

DESIGN AND IMPLEMENTATION OF A ROBOTIC ARM FOR METAL SHEET CUTTING TASK

Samuel Mbakara John

MSc Robotics and Autonomous Systems, Aston University, Birmingham, United Kingdom

Abstract

The increasing demand for precision, repeatability, and safety in manufacturing has accelerated the adoption of robotic automation in metal cutting operations. However, conventional industrial robotic cutting systems remain prohibitively expensive and complex for small and medium-sized enterprises (SMEs), limiting wider adoption. This dissertation presents the design, implementation, and experimental validation of a low-cost, multi-degree-of-freedom robotic arm developed specifically for metal sheet cutting tasks, with an emphasis on accessibility, functional performance, and engineering robustness.

The project adopts a systematic engineering methodology encompassing mechanical design, kinematic and dynamic modelling, control system development, and practical system integration. A multi-DOF robotic arm was designed and modelled using established kinematic frameworks, including forward and inverse kinematics, with motion planning algorithms implemented on a microcontroller-based control architecture. Structural integrity and thermal considerations associated with cutting operations were analysed through computer-aided design (CAD) and finite element analysis (FEA) to ensure safe and reliable operation. The complete system was constructed using commercially available components to maintain cost-effectiveness while meeting functional and safety requirements.

Experimental testing was conducted to evaluate positional accuracy, repeatability, cutting quality, thermal performance, and system reliability. The results demonstrate that the proposed system achieves acceptable accuracy and consistent cutting performance for thin metal sheet materials, while operating within defined safety and thermal limits. Although limitations related to stiffness and cutting speed were identified, the findings confirm the feasibility of low-cost robotic solutions for selected manufacturing applications.

This work contributes a practical and reproducible framework for affordable robotic metal cutting systems, offering valuable insights for future research and development aimed at expanding robotic automation within resource-constrained industrial environments.

Keywords: Robotic sheet metal cutting, Kinova Gen3, articulated robot, ROS control, kinematic modelling, system integration, experimental validation, small scale automation

Table of Contents

Abstract.....	0
Chapter 1 – Introduction	8
1.1 Background and Context.....	8
1.2 Problem Statement	10
1.3 Research Aim and Objectives	11
1.4 Research Questions	12
1.5 Scope, Assumptions, and Limitations	12
1.6 Dissertation Structure.....	13
Chapter 2 – Literature Review	14
2.1 Industrial Automation in Metal Sheet Cutting.....	14
2.2 Low-Cost Robotic Systems: A Comparative Analysis.....	16
2.3 Kinematics and Control of Multi-DOF Robotic Arms	18
2.3.1 Forward and Inverse Kinematics	18
2.3.2 Motion Planning and Path Generation	19
2.3.3 Stepper Motor Control Architectures.....	20
2.4 End-Effector Design for Metal Cutting Applications	21
2.5 Material Selection and Structural Optimisation.....	23
2.6 Thermal Effects and Heat Management in Cutting Operations.....	25
2.7 Performance Metrics and Evaluation Methods.....	27
2.8 Safety, Risk Management, and Ethical Considerations	29
2.9 Research Gap and Chapter Summary	30
Chapter 3 – System Design Methodology	32
3.1 Introduction.....	32
3.2 System Requirements Analysis.....	33
3.2.1 Functional Requirements	33

3.2.2 Non-Functional Requirements	34
3.2.3 Design Constraints	35
3.3 Platform Selection and System Overview	35
3.3.1 Justification for an Articulated Six-Axis Robot.....	35
3.3.2 Relevant Characteristics of the Kinova Gen3	36
3.3.3 Coordinate Frames and Reference Definitions	38
3.4 Mechanical Integration for Sheet Cutting.....	39
3.4.1 Workpiece Fixturing and Cutting Zone Layout	39
3.4.2 End Effector Mounting Strategy	40
3.4.3 Safety and Physical Risk Controls.....	41
3.5 ROS Based Control Architecture	42
3.5.1 Overview of the ROS Control Stack.....	42
3.5.2 Motion Planning Strategy	43
3.5.3 Execution and Monitoring	44
3.6 Software Methodology for Toolpath Execution.....	45
3.6.1 Path Representation	45
3.6.2 Trajectory Smoothing and Corner Handling.....	46
3.6.3 User Interaction Workflow.....	47
3.7 Chapter Synthesis and Transition.....	48
Chapter 4 – Modelling, Analysis, and Simulation	50
4.1 Kinematic Modelling of the Robotic Arm	50
4.1.1 Kinematic Structure and Coordinate Frame Definition	50
4.1.2 Denavit–Hartenberg Parameterisation	52
4.1.3 Forward Kinematics Formulation	52
4.1.4 Inverse Kinematics Solution Strategy.....	53
4.1.5 Workspace Analysis and Singularity Identification	54

4.2 Dynamic and Torque Analysis	54
4.2.1 Modelling Assumptions and Load Conditions.....	55
4.2.2 Joint Torque Estimation Under Cutting Loads	56
4.2.3 Motor and Transmission Sizing Validation.....	57
4.2.4 Vibration, Compliance, and Motion Smoothness Considerations	58
4.3 CAD Modelling and Structural Analysis	58
4.3.1 CAD Development and Assembly Modelling	60
4.3.2 Static Stress and Deformation Analysis.....	61
4.3.3 Modal Analysis for Structural Stability	62
4.3.4 Thermal Analysis of the Cutting End Effector.....	63
4.4 Control System Modelling and Simulation.....	64
4.4.1 Control System Architecture for Simulation.....	64
4.4.2 MATLAB and Simulink Model Development.....	65
4.4.3 PID Control Strategy and Parameter Tuning	66
4.5 Synthesis of Modelling and Analysis Results.....	68
Chapter 5 – System Implementation and Assembly	69
5.1 Introduction to System Implementation.....	69
5.2 Component Procurement and Verification.....	69
5.3 Mechanical Assembly	70
5.3.1 Base and Joint Assembly	71
5.3.2 Motor Installation and Alignment.....	71
5.3.3 End Effector Mounting and Calibration	72
5.3.4 Assembly Tolerances and Precision Issues	72
5.4 Electrical Integration.....	73
5.4.1 Power Supply Selection and Distribution.....	73
5.4.2 Motor Driver Configuration.....	74

5.4.3 Wiring, Grounding, and Safety Considerations	74
5.4.4 Signal Integrity and Noise Mitigation.....	75
5.4.5 Electrical Integration Verification.....	75
5.5 Software Development.....	76
5.5.1 Software Architecture and Design Approach.....	76
5.5.2 Motion Control and Trajectory Execution	77
5.5.3 Feedback Handling and Monitoring	77
5.5.4 Safety and Fault Handling Logic	78
5.5.5 User Interaction and Operational Workflow	78
5.5.6 Debugging and Code Optimisation.....	78
5.5.7 Software Scope and Constraints	79
5.6 System Integration and Preliminary Testing.....	79
5.6.1 Integration Sequence and Verification Strategy.....	79
5.6.2 Incremental Motion Testing	80
5.6.3 Preliminary Cutting Trials.....	80
5.6.4 Observation, Logging, and Fault Handling.....	81
5.6.5 Integration Outcomes and Readiness for Experimental Evaluation	81
Chapter 6 – Experimental Testing and Validation	82
6.1 Experimental Setup and Methodology.....	82
6.1.1 Test Environment and Equipment.....	82
6.1.2 Measurement Instruments and Procedures	83
6.1.3 Test Materials and Specimen Preparation.....	83
6.1.4 Risk Assessment and Safety Measures	84
6.2 Mechanical Performance Evaluation	84
6.2.1 Positional Accuracy and Repeatability	84
6.2.2 Practical Workspace Validation Under Load	85

6.2.3 Joint Backlash and Stiffness Assessment.....	85
6.3 Cutting Performance Evaluation.....	85
6.3.1 Cutting Path Accuracy	85
6.3.2 Edge Quality and Surface Finish	86
6.3.3 Cutting Force and Thermal Behaviour.....	87
6.3.4 Tool Wear and Durability.....	87
6.4 Reliability and Endurance Testing	88
6.4.1 Continuous Operation Tests	89
6.4.2 Thermal Behaviour Over Extended Use	89
6.4.3 Observed Failure Modes and Practical Limitations.....	90
6.5 Comparison with Existing Solutions	90
6.5.1 Cost and Performance Comparison	90
6.5.2 Practical Advantages and Limitations.....	91
Chapter 7 – Results and Analysis.....	92
7.1 Mechanical System Performance.....	92
7.2 Control Performance and Motion Accuracy	92
7.3 Cutting Quality and Process Consistency	93
7.4 Power Demand and Thermal Behaviour.....	94
7.5 Economic and Practical Evaluation	95
Chapter 8 – Discussion	97
8.1 Alignment with Project Aim and Objectives	97
8.2 Interpretation of Experimental Findings.....	98
8.3 Comparison with Literature and Commercial Systems	99
8.4 Design Decisions and Engineering Judgement.....	102
8.5 Implications for Small Scale Manufacturing and Future Development	103
Chapter 9 – Conclusions and Future Work	105

9.1 Summary of Contributions.....	105
9.2 Key Engineering Outcomes	105
9.3 Project Limitations.....	106
9.4 Recommendations for Future Development	107
9.4.1 Advanced Control Strategies.....	107
9.4.2 Sensor Integration and Feedback Control.....	108
9.4.3 Vision Assisted or Learning Supported Path Planning	108
9.4.4 Scalability and Design Improvements	109
9.5 Final Remarks	109
References.....	110
Appendices.....	112

Chapter 1 – Introduction

1.1 Background and Context

Manufacturing sectors across the globe are increasingly integrating automation technologies in response to growing demands for productivity, product consistency, and safer working conditions. Within this context, robotics has become a fundamental driver of industrial transformation, enabling automated systems to undertake tasks that are repetitive, accuracy-critical, or potentially hazardous. In factory settings, robotic platforms are now routinely used for processes such as welding, assembly, surface finishing, and material handling, where dependable performance and repeatable motion are essential to achieving reliable manufacturing outcomes (Asada and Slotine, 1986).

One manufacturing process that continues to present significant challenges is metal sheet cutting. Sheet metal components are fundamental to industries such as aerospace, automotive, construction, and general fabrication, where dimensional accuracy and edge quality are essential for downstream assembly and structural integrity. Despite advances in computer numerical control (CNC) machinery and laser cutting systems, a considerable proportion of metal sheet cutting within small and medium-sized enterprises (SMEs) is still performed using manual or semi-automated tools. These approaches often rely heavily on operator skill and experience, leading to variability in cut quality, reduced repeatability, and increased material waste.



Figure 1.1: Manual sheet metal cutting vs automated robotic cutting processes

Manual cutting operations also introduce substantial health and safety risks. Operators are routinely exposed to sharp cutting tools, elevated temperatures at the cutting interface, flying debris, and repetitive motion, all of which contribute to an increased likelihood of injury and long-term musculoskeletal disorders. As production demands increase, operator fatigue further exacerbates these risks, reducing both productivity and safety. These limitations highlight the growing need for automated solutions that can perform cutting tasks reliably while reducing direct human exposure to hazardous conditions.

