the internal torque current value of the motor gave inconsistent values being produced, which also led to a change in measuring the torque generated.

To prove that the motor was still operating at the same torque levels as before the vacuum chamber, a torque curve was generated and matched to the manufacturer's specification of torque values. The torque values were measured directly by using a scale to quantify the force of the lever arm. Using the distance to the torque normal from the centre of the motor, the torque could then be derived. Readings were taken at 1A, 2A and 3A current limits, and the

## Implementation and Testing

respective max torque was measured. This was plotted and the nominal current and torque values were compared to the plot.

### 5.2.4.3 Vibration

One of the environments experienced by the prototype will be the launch flight environment via the launch vehicle on route to low earth orbit and transfer manoeuvres while in orbit. The purpose of these tests is to show that the project will be able to perform predictably after transport to its operational environment.

Vibrations are the results of axial acceleration from engine thrust and drag, lateral acceleration from wind gusts, and engine gimbal manoeuvres. The Falcon 9 User Test guides were used as a reference.

Vibrational testing was conducted on the prototype robotic arm to attain whether the system would survive the launch environment. First, an operational test was conducted to assess the mobility of the arm. The arm was inspected for any possible defects or loose fasteners that might cause damage. A Load of 8gs was applied to the prototype arm Axially and laterally. Next sinusoidal forces were applied axially and laterally. The system was then inspected for faults and defects

### 5.2.4.4 Conclusion

The actuator motor has measured an expected torque curve following exposure to low vacuum (24 Torr), sinusoidal vibration (~1 G 6 Hz and ~1 G 12 Hz) and peak acceleration (>7g in x, y and z) demonstrating component validation in relevant orbit and launch environments.

## 5.3 Challenges or issues encountered

A major issue with the arm; which was an oversight during the requirements stage of this prototype, is that the arm is not able to fully actuate itself in Earth's gravity. The mechanical and mechatronic design of the arm had been done on the requirements that had been defined

## Implementation and Testing

for a space application, a micro-gravity environment. Because of this, the actuators within the robotic arm do not have sufficient torque to move the weight of the arm to all points within its reach.

Another issue is the quality and effectiveness of the slip rings that were selected for this prototype. The continuous movement of each joint was defined as a requirement for the robot, and thusly a method of stopping cables from twisting and breaking was required. However, the slip rings that were chosen had very thin cables, were prone to breaking, and were barely capable of carrying the full current needed to operate all joints at once. Larger slip rings are required and will require a larger robot arm because of it.

The arm only uses a relative encoder rather than an absolute, meaning that after it is powered off it has no understanding of where it is in space relative to the environment. This makes doing complex movements of the arm exceedingly difficult and tedious to develop.

There was no brake included in the prototype, as prior to its testing it was considered surplus to requirements. However, after testing this prototype the advantages of including a brake are clear. The two main advantages are that it will act as a fail-safe in the case where the arm loses power, as it will engage and stop the arm from moving. The second advantage is that it will help with the slowing down of satellites that are being actuated by the arm when in orbit.

The through the bore of the actuator is too small. It is difficult to feed through cables during the assembly of the arm.

Joints 3-4 aren't aligned with Joints 1-2. This isn't a huge issue and isn't affecting functionality in any way. But the joints 3-4 are about 1mm off the centre of 1-2.

It will look better if I make them align in the next design.

## Implementation and Testing

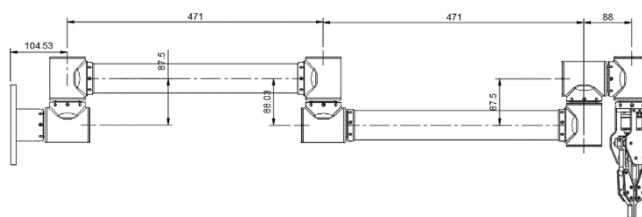


Figure 5-7: Space robotic arm.