Robotic arms offer a compelling alternative by enabling programmable, repeatable, and highly controlled motion. By integrating mechanical actuation with embedded control systems, robotic arms can execute predefined cutting paths with a high degree of consistency, independent of operator fatigue or environmental variation. In addition, software-based control allows rapid modification of cutting geometries without the need for extensive mechanical reconfiguration, providing flexibility that is particularly valuable for low-volume or customised production.

Even with the growing advantages of robotic cutting systems, their use isn't consistent across the industry. While large manufacturers often invest in industrial-grade robots, these systems tend to be costly, take up significant space, and are built for demanding, high-speed operations. This combination of high expense, system complexity, and reliance on closed, proprietary software often makes them impractical for smaller companies and educational institutions (Krüger and Yang, 2022). As a result, there exists a clear gap between manual cutting methods and industrial-grade robotic automation. The versatility of sheet metal fabrication is evidenced by its widespread application across diverse sectors, including aerospace and automotive manufacturing, as illustrated in Figure 1.2.

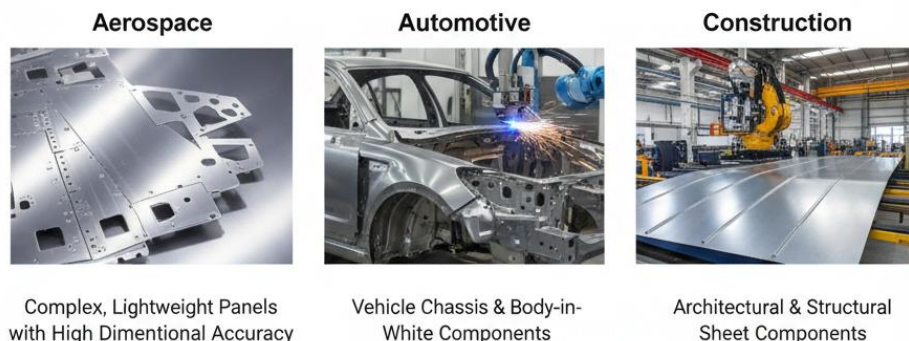


Figure 1.2: Key industrial application areas for precision sheet metal cutting.

Recent advancements in low-cost embedded systems have begun to address this gap. Microcontrollers such as the Arduino Mega 2560, when combined with affordable stepper motors, open-source firmware libraries, and modular mechanical components, enable the development of capable robotic systems at significantly reduced cost (Ali et al., 2023). Furthermore, modern computer-aided design (CAD) tools and simulation platforms allow engineers to model, analyse, and optimise robotic systems prior to physical construction, reducing development risk and supporting informed design decisions.

Motivated by these developments, this project aims to design and implement a cost-effective, programmable robotic arm specifically tailored for metal sheet cutting tasks. The intention is not to replicate industrial CNC or laser cutting systems, but rather to explore how an accessible robotic solution can improve cutting precision, repeatability, and safety within resource-constrained environments. By focusing on modularity, affordability, and practical performance, the project seeks to demonstrate the feasibility of low-cost robotic automation for small-scale manufacturing and educational applications.

1.2 Problem Statement

Despite the recognised benefits of robotic automation in metalworking, SMEs continue to face significant barriers to adoption. Commercial robotic cutting systems are often prohibitively expensive, require specialist training, and involve complex integration with existing workflows. Many of these systems are also over-specified for lightweight sheet metal cutting, resulting in unnecessary cost and complexity for relatively simple tasks.

Consequently, manual and semi-automated cutting methods remain prevalent. These methods are associated with inconsistent cutting accuracy, poor repeatability, increased scrap rates, and elevated safety risks. Variations in operator skill, tool wear, and working conditions can all negatively affect cut quality, making it difficult to achieve reliable and repeatable outcomes.

Although a growing body of academic and hobbyist literature explores low-cost robotic arms, many existing designs exhibit notable limitations. Common issues include insufficient joint torque, structural flexibility, excessive vibration, and inaccuracies caused by backlash in mechanical joints (Chauhan et al., 2015). In cutting applications, these issues are further compounded by resistive forces at the cutting interface and thermal effects generated by prolonged tool operation. If not adequately addressed, these factors can significantly degrade cutting performance and reduce system reliability.

Another challenge lies in control system implementation. Resource-constrained microcontrollers must coordinate multiple joints in real time while maintaining smooth motion and positional accuracy. Poorly tuned motion profiles or inadequate synchronisation can result in path deviation, overshoot, and uneven cutting edges. These challenges highlight the need for careful integration of mechanical design, kinematic modelling, and embedded control.

The central problem addressed in this dissertation is therefore the absence of an affordable, programmable robotic arm that can perform clean, consistent metal sheet cutting operations while maintaining acceptable levels of accuracy, repeatability, and safety. Addressing this problem requires a balanced engineering approach that considers mechanical rigidity, actuator selection, control architecture, thermal behaviour, and system usability within realistic cost and resource constraints.

1.3 Research Aim and Objectives

Research Aim

The primary aim of this project is to design, construct, and evaluate a cost-effective, programmable robotic arm capable of executing accurate and repeatable metal sheet cutting tasks using widely available mechanical and electronic components.

Research Objectives

To achieve this aim, the following objectives are defined:

1. To design a multi-degree-of-freedom robotic arm structure using CAD tools, with joint configurations optimised for reach, mechanical stability, and effective torque distribution during cutting operations.
2. To develop an embedded control architecture based on an Arduino Mega 2560 microcontroller and compatible stepper motor drivers, enabling coordinated multi-axis motion control.
3. To implement forward and inverse kinematics algorithms that allow precise positioning of the cutting end-effector along predefined cutting paths.
4. To design and integrate a rotary cutting end-effector capable of cutting thin metal sheets, including aluminium and mild steel up to approximately 1.5 mm thickness.

5. To experimentally evaluate the performance of the robotic arm in terms of positional accuracy, repeatability, cutting quality, and thermal behaviour under practical operating conditions.

1.4 Research Questions

This study is guided by the following research questions:

1. How can a low-cost robotic arm be mechanically designed to provide sufficient rigidity and stability for metal sheet cutting tasks?
2. To what extent can Arduino-based control systems and stepper motors deliver the positional accuracy and repeatability required for cutting applications?
3. How effectively can inverse kinematics and motion planning algorithms be implemented on a microcontroller-based platform?
4. What impact do mechanical design choices and control parameters have on vibration, thermal behaviour, and overall cutting quality?
5. How does the developed system compare with existing manual methods and low-cost robotic solutions in terms of performance, cost, and practicality?

1.5 Scope, Assumptions, and Limitations

This project focuses on the development of a robotic arm intended for lightweight metal sheet cutting in laboratory and small-scale manufacturing environments. The system is designed to cut thin aluminium and mild steel sheets with thicknesses of up to approximately 1.5 mm. High-speed or high-volume industrial production is outside the scope of this work.

It is assumed that the robotic arm will operate in a controlled indoor environment with a stable power supply and limited external disturbances. Cutting paths are predefined and executed without real-time sensory feedback or adaptive control. Passive thermal management techniques are considered sufficient for the intended operating duty cycle.

Several limitations are acknowledged. Advanced sensing technologies such as force feedback, machine vision, and closed-loop servo control are not implemented due to time and resource constraints. The reliance on open-loop stepper motor control may limit absolute positional accuracy under varying load conditions. Additionally, the system is not intended to compete directly with industrial CNC or laser cutting machines in terms of speed or throughput.

Nevertheless, the defined scope is appropriate for demonstrating fundamental principles of robotic design, embedded control, and automated manufacturing at MSc level.

1.6 Dissertation Structure

This dissertation is organised into nine chapters.

Chapter 1 introduces the project background, motivation, problem statement, research objectives, scope, and structure.

Chapter 2 presents a critical review of literature related to robotic automation in metal cutting, low-cost robotic systems, kinematics and control strategies, end-effector design, thermal considerations, safety, and performance evaluation.

Chapter 3 describes the overall system design methodology, including mechanical design, electrical and control system architecture, and software structure.

Chapter 4 details the mathematical modelling and simulation work undertaken, covering kinematic analysis, torque estimation, CAD modelling, finite element analysis, and control system simulation.

Chapter 5 outlines the practical implementation and assembly of the robotic arm, including mechanical construction, electrical integration, and firmware development.

Chapter 6 describes the experimental testing and validation procedures used to assess system performance and safety.

Chapter 7 presents and analyses the experimental results obtained from mechanical, control, and cutting performance tests.

Chapter 8 discusses the results in relation to the project objectives, highlighting design concessions, limitations, and implications for small-scale manufacturing.

Chapter 9 concludes the dissertation by summarising the project contributions and identifying opportunities for future development.

Chapter 2 – Literature Review

2.1 Industrial Automation in Metal Sheet Cutting

Industrial automation has become a defining feature of modern manufacturing, enabling higher levels of productivity, consistency, and safety across a wide range of processes. Within this context, metal sheet cutting represents a critical operation, forming the basis for components used in aerospace, automotive, construction, and general engineering applications. Traditionally, metal sheet cutting has been performed using manual methods such as hand shears, plasma cutters, or mechanically assisted tools. While these techniques remain widespread, particularly within small and medium-sized enterprises (SMEs), they are inherently limited by operator dependency, variability in cut quality, and elevated safety risks. The introduction of automated cutting technologies such as computer numerical control (CNC) milling, laser cutting, and waterjet cutting has significantly improved precision and repeatability in high-volume manufacturing environments. These systems are capable of achieving tight dimensional tolerances and superior edge quality through precise control of tool motion and cutting parameters. However, they are often associated with high capital costs, substantial spatial requirements, and complex maintenance demands. As a result, their adoption is largely confined to large-scale industrial facilities with sufficient financial and technical resources.

To contextualise the role of robotic automation within the broader landscape of metal sheet cutting technologies, Table 2.1 presents a comparative overview of manual, CNC-based, and robotic cutting approaches commonly adopted in manufacturing environments.

Table 2.1: Comparison of Manual, CNC-Based, and Robotic Metal Sheet Cutting Approaches

Criterion	Manual Cutting Methods	CNC-Based Cutting Systems	Robotic Metal Sheet Cutting Systems
Capital cost	Very low initial cost; minimal equipment investment	Very high capital cost, including machinery, installation, and infrastructure	Moderate to high depending on system complexity; low-cost variants are increasingly accessible
Operating skill requirement	High dependence on operator skill and experience	High dependence on operator skill and experience	High dependence on operator skill and experience

Accuracy and repeatability	Low to moderate; significant variability between operators	Low to moderate; significant variability between operators	Low to moderate; significant variability between operators
Flexibility and reconfigurability	High flexibility but limited precision	High flexibility but limited precision	High flexibility but limited precision
Productivity	Low to moderate; limited by operator fatigue	Very high; optimised for mass production	Moderate; suitable for low- to medium-volume production
Safety exposure	High operator exposure to sharp tools, heat, and debris	High operator exposure to sharp tools, heat, and debris	High operator exposure to sharp tools, heat, and debris
Space requirements	Minimal	Large footprint with dedicated workspace	Moderate; smaller than CNC systems, scalable layouts
Maintenance complexity	Low	High; specialist maintenance often required	Moderate; simpler hardware in low-cost systems
Suitability for SMEs	Common but inefficient and inconsistent	Often unsuitable due to cost and scale	Increasingly suitable, especially low-cost robotic solutions

As shown in Table 2.1, robotic cutting systems occupy a middle ground between manual and CNC-based approaches, offering improved flexibility and safety without the high capital cost associated with fully automated CNC solutions.

Robotic automation offers an alternative approach by decoupling cutting performance from rigid, task-specific machinery. Articulated robotic arms can be programmed to follow complex trajectories, adapt to different workpiece geometries, and perform multiple tasks using interchangeable end-effectors. In metal cutting applications, robotic systems have been successfully employed for plasma cutting, laser trimming, and abrasive cutting, particularly where flexibility and reconfigurability are required. The key advantage of robotic automation lies in its ability to combine precision with adaptability, allowing manufacturers to respond rapidly to changes in product design or production volume (Asada and Slotine, 1986).

Despite these advantages, the majority of robotic cutting solutions reported in industry literature are designed for high-load, high-speed operations. Such systems typically rely on industrial-grade servomotors, proprietary controllers, and rigid safety enclosures, all of which contribute to increased cost and system complexity. For SMEs engaged in lightweight sheet metal fabrication, these solutions are frequently disproportionate to operational needs.

Consequently, manual and semi-automated cutting methods continue to dominate this segment of the manufacturing sector.

Recent research has highlighted the potential of lightweight robotic systems for material processing tasks traditionally considered unsuitable for low-cost automation. Ali et al. (2023) demonstrated that appropriately designed multi-degree-of-freedom (DOF) robotic arms, when combined with suitable control strategies, can achieve acceptable accuracy and repeatability for lightweight industrial tasks. These findings suggest that robotic automation in metal sheet cutting does not necessarily require industrial-scale hardware, provided that mechanical design, actuation, and control are carefully optimised.

2.2 Low-Cost Robotic Systems: A Comparative Analysis

Low-cost robotic systems have attracted significant academic and industrial interest over the past decade, driven by advances in embedded electronics, open-source software, and additive manufacturing. These developments have lowered the barriers to entry for robotic system design, enabling researchers, educators, and SMEs to explore automation solutions without reliance on expensive proprietary platforms.

In contrast to industrial robots, which prioritise high payload capacity, speed, and durability, low-cost robotic arms are typically designed for lightweight tasks and moderate operating speeds. They commonly employ stepper motors or low-cost servomotors, aluminium or polymer-based structural components, and microcontroller-based control units. While these design choices impose certain performance limitations, they also offer advantages in terms of affordability, ease of modification, and accessibility.

To clearly distinguish between industrial robotic platforms and low-cost robotic systems, Table 2.2 summarises the key differences in performance characteristics, control architecture, cost, and suitability for small-scale manufacturing environments.

Table 2.2: Comparison of Industrial Robotic Arms and Low-Cost Robotic Arms

Parameter	Industrial Robotic Arms	Low-Cost Robotic Arms
Typical application domain	High-load, high-speed industrial manufacturing	Education, research, prototyping, lightweight manufacturing
Payload capacity	High (often >10 kg)	Low to moderate (typically <5 kg)

Actuation technology	Closed-loop servo motors with high-resolution encoders	Stepper motors or low-cost servomotors, often open-loop
Control architecture	Proprietary controllers with advanced motion planning	Microcontroller-based or open-source control platforms
Positional accuracy	Very high absolute accuracy	Moderate absolute accuracy; repeatability often acceptable
Repeatability	Excellent	Good when mechanically and dynamically well designed
Structural stiffness	High rigidity using industrial-grade materials	Lower stiffness; dependent on material choice and design optimisation
Cost	Very high acquisition and maintenance cost	Low to moderate cost; accessible to SMEs and academia
System flexibility	High but constrained by proprietary ecosystems	Very high; modular and easily modified
Maintenance and repair	Specialist servicing often required	Repairable and user-maintainable
Integration complexity	High; requires specialist knowledge	Lower; suitable for iterative development
SME suitability	Limited	High, particularly for task-specific automation

As illustrated in Table 2.2, low-cost robotic systems sacrifice speed and payload capacity in favour of affordability, modularity, and accessibility, making them more appropriate for educational settings and SMEs with limited resources.

A comparative analysis of low-cost robotic arms reveals recurring design concessions. Chauhan et al. (2015) highlighted that modular robotic arms constructed using off-the-shelf components offer improved maintainability and scalability, but often suffer from reduced structural stiffness and increased joint backlash. Similarly, Ali et al. (2023) noted that torque limitations in low-cost actuators can restrict the range of tasks that such systems can perform reliably.

From a control perspective, low-cost systems frequently rely on open-loop control architectures due to the absence of high-resolution feedback sensors. While this simplifies implementation, it places greater emphasis on accurate mechanical design and careful calibration to minimise cumulative positioning errors. Nevertheless, studies have shown that for applications involving moderate loads and well-defined trajectories, open-loop control setups are capable of achieving

reliable motion accuracy for specific tasks, despite the absence of feedback mechanisms (Pratheesh Kumar et al., 2023).

Economically, low-cost robotic systems align closely with the needs of SMEs. Krüger and Yang (2022) argued that repairable, modular automation solutions support circular business models by extending system lifespan and reducing dependence on specialised service providers. This perspective is particularly relevant for educational and small-scale manufacturing environments, where flexibility and long-term maintainability are often prioritised over peak performance.

2.3 Kinematics and Control of Multi-DOF Robotic Arms

The performance of a robotic arm is fundamentally governed by its kinematic structure and control architecture. In multi-degree-of-freedom (DOF) systems, the relationship between joint variables and end-effector pose is inherently nonlinear and highly coupled, necessitating rigorous mathematical modelling and carefully selected control strategies. For material processing applications such as metal sheet cutting, these considerations are particularly critical, as even small positioning errors or dynamic instabilities can lead to poor cut quality, tool wear, or mechanical failure.

In low-cost robotic arms, kinematic and control design must also account for practical constraints, including limited actuator torque, structural compliance, sensor availability, and computational capacity. Consequently, an effective system design balances theoretical precision with implementable, resource-efficient solutions.

2.3.1 Forward and Inverse Kinematics

Forward kinematics defines the mapping between joint space and Cartesian space, allowing the position and orientation of the end-effector to be determined from known joint variables and link dimensions. This formulation is essential for workspace analysis, collision checking, and offline simulation prior to physical implementation. The Denavit–Hartenberg (D–H) convention remains one of the most widely adopted methods for modelling serial manipulators, providing a standardised approach to defining coordinate frames and homogeneous transformation matrices (Asada and Slotine, 1986).

In the context of low-cost robotic arms, forward kinematic models are particularly valuable during the design stage, as they enable designers to assess reachability and identify singular

configurations before fabrication. Furthermore, accurate forward models support visualisation and debugging during system integration, especially when external sensing is limited.

Inverse kinematics (IK) addresses the complementary problem of determining the joint variables required to achieve a desired end-effector pose. Unlike forward kinematics, IK does not always yield a unique or closed-form solution, particularly for manipulators with redundant or constrained degrees of freedom. Multiple joint configurations may satisfy the same Cartesian pose, while mechanical joint limits and link interference can further restrict feasible solutions.

Motta et al. (2016) demonstrated that iterative numerical methods, such as Jacobian-based solvers and optimisation-driven approaches, are effective for multi-DOF robotic arms performing surface processing tasks. These methods allow the incorporation of constraints related to joint limits, smoothness, and energy efficiency. However, they are computationally intensive and may be unsuitable for real-time execution on low-power microcontrollers.

As a result, low-cost robotic systems frequently employ simplified inverse kinematic solutions. Geometric approaches, which exploit known link geometries and planar assumptions, offer deterministic and computationally efficient alternatives when applicable. In more complex configurations, precomputed lookup tables or discretised workspace mappings may be used to reduce online computation. While these approaches sacrifice absolute accuracy for practicality, they are often sufficient for cutting tasks involving predefined paths and limited workspace variability.

2.3.2 Motion Planning and Path Generation

Motion planning determines how a robotic arm transitions between configurations while satisfying constraints related to joint limits, collision avoidance, and dynamic feasibility. In metal sheet cutting applications, motion planning is intrinsically linked to process quality, as the cutting tool must follow a continuous and stable trajectory to maintain consistent kerf width and edge finish.

For low-cost robotic arms, motion planning strategies are typically simplified to reduce computational overhead. Linear interpolation in Cartesian space is commonly adopted for cutting paths, as it aligns naturally with geometric definitions of cut profiles. This approach is often combined with joint-space interpolation to ensure that individual actuators operate within safe limits.

Velocity and acceleration profiling play a critical role in reducing vibration and mechanical stress. Trapezoidal velocity profiles are widely used due to their simplicity, while S-curve

profiles provide smoother acceleration transitions by limiting jerk. Reduced jerk is particularly beneficial for lightweight robotic arms, where structural compliance can amplify dynamic disturbances. Cong et al., (2022) reported that appropriate motion profiling significantly improves positional stability in stepper-driven robotic systems.

In practice, open-source motion control libraries such as AccelStepper enable coordinated multi-axis control with configurable acceleration limits. These tools abstract low-level timing and step generation, allowing designers to focus on higher-level path planning logic. However, their effectiveness depends on accurate parameter tuning and an understanding of the mechanical system's dynamic behaviour.

2.3.3 Stepper Motor Control Architectures

Stepper motors are widely employed in low-cost robotic systems due to their affordability, ease of control, and inherent ability to maintain position without feedback. When operated in microstepping mode, stepper motors can achieve fine angular resolution and smoother motion compared to full-step operation. This characteristic is advantageous for cutting applications, where gradual tool movement reduces chatter and improves surface finish.

Despite these advantages, stepper motors are typically operated in open-loop control architectures, meaning that actual motor position is inferred rather than measured. Under conditions of excessive load, rapid acceleration, or unexpected disturbances, stepper motors may lose synchronisation, resulting in missed steps and cumulative positioning errors. This limitation is particularly relevant in cutting tasks, where resistive forces can vary along the cutting path due to changes in material thickness or tool engagement.

Effective stepper motor control, therefore, requires careful consideration of motor sizing, driver selection, and current regulation. Modern stepper drivers incorporate features such as adjustable current limiting and decay modes, which influence torque output and thermal performance. Park et al., (2020) emphasised that coordinated control of multiple stepper motors, combined with conservative acceleration profiles, is essential for maintaining trajectory accuracy in multi-axis robotic applications. The functional relationship between the microcontroller, stepper drivers, and actuators in a low-cost robotic arm is illustrated in Figure 2.1.