Although there are several issues with this prototype, it does satisfy the initial scope that it was set out with, which was to develop a simple TRL5 prototype that would mainly be used to evaluate the mechanical architecture and structure. There were several extremely valuable learning outcomes from this prototype, all of which can now be addressed in future prototypes where we will also be testing out solving new requirements such as thermal shielding and launch conditions.

### 5.4 Passed test cases.

Test cases	Test Method
The control system should automate operations with human in-loop decisions	Inspection
The control system should allow manually input commands	Inspection
The control system shall have a process management unit	Inspection
The control system shall have a complete system on the module	Inspection
The control system shall operate within the data budget	Analysis
The control system shall operate within the power budget	Analysis

## Implementation and Testing

The control system processing shall receive and execute commands from the host	Inspection
The control system processing shall have a booting mechanism	Inspection
The control system processing shall have scheduling and event handling	Inspection
The control system shall give commands to the robotic arm	Inspection
The control system shall be able to receive XYZ coordinate commands	Demonstration
The control system shall be able to executive XYZ coordinate commands	Demonstration
The control system shall moderate motor drive power	Analysis
The control system standby mode shall minimise power draw	Analysis
The control system structure should have a cable management system	Inspection
The control system structure shall physically enclose wires and electronic components	Analysis

## 5.5 Conclusion

We examined the firmware and software components of the space robotic arm. We discussed the importance of implementing robust and fault-tolerant firmware and software to ensure the arm's safe and efficient operation in space environments. We also highlighted the critical role



## Implementation and Testing

of the control system in executing tasks accurately and efficiently and discussed the use of mapping algorithms and collision avoidance functions.

## 6 Research conclusions

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In this chapter, a summary of the main contributions of this research and the future direction to extend the research is presented.

This experiment has validated the space environment suitability for this prototype in the areas of power, positioning, control system and torque requirements. The main shortcomings of this design, however, is the fact that it was designed with 3D printed components and terrestrial testing in mind. Neither of these factors will be considered suitable requirements for the final mission and thus the next prototype must improve upon these.

It is for this reason that the next prototype that Sperospace will be selecting will be a considerably new design, which incorporates the successes and learnings from this prototype but crucially is more suitable to the space environment

### 6.1 Contributions

The development of a new control unit for a robotic arm has the potential to make a significant contribution to the field of robotics. The new control unit could be more efficient and accurate than existing control units, which could lead to improved performance of robotic arm in a variety of applications. Additionally, the new control unit could be more user-friendly and intuitive, which could make it easier for people to use robotic arm in their work or everyday lives. The specific research objectives of this research were achieved as follows.

- Develop a new control algorithm that is more efficient and accurate than existing algorithms.
- Develop a new sensor that can provide more accurate feedback to the control system.
- Develop a new way to interact with the robotic arm that is more user-friendly and intuitive.
- Apply the control unit to a new application that has not been explored before.

## 6.2 Future research

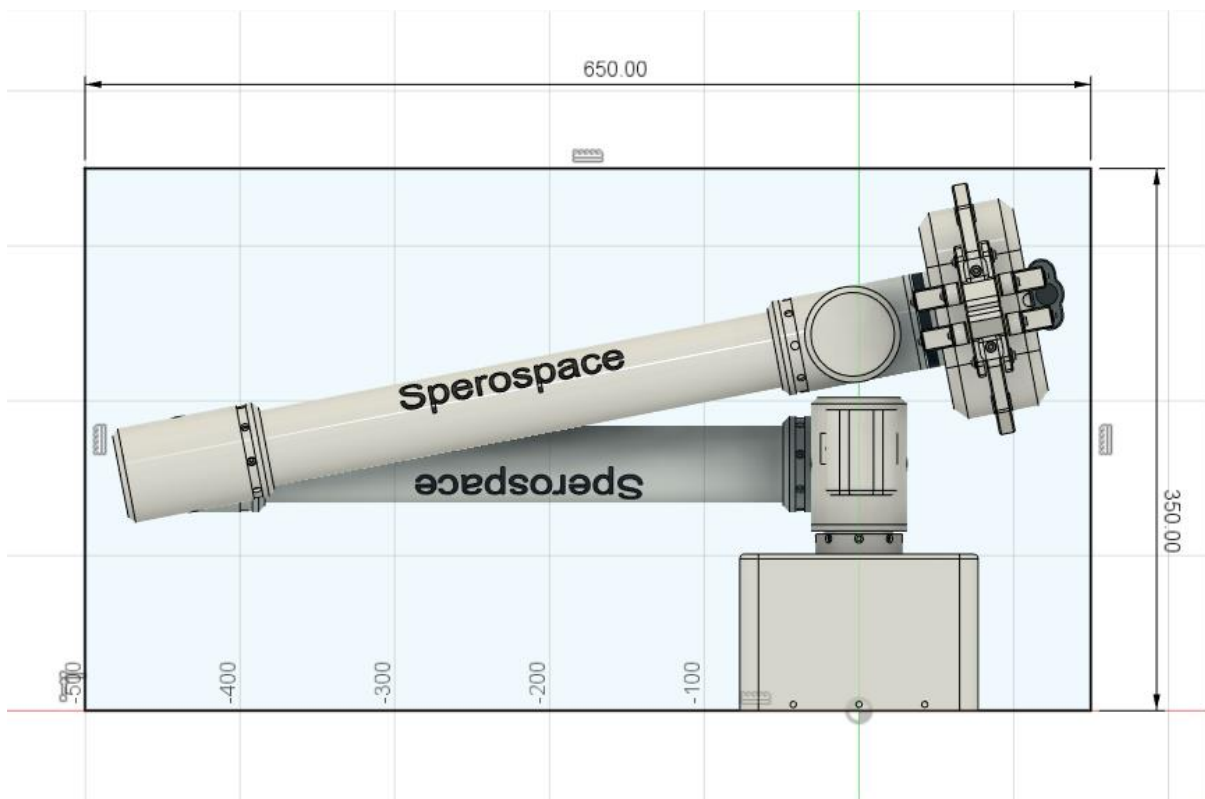
Improved inverse kinematics through a more optimised set of motion planners (via OMPL,/ CHOMP).

Researching inverse kinematic and object manipulation strategies for low-weight robotic arms. And the comparison of that against heavier arms

### 6.2.1 Design consideration for the stowed position

Stowed position of the arm was not taken into consideration for this prototype but definitely should be for the next design.

- Linkage two should be shorter than linkage 1, to allow for it to fold up neatly.
- Joint designs might need to be adapted to allow for this.
- Including features to allow the end of the arm to be attached to the base in this position



### 6.2.2 Include sensors and cameras in the chassis design

## Research conclusions

Cameras and sensors were also not considered in the current arm.

- Joints should either have space for a camera to be integrated or at least have the amenities/holes to allow for cables to go externally.
- Make sure there is extra space for cables and sensors

### **6.2.3 Explore second stage/compound gearing**

We currently have a 100:1 reduction ratio harmonic drive, that can output a max of 15 Nm and will back drive at about 20 Nm (unpowered). It is thought that we might want to make it harder to back drive the actuators because the arm may need to resist the thrust from target satellites in order to slow it down.

- The idea is that we add a second stage gearing to the output of the harmonic drive. So an extra 10:1 ratio gearing would give us a total of 1000:1 (100:1 x 10:1) and would thusly increase our back driving force significantly.
- The added torque will also allow us to move in a 1g environmentally much more easily. And it would also technically make the arm's precision 10x better too, as any motor inaccuracies are 1/1000th as bad.

### **6.2.4 Arm thermals should be considered**

No thermal management was considered in this arm. Even if it is simple and low-level, we should include some thermal management or at least the capability of adding some to the next arm.

- This could include adding a resistor heating array to the arm, or paraffin wax to deal with the heat.