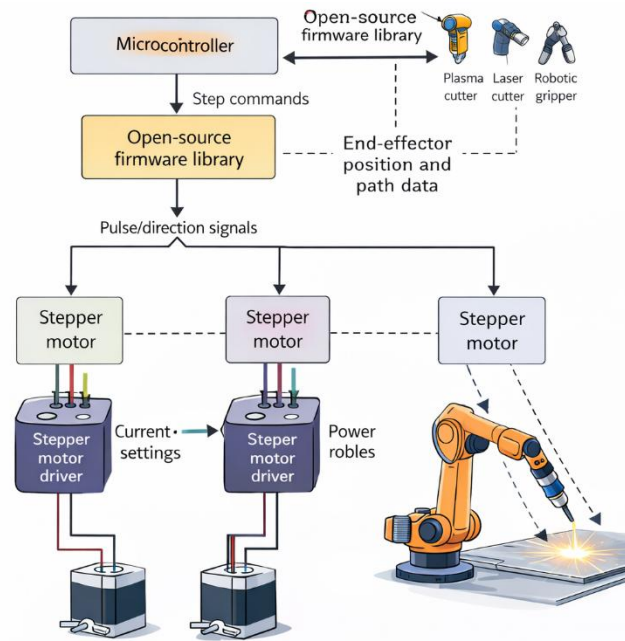


Figure 2.1: Stepper motor control architecture for a multi-axis robotic arm

This architecture highlights the reliance on open-loop position control and underscores the importance of conservative acceleration and current settings in cutting applications. In low-cost robotic cutting systems, reliability is often prioritised over speed. By operating motors well below their maximum torque and speed limits, designers can mitigate the risk of missed steps without the need for closed-loop feedback. While this approach reduces throughput, it aligns with the performance requirements of lightweight metal sheet cutting and supports robust operation within constrained budgets.

2.4 End-Effector Design for Metal Cutting Applications

The end-effector constitutes the most application-critical subsystem in a robotic metal sheet cutting system, as it directly governs the interaction between the robotic arm and the workpiece. Its design has a decisive influence on cutting accuracy, edge quality, process stability, and operational safety. In contrast to tasks such as pick-and-place or material handling, cutting operations introduce continuous resistive forces, vibration, and thermal loads, all of which must be accommodated without compromising the positional integrity of the robotic arm.

In industrial environments, metal sheet cutting is commonly performed using high-energy processes such as laser cutting, plasma cutting, or waterjet systems integrated with CNC gantries or industrial robotic arms. These end-effectors offer exceptional cutting speed and precision but require substantial capital investment, complex safety infrastructure, and high

power consumption. Consequently, their application is largely restricted to large-scale manufacturing facilities. For low-cost and SME-oriented robotic systems, mechanically driven cutting tools present a more practical alternative due to their simplicity, affordability, and ease of integration (Ali et al., 2023).

Among mechanically driven solutions, rotary cutting end-effectors are widely reported in the literature as a suitable option for lightweight metal sheet cutting. Rotary cutters operate through continuous rotational motion of a circular blade, generating a controlled shearing action at the cutting interface. Compared with reciprocating or impact-based tools, rotary mechanisms produce smoother cutting forces, reduced vibration, and more predictable tool–workpiece interaction, which are advantageous for serial robotic arms with limited structural stiffness (Pratheesh Kumar et al., 2023). Their compact geometry also minimises added mass and inertia at the wrist, which is critical for maintaining dynamic stability in multi-DOF robotic systems.

The mechanical design of a rotary cutting end-effector must account for blade material, blade geometry, drive motor selection, and mounting configuration. Hardened steel and tungsten-carbide-tipped blades are commonly used for cutting aluminium and mild steel sheets, offering a balance between wear resistance and cost. Blade diameter directly influences cutting depth, kerf width, and required cutting torque. Larger blades enable deeper cuts but increase rotational inertia and torque demand, which may exceed the capabilities of low-cost drive motors. As a result, blade selection must be aligned with both material thickness and the torque limitations of the end-effector motor.

Mounting rigidity represents a critical design consideration, particularly in serial robotic arms where compliance accumulates along the kinematic chain. Any flexibility or misalignment at the end-effector interface can amplify vibration, leading to chatter, uneven kerf geometry, and accelerated tool wear. Reddy and Eranki (2016) demonstrated that end-effector compliance has a disproportionate effect on positional accuracy compared to equivalent compliance in upstream links. Consequently, reinforced brackets, short tool overhangs, and rigid fastening methods are strongly recommended to preserve alignment during cutting operations.

A further consideration is the relationship between cutting forces, torque demand, and upstream joint loading. During cutting, resistive forces generated at the blade–material interface translate into reaction torques at the end-effector motor and reaction moments transmitted through the wrist and arm joints. In low-cost robotic systems, where joint actuators operate near their torque limits, unaccounted cutting forces can result in joint deflection, missed steps in stepper motors,

or cumulative positioning error. The literature emphasises that conservative cutting parameters and robust end-effector mounting are essential to limit force transmission and maintain overall system stability (Ali et al., 2023). This force–torque coupling highlights the importance of treating end-effector design as an integral component of the robot’s mechanical and control architecture, rather than an isolated attachment.

Modularity is increasingly identified as a key design principle in low-cost robotic systems. Modular end-effector interfaces allow tools to be replaced, upgraded, or reconfigured without extensive mechanical redesign, enhancing system versatility and longevity (Chauhan et al., 2015). For educational and SME applications, this modularity enables a single robotic platform to support multiple manufacturing tasks, including marking, trimming, drilling, or light milling, thereby improving cost-effectiveness and return on investment.

This literature indicates that rotary cutting end-effectors provide a pragmatic and technically sound solution for low-cost robotic metal sheet cutting when designed within clearly defined operating limits. While they cannot match the speed or material capacity of industrial cutting technologies, their favourable balance of performance, affordability, and integration simplicity makes them well-suited to small-scale manufacturing, prototyping, and educational environments. Careful consideration of cutting forces, torque transmission, and structural rigidity is essential to ensuring reliable operation and acceptable cutting quality in such systems. However, a clear gap remains in the integration of these concepts specifically for metal sheet cutting using affordable, modular robotic arms.

Many existing studies focus either on industrial-scale cutting systems or on low-cost robotic arms designed for material handling and educational purposes. Limited attention has been given to the combined challenges of cutting force management, thermal effects, and positional accuracy within resource-constrained robotic platforms. Furthermore, few studies provide comprehensive experimental evaluations that consider mechanical, control, and cutting performance simultaneously.

2.5 Material Selection and Structural Optimisation

Material selection plays a decisive role in determining the structural performance, accuracy, and durability of robotic arms, particularly in cutting applications where external forces and vibrations are present. The primary challenge lies in achieving adequate stiffness and strength while minimising mass, as excessive weight increases actuator load, reduces dynamic performance, and raises system cost.

Industrial robotic arms are typically constructed from cast iron, steel alloys, or high-strength aluminium, selected to provide exceptional rigidity and fatigue resistance. However, such materials and manufacturing processes are often impractical for low-cost or educational robotic systems. As a result, researchers increasingly explore alternative materials and hybrid structures that balance mechanical performance with affordability (Hameed and Ay, 2024).

Aluminium alloys are among the most commonly adopted materials in low-cost robotic arms due to their favourable strength-to-weight ratio, corrosion resistance, and ease of machining. Aluminium profiles and plates can be readily sourced and assembled using standard fasteners, making them well-suited for modular designs. Studies demonstrate that aluminium-based robotic arms can achieve acceptable stiffness for lightweight cutting and handling tasks when appropriately dimensioned and reinforced (Ali et al., 2023).

High-strength polymers and composite materials are also explored as structural elements, particularly for non-load-bearing components or joint housings. Polymers such as ABS and nylon offer low density and ease of fabrication through additive manufacturing, enabling rapid prototyping and iterative design. However, their lower elastic modulus compared to metals can lead to increased deflection under load, which may negatively affect cutting accuracy if not carefully managed (Rajeshkumar, 2025).

Structural optimisation techniques are frequently employed to mitigate these limitations. Finite element analysis was used during the design stage to simulate how the robotic structure would respond under load. This helped identify areas of high stress and guided improvements in component geometry to enhance strength while minimising unnecessary material use. By selectively reinforcing high-stress regions and reducing material in low-load areas, designers can improve stiffness without significantly increasing mass or cost (Reddy and Eranki, 2016).

Joint design is particularly critical in cutting applications. Backlash, bearing compliance, and joint flexure can accumulate along the kinematic chain, resulting in noticeable positional errors at the end-effector. The literature highlights the importance of using preloaded bearings, rigid couplings, and short link lengths to minimise these effects (Chauhan et al., 2015). Where cost constraints limit the use of precision components, careful geometric design and conservative load assumptions become essential.

The reviewed studies emphasise that material selection and structural optimisation must be treated as an integrated design problem. For low-cost robotic cutting systems, aluminium-based

modular structures supported by targeted reinforcement and simulation-driven optimisation provide a viable pathway to achieving acceptable mechanical performance.

2.6 Thermal Effects and Heat Management in Cutting Operations

Thermal effects play a significant yet often underappreciated role in robotic metal sheet cutting, particularly within low-cost and lightweight robotic systems. During cutting operations, friction at the tool–workpiece interface generates heat, which can influence material behaviour, tool integrity, dimensional accuracy, and the reliability of surrounding electronic components. While industrial cutting systems often employ active cooling strategies and thermally robust structures, such approaches are rarely feasible in low-cost robotic platforms due to constraints on power, weight, and system complexity.

In metal sheet cutting applications, heat generation arises primarily from plastic deformation of the material and frictional contact between the cutting tool and the workpiece. Even at relatively low cutting speeds, localised temperature rise can be significant, especially when cutting aluminium alloys or mild steel sheets with mechanically driven tools. Elevated temperatures may lead to thermal softening of the workpiece material, which can temporarily reduce cutting forces but may also promote burr formation and inconsistent edge quality (Reddy and Eranki, 2016). The primary sources of heat generation and typical thermal conduction paths within a robotic metal sheet cutting system are illustrated in Figure 2.2.

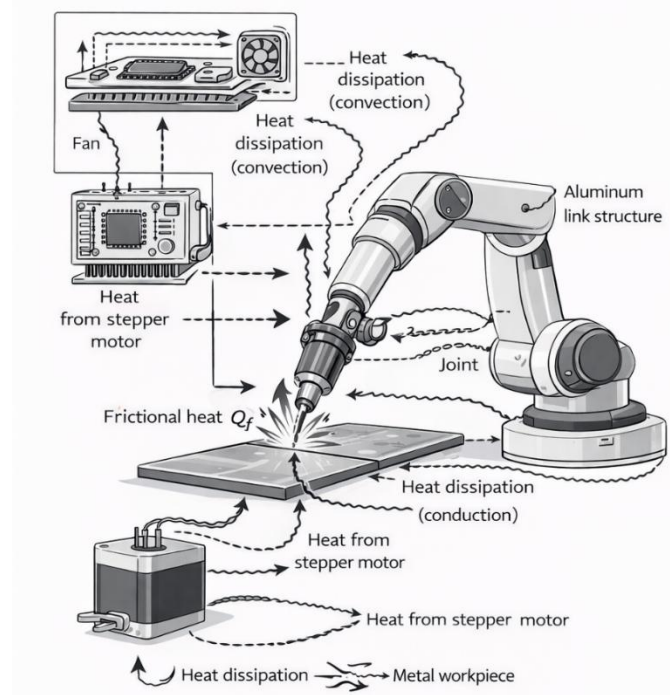


Figure 2.2: Thermal generation and heat dissipation paths in a robotic cutting system

Understanding these thermal pathways is essential for implementing effective passive heat management strategies in low-cost robotic platforms. From a structural perspective, thermal expansion represents a critical concern for robotic cutting systems. Aluminium, commonly used in low-cost robotic arm structures due to its favourable strength-to-weight ratio, exhibits a relatively high coefficient of thermal expansion. Localised heating of the end-effector or adjacent links can therefore introduce small but non-negligible dimensional changes. In precision cutting tasks, these expansions may accumulate along the kinematic chain, resulting in positional drift and reduced cut accuracy. Although such effects are less pronounced than in high-speed machining, they remain relevant in prolonged cutting operations or repetitive duty cycles.

Thermal effects also have direct implications for tool wear, which constitutes a key performance-limiting factor in mechanically driven cutting systems. Elevated temperatures accelerate wear mechanisms such as abrasion, adhesion, and edge chipping, particularly in hardened steel or carbide-tipped blades. Progressive tool wear increases cutting resistance, leading to higher torque demand on the end-effector motor and greater reaction forces transmitted to upstream joints. In stepper-driven robotic arms, this increased load heightens the risk of missed steps and cumulative positioning errors. Consequently, thermal management and tool condition are intrinsically linked to both cutting quality and robotic control reliability.

Electronic components integrated within the robotic arm, including motor drivers, microcontrollers, and power regulation circuits, are similarly sensitive to thermal stress. Excessive heat can degrade electronic performance, reduce component lifespan, and, in extreme cases, lead to system failure. In low-cost robotic systems, where active cooling solutions such as forced air or liquid cooling are typically impractical, thermal protection strategies rely predominantly on passive measures. These include appropriate component placement, the use of heat sinks, and conservative current limiting in motor drivers to minimise heat generation during sustained operation (Park et al., (2020).

The literature consistently emphasises that passive thermal management is the most practical approach for low-cost robotic cutting applications. By selecting cutting parameters that limit frictional heating, employing materials with favourable thermal conductivity for end-effector mounts, and avoiding continuous high-duty operation, designers can mitigate thermal risks without introducing additional system complexity. Furthermore, intermittent cutting strategies and scheduled tool inspection can help manage temperature rise and slow the progression of tool wear.

Thermal effects in robotic metal sheet cutting influence material behaviour, structural accuracy, tool longevity, and electronic reliability. Although low-cost robotic systems lack the sophisticated cooling infrastructure of industrial machines, careful mechanical design, conservative operating parameters, and passive heat management strategies can effectively control thermal risks. Importantly, the interdependence between heat generation, tool wear, and robotic accuracy underscores the need for an integrated design approach that considers thermal phenomena alongside mechanical and control system considerations.

2.7 Performance Metrics and Evaluation Methods

The evaluation of robotic metal sheet cutting systems requires a structured and application-specific performance assessment framework that captures both robotic motion accuracy and the resulting quality of the cutting process. Unlike general-purpose robotic applications, where static positioning accuracy may be sufficient, cutting operations impose additional demands related to dynamic loading, vibration, and interaction between the tool and workpiece. As a result, performance metrics must reflect the combined influence of mechanical design, control strategy, and process conditions.

Positional accuracy and repeatability are among the most widely reported metrics in robotic system assessment. Positional accuracy describes the difference between where the system is programmed to move and where it actually ends up. In practical cutting applications, repeatability is often more critical than absolute accuracy, as consistent toolpath execution ensures uniform kerf geometry even when small systematic errors are present (Asada and Slotine, 1986). For low-cost robotic arms, which may exhibit reduced absolute accuracy due to open-loop control and structural compliance, repeatability therefore represents a more meaningful indicator of functional performance.

Measurement of positional performance in low-cost robotic systems is typically conducted using accessible but reliable tools such as digital callipers, dial indicators, and calibrated rulers referenced to fixed datum points. These methods, while less sophisticated than laser tracking or photogrammetry systems, are commonly adopted in academic prototyping studies due to their availability and sufficient resolution for millimetre-scale evaluation (Ali et al., 2023). Repeated positioning trials allow statistical analysis of deviation and variance, providing insight into mechanical stability and control consistency.

Cutting quality metrics provide a direct assessment of the system's suitability for material processing tasks. Common indicators include edge straightness, burr formation, kerf width

uniformity, and surface finish. Surface roughness comparators or optical inspection techniques are frequently used to assess edge quality qualitatively, while the dimensional accuracy of cut features can be verified using callipers or gauges. Although achieving an industrial-grade surface finish may be unrealistic for low-cost robotic systems, the literature emphasises that consistent and predictable cut quality is often sufficient for small-scale manufacturing, prototyping, and educational applications (Ali et al., 2023).

Dynamic performance metrics are particularly relevant for serial robotic arms engaged in cutting operations. Vibration amplitude, oscillatory behaviour during direction changes, and settling time following motion transitions all influence cut quality and tool longevity. Excessive vibration can result in chatter marks, uneven kerf width, and accelerated mechanical wear. Dynamic behaviour is commonly evaluated through repeated cutting trials, visual inspection of cut edges, and, where available, low-cost accelerometers mounted near the end-effector to provide qualitative or semi-quantitative insight into system stability (Reddy and Eranki, 2016).

Thermal and energy-related performance indicators are also important, particularly during prolonged cutting tasks. Monitoring stepper motor temperature rise and overall power consumption provides insight into system efficiency and operational limits. Sustained overheating may indicate excessive cutting forces, inadequate thermal dissipation, or inappropriate motion parameters. Maintaining components within safe thermal operating ranges is essential for ensuring reliability and preventing premature failure in microcontroller-based robotic systems.

It is important that performance evaluation of low-cost robotic cutting systems is contextualised within their intended application domain. Direct comparison with industrial CNC machines or high-end robotic cells may be misleading due to fundamental differences in cost, speed, and precision. Instead, relative performance improvements over manual or semi-automated methods, combined with consistency, safety, and affordability, represent more appropriate and defensible benchmarks (Krüger and Yang, 2022).

In summary, an effective performance evaluation framework for low-cost robotic metal sheet cutting systems integrates positional repeatability, cutting quality, dynamic behaviour, and thermal performance. By employing accessible measurement techniques and application-relevant benchmarks, such a framework enables a realistic, transparent, and academically rigorous assessment of system capability.

2.8 Safety, Risk Management, and Ethical Considerations

Safety is a fundamental consideration in the design, construction, and operation of robotic systems, particularly those involving cutting tools and multi-axis mechanical motion. In robotic metal sheet cutting applications, hazards arise not only from the cutting process itself but also from unintended robotic movement, electrical faults, and system-level control failures. As such, safety must be embedded within the engineering design process rather than treated as a secondary or operational concern.

From a mechanical standpoint, the primary hazards include contact with sharp cutting edges, entanglement with moving joints, and the ejection of debris or workpiece fragments during cutting operations. Electrical hazards associated with power supplies, motor drivers, and control circuitry further contribute to the overall risk profile. Although low-cost robotic systems typically operate at lower power levels than industrial robots, the literature emphasises that they still pose significant injury risks if appropriate safeguards are not implemented (Krüger and Yang, 2022).

Effective safety management in robotic systems is commonly structured around formal risk assessment methodologies. These approaches involve systematic hazard identification, evaluation of risk based on likelihood and severity, and the implementation of proportionate mitigation measures. Within the UK academic and industrial context, this methodology aligns with established machinery safety standards such as ISO 12100. Applying such a framework to robotic cutting systems enables designers to identify high-risk scenarios, including unintended tool activation, loss of positional control, or workpiece instability, and to address them through appropriate engineering and procedural controls.

Engineering control measures reported in the literature include physical guarding around the cutting zone, rigid workpiece fixturing to prevent unintended motion, and clearly accessible emergency stop mechanisms that immediately disable actuator power (Cong et al., 2022). Software-based safeguards provide additional layers of protection, including motion limits, controlled start-up and shutdown routines, and fault-handling logic to prevent erratic behaviour following system errors. In low-cost robotic platforms, where redundant safety hardware may be impractical due to cost and complexity, the careful integration of mechanical design, conservative motion parameters, and software constraints becomes particularly important.

Operational safety is further reinforced through procedural controls, such as defined operating instructions, pre-use inspection checklists, and routine maintenance schedules. In educational

and laboratory environments, supervision and user training play a critical role in mitigating risk. Studies indicate that many incidents involving robotic systems result not from component failure but from misuse, inadequate understanding of system limitations, or deviation from intended operating conditions (Krüger and Yang, 2022). Clear documentation and adherence to institutional safety protocols are therefore essential components of responsible system deployment.

Beyond physical safety, ethical considerations associated with robotic automation must also be addressed. The increasing adoption of automation has raised concerns regarding workforce displacement and the erosion of manual skills. However, the literature suggests that low-cost robotic systems occupy a distinct ethical position compared to large-scale industrial automation. In SME and educational contexts, such systems are more commonly used to reduce exposure to hazardous tasks, enhance productivity, and support skills development rather than replace human labour outright (Cong et al., 2022).

Within an academic context, ethical responsibility further encompasses responsible experimentation, transparent reporting of system limitations, and compliance with institutional risk assessment and safety approval processes. Ensuring that experimental work is conducted within approved safety frameworks protects both researchers and equipment while reinforcing professional engineering standards expected at postgraduate level.

2.9 Research Gap and Chapter Summary

The reviewed literature demonstrates significant progress in the development of robotic systems for metal cutting and related manufacturing processes. Industrial solutions offer exceptional performance but remain inaccessible to many SMEs due to cost and complexity. Conversely, low-cost robotic arms show promise but often suffer from limitations in stiffness, control precision, and cutting performance.

A clear research gap exists in the systematic design and evaluation of low-cost, programmable robotic arms specifically tailored for metal sheet cutting. Many existing studies focus on material handling or demonstration tasks, with limited attention given to cutting forces, thermal effects, and long-term reliability. Furthermore, there is a lack of integrated studies that combine mechanical design, kinematic control, thermal considerations, and experimental validation within a single coherent framework.