Finally, we discussed some of the current and future applications of space robotic arms, including satellite servicing, assembly and maintenance, planetary exploration, and space

## Research conclusions

debris removal. We emphasised the significant role that spaces robotic arms will play in advancing space exploration and development and highlighted the need for continued research and development in this area.

### 6.2.5 Explore the design of separating the Harmonic Drive and motor

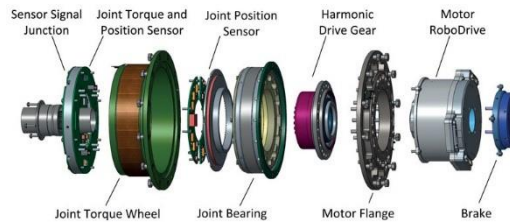


Figure 6-1: Torque Current [Link](#)

Currently, the Harmonic Drive and motor are bolted together to form what we call the “Actuator”. There is the capability of redesigning such that they are bolted to the joint rather than each other, allowing for the motor and electronics to be removed without needing to touch the harmonic drive, and thus the arm can remain assembled.

- This would require a different design/architecture than what we currently use.
- It will use a drive shaft design. A shaft is connected to the input of the HD and magnets are placed on it further down so that the motor can make it spin.

In conclusion, the development of a space robotic arm requires a comprehensive understanding and integration of electrical, mechatronics, firmware, and software components. Through careful design and consideration of the unique challenges and constraints of space environments, a reliable and functional space robotic arm can be developed to support a range of applications in space exploration and development.

# APPENDICES

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## Appendix A : URL

The below URL contains:

- A.1 **Research softcopy**
- A.2 **Presentation**
- A.3 **Lab videos and photos**

URL:

<https://sites.google.com/view/mohamedawadallah/thesis/Space-Robotic-Arm>

## Appendix B : Technical

### B.1 Control unit

[Link](#)

AI Performance	472 GFLOPs
GPU	128-core NVIDIA Maxwell™ GPU
GPU Max Frequency	921MHz
CPU	Quad-Core Arm® Cortex®-A57 MPCore processor
Memory	4 GB 64-bit LPDDR4 25.6GB/s
Storage	16GB eMMC 5.1 †
Video Encode	1x 4K30 2x1080p60 4x1080p30 4x720p60 9x720p30 (H.265 & H.264)
CSI Camera	Up to 4 cameras 12 lanes MIPI CSI-2D-PHY 1.1 (up to 18 Gbps)
PCIE*	1 x4 (PCIe Gen2)
USB*	1x USB 3.0 (5 Gbps) 3x USB 2.0
Networking	1x GbE
Display	2 multi-mode DP 1.2/eDP 1.4/HDMI 2.01 x2 DSI (1.5Gbps/lane)
Other IO	3x UART, 2x SPI, 2x I2S, 4x I2C, GPIOs
Power	5W - 10W
Mechanical	69.6 mm x 45 mm 260-pin SO-DIMM connector

### B.2 Vacuum

The definition of low vacuum can vary depending on the context. In the space industry, low vacuum is typically defined as a pressure of less than 100 millibars (mbar). This is equivalent to a vacuum of 100 torr.

There are a number of space industry standards that define low vacuum. One example is the International Organisation for Standardisation (ISO) standard ISO 14644-1:2015, which defines low vacuum as a pressure of less than 100 mbar.

Another example is the American Society for Testing and Materials (ASTM) standard ASTM E1756-11, which defines low vacuum as a pressure of less than 100 mbar.

In your research, you can cite the ISO or ASTM standard to define low vacuum. You can also cite the specific source that you used to define low vacuum.

Here are some references that you may find helpful:

ISO 14644-1:2015

This standard defines the terminology and classification of cleanrooms and associated controlled environments. It includes a definition of low vacuum as a pressure of less than 100 mbar.

ASTM E1756-11

This standard defines the methods for measuring the pressure in low vacuum environments. It includes a definition of low vacuum as a pressure of less than 100 mbar.