This dissertation addresses this gap by proposing and implementing a cost-effective robotic arm designed explicitly for metal sheet cutting applications. By adopting a holistic approach

that integrates mechanical design, embedded control, and experimental evaluation, the project aims to contribute practical insights into the feasibility and limitations of low-cost robotic automation.

Chapter 3 builds upon this literature review by presenting the detailed system design methodology, translating the identified requirements and research gaps into concrete engineering solutions.

Chapter 3 – System Design Methodology

3.1 Introduction

Chapter 2 established that the limited adoption of robotic metal sheet cutting within small and medium-sized manufacturing environments is not driven by a lack of technological capability, but rather by a misalignment between available automation solutions and practical operational needs. Industrial robotic cutting cells deliver high throughput and precision, yet their financial cost, proprietary control ecosystems, and complex integration requirements frequently exceed what is justified for thin sheet cutting tasks in laboratories, educational settings, and SMEs (Krüger and Yang, 2022). At the opposite end of the spectrum, low-cost robotic arms offer accessibility and flexibility but often exhibit insufficient stiffness, limited sensing, and reduced control robustness when exposed to continuous process forces such as those generated during cutting operations (Ali et al., 2023; Chauhan et al., 2015).

This chapter translates the findings of Chapter 2 into a structured, defensible system design methodology for robotic metal-sheet cutting using an articulated six-axis robotic arm. Rather than developing a bespoke robotic platform, the methodology leverages an industrial-grade robotic system already available within the laboratory environment, namely the Kinova Gen3. This decision allows the research to focus on the integration of cutting tools, motion planning strategies, and performance evaluation rather than on the fundamental development of actuators and structural components. The Kinova Gen3 provides manufacturer validated kinematic models, integrated sensing at both joint and tool levels, and native support for Robot Operating System integration, making it suitable for controlled experimental investigation while remaining representative of modern industrial robotic systems (Asada and Slotine, 1986).

The design approach adopted in this chapter is explicitly systems based. Functional and non functional requirements are defined first to establish clear performance expectations and operational boundaries. Mechanical integration decisions, control architecture selection, and software execution strategies are then developed in direct response to these requirements. Particular emphasis is placed on repeatability, safety, observability, and reproducibility rather than maximum cutting speed or industrial throughput. This focus directly reflects the conclusions of Chapter 2, which identified consistent cutting performance and controlled tool workpiece interaction as the most relevant success criteria in resource constrained environments (Reddy and Eranki, 2016).

The chapter is organised as follows. Section 3.1 defines the system requirements and design constraints. Section 3.2 introduces the Kinova Gen3 platform and justifies its selection. Section 3.3 addresses mechanical integration and workspace configuration for sheet cutting. Section 3.4 presents the ROS based control architecture. Section 3.5 outlines the software methodology for toolpath execution and user interaction. The chapter concludes by explicitly linking the methodology back to the research gap identified in Chapter 2 and forward to the modelling and simulation work presented in Chapter 4.

3.2 System Requirements Analysis

System requirements analysis forms the foundation of all subsequent design decisions in this project. Rather than serving as abstract specifications, requirements are treated as practical constraints that guide engineering choices and provide objective criteria for later evaluation. This is particularly important in research involving industrial robotic platforms, where it is easy to benchmark performance against inappropriate industrial standards rather than against the realistic needs of the intended application domain (Krüger and Yang, 2022).

In this project, system performance is assessed relative to defined requirements rather than against high end industrial cutting cells. This ensures that conclusions drawn from experimental testing remain meaningful within the scope of thin sheet cutting tasks carried out in laboratory and SME contexts. The requirements are grouped into functional requirements, non functional requirements, and design constraints.

3.2.1 Functional Requirements

FR1 Repeatable toolpath execution

The robotic system must execute predefined cutting paths with consistent spatial tracking across repeated trials. In cutting applications, repeatability is often more critical than absolute positioning accuracy, as consistent motion produces uniform kerf geometry even with small systematic offsets. Classical robotics literature emphasises that repeatability under load is a more relevant indicator of functional performance than nominal positioning accuracy for many manufacturing tasks (Asada and Slotine, 1986; Ali et al., 2023).

FR2 Stable tool workpiece interaction

The system must maintain controlled engagement between the cutting tool and the sheet material throughout the cutting process. Sudden changes in velocity, acceleration, or tool orientation must be avoided, as these can induce vibration, increase tool wear, and degrade

edge quality. This requirement is particularly important for articulated robots, where structural compliance accumulates along the kinematic chain and amplifies disturbances at the tool tip (Reddy and Eranki, 2016).

FR3 Cartesian path capability

The robot must support Cartesian motion planning and execution along planar cutting paths. Sheet metal cutting geometry is naturally defined in workspace coordinates rather than joint space, making Cartesian planning essential for predictable and interpretable tool behaviour. This capability also simplifies the definition and modification of cutting paths during experimentation.

FR4 Safe start stop and interruption behaviour

The system must provide predictable behaviour during start up, pause, and emergency stop conditions. Even moderate power cutting tools introduce hazards, and uncontrolled motion following interruption is unacceptable. Safe interruption behaviour is therefore treated as a core functional requirement rather than as an auxiliary feature.

FR5 System state feedback and monitoring

The system must provide access to real-time feedback data, including tool pose, velocity, and estimated external forces. This observability supports experimental validation, safety monitoring, and post process analysis of cutting performance. Feedback evaluation is a fundamental principle in robotic system analysis (Asada and Slotine, 1986).

3.2.2 Non-Functional Requirements

NFR1 Reproducibility

The system configuration must be reproducible using the same robotic platform and software stack. A clear definition of coordinate frames, control modes, and execution procedures is therefore required to ensure that results can be repeated and verified

NFR2 Maintainability and modularity

The system should allow changes to tooling, cutting parameters, and path definitions without requiring extensive redesign. Modular approaches are consistently recommended for robotic systems intended for iterative development and experimental work (Chauhan et al., 2015).

NFR2 Maintainability and modularity

The system should allow changes to tooling, cutting parameters, and path definitions without

requiring extensive redesign. Modular approaches are consistently recommended for robotic systems intended for iterative development and experimental work (Chauhan et al., 2015).

NFR3 Laboratory safety compliance

The system must be suitable for supervised laboratory operation. This includes compliance with institutional safety procedures, clear emergency stop functionality, and predictable system behaviour during faults or interruptions

NFR4 Practical integration effort

The methodology should rely on supported interfaces and documented control pathways rather than experimental actuator-level control methods. This improves stability, reduces development risk, and ensures alignment with manufacturer recommended practices.

3.2.3 Design Constraints

Three primary constraints influence the system design.

First, robot workspace and payload limits. The Kinova Gen3 has defined reach, payload, and wrist torque limits that constrain tool selection and cutting parameters. Exceeding these limits risks degraded motion quality and increased vibration.

Second, control abstraction under ROS. While the Kinova platform provides rich feedback and cyclic control data, high level ROS operation abstracts direct actuator torque control. Motion planning must therefore remain conservative and compatible with supported interfaces.

Third, cutting process forces. Even thin sheet cutting generates reaction forces that can influence tool alignment and motion stability if not considered during trajectory planning and mechanical integration (Reddy and Eranki, 2016).

3.3 Platform Selection and System Overview

3.3.1 Justification for an Articulated Six-Axis Robot

An articulated six-axis robotic arm was selected due to its flexibility and suitability for planar cutting tasks that still require controlled tool orientation. Compared with Cartesian or gantry based systems, articulated robots offer greater adaptability while maintaining a compact footprint, which is advantageous in laboratory environments where space and reconfiguration flexibility are important (Asada and Slotine, 1986).

While Chapter 2 discussed the limitations of low cost robotic arms, the use of an industrial grade articulated robot allows the research to isolate cutting process behaviour from

fundamental mechanical deficiencies. The Kinova Gen3 provides reliable kinematics, known stiffness characteristics, and integrated sensing, enabling a clearer evaluation of cutting performance and motion planning strategies without compensating for unknown structural behaviour (Ali et al., 2023).

3.3.2 Relevant Characteristics of the Kinova Gen3

The Kinova Gen3 is a six-axis articulated robotic arm designed to support both industrial deployment and advanced research applications. Its architecture combines lightweight mechanical construction with integrated sensing and embedded safety features, making it particularly suitable for experimental process tasks such as robotic metal sheet cutting. Each of the six revolute joints incorporates internal sensing for joint position, velocity, applied torque, motor current, and temperature, enabling continuous observation of the robot's internal state during operation. This level of joint level feedback represents a clear advantage over low cost robotic platforms, where sensing is often limited or entirely absent, and where internal loading conditions must be inferred indirectly (Ali et al., 2023).

At the tool level, the Kinova Gen3 exposes real time Cartesian feedback including tool centre point position, orientation, linear and angular velocity, and estimated external wrench components. Access to these variables is especially valuable for cutting applications, where interaction forces between the tool and workpiece influence motion stability, edge quality, and system safety. Even without implementing full force control, the ability to observe estimated forces and torques at the tool provides meaningful insight into cutting engagement and allows qualitative assessment of process consistency across experimental runs. Tereda and Yi (2023) demonstrated that accurate modelling and monitoring of the Kinova Gen3 dynamics significantly improves interpretability of system behaviour during interaction tasks, reinforcing the value of integrated feedback for experimental manipulation and process control.

Thermal feedback from both joint actuators and the robot control electronics further supports safe operation by enabling monitoring of temperature rise during sustained cutting sequences. Continuous observation of actuator temperature and electrical load is particularly relevant in process tasks involving prolonged tool engagement, where thermal accumulation can affect actuator performance and long term system reliability (Reddy and Eranki, 2016).

From a control and integration perspective, the Kinova Gen3 supports native integration with the Robot Operating System through the Kortex software stack. This interface provides structured access to robot state feedback, Cartesian and joint space command services, and

safety related status information, while maintaining the manufacturer’s internal control loops and fault handling mechanisms. The use of Kortex allows high level motion planning and execution to be performed within the ROS ecosystem using standard tools, without bypassing the robot’s validated safety architecture. This layered control structure reflects established robotic control principles, where separation between high level planning and low level actuation improves system robustness and maintainability (Asada and Slotine, 1986; Chitta et al., 2017).

The combination of integrated sensing, ROS compatibility, and documented application programming interfaces aligns closely with the project requirements for reproducibility and practical integration effort. Rather than relying on experimental drivers or undocumented interfaces, the methodology leverages supported control pathways that are consistent with best practice in modern robotic system development. Studies on real time robotic systems have shown that such structured control frameworks improve timing reliability, observability, and system stability in multi component robotic architectures (Park et al., 2020).

Taken together, these characteristics position the Kinova Gen3 as an appropriate experimental platform for investigating robotic metal sheet cutting. The robot provides sufficient sensing resolution to observe cutting interaction effects, adequate stiffness and payload capacity for lightweight cutting tools, and a mature software interface that supports structured experimentation. Importantly, the platform allows the research to focus on motion planning strategies, tool integration, and cutting behaviour rather than compensating for fundamental mechanical or sensing limitations, thereby strengthening the validity and interpretability of the results (Tereda and Yi, 2023).