## Appendix C : Completion Letter



TO WHOM IT MAY CONCERN

8<sup>th</sup> June 2023

I write to confirm the completion of the project "Developing a robotic arm for space applications", a project led by Sperospace Pty Ltd in partnership with the University of Technology, Sydney, funded by the NSW Node of the SmartSat CRC under our Space Sector Mobility Program. This program funds placements of up to 6 months for industry representatives to work within NSW Universities, or for NSW researchers to work within industry. In this case, Dr Mohamed Awadallah was placed with Sperospace as an Industry Postdoctoral Fellow, under the supervision of Dr Nic Surawski.

Completed in May 2023, the project leveraged Dr Awadallah's and UTS research team knowledge to develop the control and mechanical systems of the Sperospace robotic arm for space applications, such as assembling satellites and repairing spacecraft. The robotic arm is capable of performing a variety of complex spatial tasks, including gripping, lifting, and manipulating objects.

I attended a recent IEEE-organised end-of-project event where an impressive demonstration of the robotic arm's capabilities was given, and I had an opportunity to publicly congratulate the Sperospace and UTS teams and individuals on their successful partnership. Sperospace CEO and founder Bohan Deng also presented project outcomes, and discussed how proud he was of the robotic arm developed together with Dr Awadallah, describing how it is a key part of their roadmap to proving their technical and economic viability. They are hopeful – as are we – that the work could revolutionize how space missions are conducted.

This was an exemplary project for us, with industry and research collaborating on a high-value project together. Congratulations to all involved.

Yours Faithfully,

Production Note:  
Signature removed prior to publication.

**Dr Tim Parsons**  
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# Biography

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 Dr Awadallah is a senior industry fellow in Engineering who joined UTS in 2013. Experienced engineering professional covering a variety of highly technical roles in both academia and industry. With over a decade of experience in design and development, leading multi-disciplinary teams of engineers in global enterprise environments, and a proven track record for delivering challenging and innovative projects covering a wide range of activities, including operation, tendering and technical evaluation, vendor management, assets management, troubleshooting and reporting. Cost reduction and technical optimisation for different LV and MV equipment ranges to maintain offer competitiveness. Also, I'm MIEAust, SM IEEE, and Mentor Chair VTS and RAS of Australia.



 A/PROF Surawski is a senior lecturer in Environmental Engineering who joined UTS in 2016. Prior to this appointment, he undertook doctoral studies in vehicle emissions at QUT, followed by postdoctoral positions at the CSIRO in pyrogenic carbon cycle dynamics and the Cyprus Institute in atmospheric aerosols. Through these research experiences, Nic has well-developed expertise in the measurement of gaseous and particulate pollutants from combustion systems with emissions from vehicles and bushfires representing typical applications. Nic has significant experience with the quantification of greenhouse gas emissions, criteria pollutants and also unregulated emissions species with a major focus on particle phase species. He also has experience with a range of analytical tools for improving understanding of empirical results such as the development of statistical models, uncertainty analysis and simulation methods. Nic has delivered externally funded research projects (> AUD \$1.2 million) to a variety of stakeholders both within Australia and overseas in his work such as with city councils, alternative engine design companies and federal environmental departments. Dr Surawski is a core member for the Centre for Green Technology (led by Professor John Zhou) and leads a research group focused on Air Quality, Climate and Health research at UTS. In 2017, Dr Surawski was appointed as a member of Working Group III for the IPCC Sixth Assessment Report as an expert reviewer. Nic also acts as a Review Editor for Frontiers in Environmental Engineering.

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"Robotic Arms in Space: A Review of Current Technologies and Future Challenges" by M. A. Khan et al. (2012). This paper reviews the current state of the art in robotic arms in space and discusses the challenges that need to be addressed for future development.

"Robotic Arms for Space Exploration: A Survey of Recent Developments" by S. B. Kelleher et al. (2011). This paper surveys recent developments in robotic arms for space exploration, including new designs, control algorithms, and applications.