The key technical characteristics of the Kinova Gen3 that are directly relevant to robotic metal sheet cutting, including sensing capability, control interfaces, and operational limits, are summarised in Table 3.1 to clarify how the platform supports the requirements defined in Section 3.1.

Table 3.1: Key Kinova Gen3 characteristics relevant to sheet metal cutting tasks

Characteristic	Description	Relevance to Sheet Metal Cutting
Robot type	Articulated six-axis robotic arm	Enables flexible positioning and orientation of the cutting tool within a planar workspace

Degrees of freedom	Six revolute joints	Allows control of tool pose while maintaining stable orientation during cutting
Joint sensing	Position, velocity, torque, motor current, and temperature sensing at each joint	Supports monitoring of loading conditions, thermal behaviour, and motion stability during cutting
Tool level feedback	Cartesian position, orientation, linear and angular velocity, estimated external wrench	Enables observation of tool motion accuracy and qualitative assessment of cutting interaction forces
Payload capacity	Manufacturer specified lightweight payload class	Suitable for rotary or lightweight cutting tools without exceeding wrist torque limits
Control interface	Kortex software stack with native ROS integration	Supports structured motion planning, execution, and monitoring using standard robotics tools
Motion control	Manufacturer managed low level control with high level Cartesian command support	Ensures stable execution while avoiding risks associated with direct actuator control
Safety features	Integrated joint limits, velocity limits, torque thresholds, and fault handling	Enhances safety during experimental cutting tasks in a laboratory environment
Observability	Continuous access to joint state, tool state, and diagnostic feedback	Enables detailed analysis of system behaviour and cutting performance

3.3.3 Coordinate Frames and Reference Definitions

Accurate definition of coordinate frames is essential for Cartesian cutting tasks. The system uses a base frame fixed to the robot mounting surface, joint frames defined by the manufacturer's kinematic model, and a tool frame defined at the cutting blade reference point. Consistent frame definition ensures alignment between planned trajectories and physical motion.

Classical robotics literature emphasises that inconsistencies in frame definition are a common source of error in Cartesian control and experimental evaluation (Asada and Slotine, 1986). By adopting the manufacturer validated model and explicitly defining the tool frame, the methodology reduces uncertainty and improves repeatability.

3.4 Mechanical Integration for Sheet Cutting

Mechanical integration plays a critical role in determining the success of robotic metal sheet cutting, even when an industrial grade articulated robot is used. While the Kinova Gen3 provides reliable motion and sensing, the quality of cutting outcomes remains highly sensitive to how the workpiece is constrained, how the cutting tool is mounted, and how physical risks are managed within the cutting environment. This section therefore addresses the mechanical aspects that interface directly with the robot and the cutting process, ensuring that observed performance reflects system behaviour rather than avoidable integration weaknesses.

3.4.1 Workpiece Fixturing and Cutting Zone Layout

Reliable cutting performance depends not only on robotic motion accuracy, but equally on the stability of the workpiece throughout the cutting process. In this methodology, sheet material is assumed to be rigidly fixtured within a clearly defined cutting zone. This assumption reflects common practice in both industrial and laboratory environments and is necessary to allow separation of robotic performance from external sources of variability (Reddy and Eranki, 2016).

Metal sheet cutting introduces reaction forces that can cause unrestrained or poorly supported sheets to vibrate, flex, or shift during tool engagement. Such movement can result in irregular kerf geometry, burr formation, and apparent positional error, even when the robot executes the planned trajectory accurately. By enforcing rigid fixturing, the methodology ensures that deviations in cut quality can be attributed to robotic motion, tool behaviour, or control strategy rather than to uncontrolled workpiece motion.

The cutting zone is defined relative to the robot base frame and aligned with the planar cutting surface. This spatial definition supports consistent Cartesian planning and simplifies interpretation of toolpath execution. The layout is designed to keep the cutting plane within the central region of the robot workspace, avoiding kinematic singularities and extreme joint configurations that could amplify joint torque demands or reduce control smoothness. This approach reflects good practice for articulated robots, where motion quality and stiffness vary across the workspace.

Clear separation between the cutting zone and surrounding areas is also maintained. This includes designated approach paths for the tool, clearance regions to avoid unintended contact with fixtures, and safe retreat positions following tool disengagement. Defining these zones at

the mechanical integration stage reduces reliance on operator judgment during execution and contributes to repeatable and safe operation.

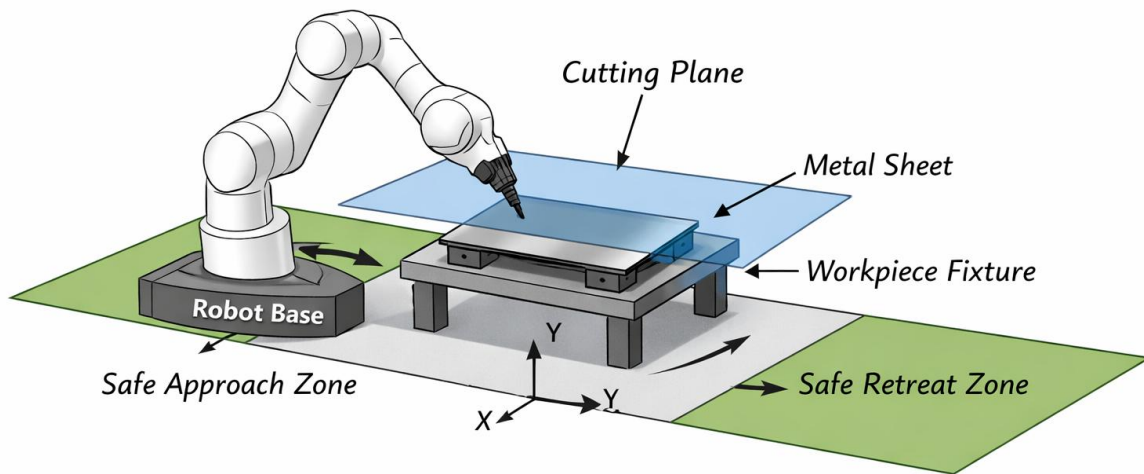


Figure 3.1: Schematic showing the robot base frame, defined cutting plane, workpiece fixture, and safe approach and retreat regions.

The spatial relationship between the robot base frame, cutting plane, workpiece fixture, and defined approach and retreat regions is illustrated in Figure 3.1.

3.4.2 End Effector Mounting Strategy

The end effector mounting strategy is a critical determinant of cutting stability in articulated robotic systems. Even with a mechanically robust robot such as the Kinova Gen3, compliance at the wrist or tool interface can significantly degrade cutting quality. The literature consistently shows that deflection and vibration near the end effector have a disproportionate impact on tool positioning accuracy compared with similar compliance near the base of a serial manipulator (Reddy and Eranki, 2016).

In this project, the cutting tool is mounted using a rigid adapter designed to minimise overhang and reduce bending moments transmitted to the wrist joints. Short load paths between the tool, adapter, and robot flange are prioritised to limit amplification of cutting forces. Alignment accuracy is treated as equally important as stiffness, as even small angular misalignments at the tool centre point can result in uneven kerf width and inconsistent edge quality during planar cutting.

While minimising mass at the wrist is generally desirable for articulated robots, this methodology deliberately prioritises stiffness and geometric stability over absolute weight

reduction. Cutting is a continuous interaction process rather than a transient handling task, and stable engagement is therefore considered more important than achieving high tool speeds. The selected mounting strategy reflects this design compromise, ensuring that vibration is suppressed and tool orientation is maintained consistently throughout the cutting path.

Serviceability is also considered within the mounting design. The adapter allows for tool replacement or adjustment without disturbing the robot flange or requiring redefinition of the base coordinate frames. This supports repeatability across experiments and reduces the likelihood of cumulative alignment errors introduced during maintenance or reconfiguration.

Thermal considerations are implicitly addressed through material choice and mounting geometry. Cutting tools and their motors can generate localised heat, and a rigid metallic adapter assists in passive heat dissipation away from sensitive components. This complements the thermal management principles discussed in Chapter 2 and reduces the risk of temperature induced drift during extended cutting sequences.

3.4.3 Safety and Physical Risk Controls

Mechanical integration for cutting must be accompanied by robust physical safety measures, particularly when operating an articulated robot in a laboratory environment. Although the Kinova Gen3 incorporates internal safety features and supports collaborative operation, the presence of a cutting tool introduces hazards that extend beyond typical manipulation tasks.

Physical risk controls implemented in this methodology include clearly defined safe approach paths, exclusion zones around the cutting area, and accessible emergency stop mechanisms. Safe approach paths ensure that the tool only engages the workpiece after the robot has reached a stable orientation and appropriate clearance has been established. Exclusion zones are maintained around the cutting plane to prevent unintended human proximity during operation, even when the robot is moving at reduced speeds.

Emergency stop access is treated as a fundamental requirement rather than a procedural consideration. The stop mechanism is positioned such that it can be reached quickly by an operator without crossing into the cutting zone. This aligns with established safety principles for robotic systems operating in proximity to human users and supports controlled shutdown behaviour under fault or unexpected conditions (Krüger and Yang, 2022).

These physical measures complement software enforced safety limits implemented at the control level. By combining mechanical layout decisions with procedural and software safeguards, the system adopts a layered safety approach. This reduces reliance on any single

protective mechanism and improves overall robustness, particularly in an experimental setting where operating parameters may be adjusted between trials.

3.5 ROS Based Control Architecture

The control architecture defines how planning intent is translated into physical motion while preserving safety, repeatability, and observability. In this project, the Kinova Gen3 is controlled using the Kortex ROS stack, which provides a structured interface between high level planning algorithms and the robot's internal control loops. This approach allows the system to leverage the robot's validated low level control while maintaining flexibility for research focused motion planning and monitoring.

The choice of a ROS architecture is deliberate. Rather than interacting with actuators directly, the methodology relies on supported abstractions that reduce implementation risk and improve reproducibility. This aligns with established robotic control principles, where separation between planning, execution, and hardware specific control improves system robustness, clarity, and long term maintainability (Asada and Slotine, 1986).

3.5.1 Overview of the ROS Control Stack

The Kinova Gen3 integrates with ROS through the Kortex software stack, which provides device drivers, robot descriptions, state feedback interfaces, and command services. Within this architecture, the robot exposes its kinematic model, joint states, tool pose, and diagnostic information to the ROS environment while internally managing low level torque, current, and safety enforcement.

This layered structure ensures that motion commands issued at the ROS level are validated and executed within the constraints defined by the manufacturer. Such constraints include joint limits, velocity bounds, torque thresholds, and fault handling behaviour. By relying on these validated mechanisms, the system avoids the instability risks associated with low level actuator control while still providing sufficient access for experimental evaluation. This design philosophy aligns with the principles of the *ros_control* framework, which formalises the separation between high level motion intent and hardware specific controllers to improve robustness and maintainability in ROS based robotic systems (Chitta *et al.*, 2017).

From a systems perspective, the ROS stack acts as an intermediary between user defined motion intent and the robot's embedded control system. High level nodes handle trajectory generation, execution timing, and monitoring, while the robot firmware manages servo level control and internal safety responses. This division of responsibility is consistent with best

practice in robotic system design and allows the research to focus on motion behaviour and cutting interaction rather than actuator level tuning (Asada and Slotine, 1986).

An additional advantage of the ROS based approach is observability. The Kortex interface provides continuous access to joint level feedback, tool pose data, and estimated external wrench information. This data stream supports detailed analysis of motion execution and cutting behaviour, enabling correlation between planned trajectories and observed system response. Prior studies have shown that modern ROS based control frameworks can support reliable timing and monitoring behaviour for robotic systems when appropriately configured, reinforcing their suitability for process driven applications such as cutting (Park *et al.*, 2020).

3.5.2 Motion Planning Strategy

Motion planning for metal sheet cutting prioritises predictability and stability over speed or throughput. Unlike pick and place tasks, cutting requires continuous and smooth interaction between the tool and the workpiece. Abrupt changes in velocity or direction can induce vibration, increase tool wear, and degrade cut quality, particularly in articulated robots where compliance accumulates along the kinematic chain (Reddy and Eranki, 2016).

For this reason, Cartesian motion planning is adopted as the primary strategy. Cutting paths are defined in workspace coordinates relative to the cutting plane, allowing direct control over tool position and orientation. This approach reduces reliance on complex joint space interpolation and ensures that tool motion aligns intuitively with the geometry of the cut.

Trajectories are generated using conservative velocity and acceleration limits. These limits are selected to remain well within the robot's dynamic capabilities, reducing the likelihood of excitation of structural compliance or internal control saturation. Although the Kinova Gen3 is capable of high precision motion, this methodology deliberately avoids operating near performance limits, as stable and repeatable cutting is the primary objective.

Corner handling and path transitions receive particular attention. Sharp directional changes introduce higher inertial loads and can result in transient deviations from the intended path. To mitigate this, the planner reduces the feed rate near corners or introduces smooth transitions between segments. This strategy reflects common findings that smooth acceleration profiles are critical for maintaining tool stability during continuous process tasks (Reddy and Eranki, 2016).

The planning strategy also incorporates explicit separation between approach, cutting, and retreat phases. The tool only engages the workpiece after reaching a stable pose above the

cutting plane and disengages before transitioning to subsequent paths, ensuring that cutting interaction occurs only under controlled conditions. This segmentation reduces unintended contact with fixtures or surrounding surfaces and supports safer and more repeatable operation. Figure 3.2 illustrates how this phased planning logic is implemented within the overall control and execution pipeline, showing the transformation of Cartesian path definitions into executable trajectories through the ROS control stack and the continuous feedback flow used for monitoring and evaluation.

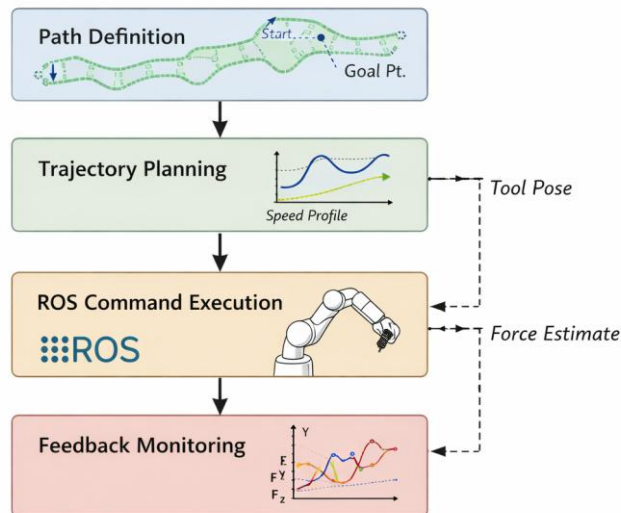


Figure 3.2: Control and Execution Pipeline

3.5.3 Execution and Monitoring

During execution, planned trajectories are streamed to the robot through the ROS control interface, where they are executed under the supervision of the robot’s internal safety and control systems. At the same time, continuous feedback is collected and monitored to assess system behaviour.

Commanded tool poses are compared against measured Cartesian feedback provided by the robot. This comparison enables verification of trajectory tracking performance and identification of deviations that may arise due to compliance, interaction forces, or conservative internal safety responses. While absolute accuracy is influenced by calibration and mechanical tolerances, consistency between commanded and measured motion is a key indicator of system reliability (Motta et al., 2016).

Although advanced force control and adaptive compliance are outside the scope of this project, monitoring estimated external wrench data at the tool provides valuable qualitative insight into

the cutting process. Changes in estimated force and torque values can indicate variations in material engagement, tool sharpness, or local geometry. This information supports interpretation of cutting results and helps distinguish between control related effects and process induced disturbances.

System state monitoring also includes observation of joint velocities, temperatures, and fault or warning flags. These indicators help ensure that experiments remain within safe operating conditions and provide early warning of abnormal behaviour. By integrating execution and monitoring within the same ROS environment, the methodology supports transparent experimentation and repeatable data collection.

3.6 Software Methodology for Toolpath Execution

The software methodology defines how cutting intent is translated into executable robot motion in a controlled, repeatable, and interpretable manner. In robotic metal sheet cutting, software design plays a decisive role in determining process stability, repeatability, and safety, particularly when Cartesian motion and continuous tool engagement are required. The objective of this section is not to develop a novel control algorithm, but to establish a clear, robust, and reproducible workflow for executing cutting paths using the Kinova Gen3 through ROS.

Consistent with the findings of Chapter 2, the methodology prioritises clarity, predictability, and experimental control over complexity or optimisation. Each stage of the software workflow is designed to minimise operator influence, reduce ambiguity in execution, and support transparent evaluation of system performance (Ali et al., 2023; Krüger and Yang, 2022).

3.6.1 Path Representation

Toolpaths are represented as ordered Cartesian waypoints defined relative to the cutting plane and expressed in the robot base coordinate frame. Each waypoint specifies both the position and orientation of the tool centre point, ensuring consistent blade alignment throughout the cutting operation. This representation reflects established manufacturing practice, where cutting geometry is naturally described in workspace coordinates rather than joint space (Ali et al., 2023).

Using Cartesian waypoints offers several advantages for sheet metal cutting. First, it provides a direct and intuitive relationship between the defined path and the physical cut on the workpiece. This simplifies verification of cutting geometry and allows visual inspection of planned paths prior to execution. Second, it decouples geometric path definition from robot

specific joint configurations, improving portability and reproducibility across experimental runs.

Waypoints are defined sequentially, forming a continuous path that represents the intended cut. For linear cuts, waypoints are spaced at regular intervals along the desired geometry. For curved or complex profiles, the path is discretised into sufficiently small segments to approximate the intended shape without introducing excessive computational overhead. The spacing between waypoints is selected to balance geometric fidelity with smooth execution, ensuring that motion remains continuous and free from abrupt transitions.

Each cutting path is augmented with approach and retreat waypoints. The approach segment positions the tool above the cutting plane before engagement, while the retreat segment lifts the tool clear of the workpiece after completion. This explicit separation between non-cutting and cutting motion reduces unintended contact and supports safe operation.

3.6.2 Trajectory Smoothing and Corner Handling

Once a sequence of Cartesian waypoints is defined, trajectory generation focuses on ensuring smooth and stable motion between points. In cutting applications, trajectory smoothness is critical, as abrupt velocity or acceleration changes can excite structural compliance, induce vibration, and negatively affect cut quality, particularly in articulated robotic arms (Reddy and Eranki, 2016).

Velocity and acceleration limits are applied uniformly across the trajectory to maintain conservative motion profiles. These limits are selected to remain well within the dynamic capabilities of the robot, prioritising stability over execution speed. This approach reflects classical motion planning principles, where limiting acceleration and jerk reduces mechanical stress and improves tracking performance (Asada and Slotine, 1986).

Corner handling receives particular attention. Sharp changes in direction are unavoidable in many cutting geometries, but they represent regions of increased dynamic load. To mitigate this, the trajectory planner reduces feed rate in the vicinity of corners or introduces smooth blending between segments. This prevents sudden deceleration and re-acceleration that could otherwise lead to transient deviations from the intended path.

The planner ensures continuity of position and velocity across successive segments. Even where waypoint spacing changes due to geometry, motion is interpolated in a manner that preserves smooth transitions. This continuity is especially important during cutting, where

interruptions or oscillations can result in uneven kerf width, surface defects, or increased tool wear.

By applying consistent smoothing and conservative corner handling, the software methodology supports stable tool workpiece interaction without requiring advanced force control or adaptive compliance. This aligns with the project's emphasis on repeatable and interpretable behaviour rather than aggressive performance optimisation.

3.6.3 User Interaction Workflow

The user interaction workflow is intentionally structured to minimise variability and ensure reproducibility across experimental trials. Rather than relying on manual teleoperation or interactive teaching, cutting operations are executed through scripted ROS nodes that follow a defined sequence of steps.

The workflow begins with path loading, where a predefined set of Cartesian waypoints is imported into the system. Prior to execution, basic validation checks are performed to ensure that waypoints lie within the robot workspace and respect orientation constraints. This verification step reduces the risk of execution errors and unintended joint limit violations.

Once validated, the trajectory is executed in a controlled manner. The user initiates execution, after which the robot follows the planned path autonomously. During execution, system state and feedback data are monitored, allowing the operator to observe motion progress without intervening directly. This separation between supervision and control reduces operator induced variability, a factor frequently identified as a limitation in SME scale automation (Krüger and Yang, 2022).

After execution, the system returns the robot to a safe pose and logs relevant feedback data. This structured sequence ensures that each experimental run follows the same operational pattern, supporting fair comparison between different cutting paths, feed rates, or tool configurations.

The simplicity of the workflow is a deliberate design choice. In laboratory and SME contexts, reliability and repeatability are often more valuable than complex user interfaces. By limiting interaction to clearly defined steps, the methodology reduces the likelihood of unintended behaviour and enhances experimental transparency.

3.7 Chapter Synthesis and Transition

This chapter has presented a complete and coherent system design methodology for robotic metal sheet cutting using an articulated six-axis Kinova Gen3 robot integrated through ROS. Building directly on the gaps and limitations identified in Chapter 2, the methodology was structured to prioritise repeatability, safety, and experimental observability over industrial throughput or optimisation. Rather than treating mechanical, control, and software elements as independent components, the chapter adopted a systems based approach in which each design decision was evaluated in relation to its impact on cutting stability and interpretability.

The system requirements established clear performance boundaries and evaluation anchors, ensuring that later assessment is grounded in realistic and defensible criteria rather than comparison with industrial cutting cells operating under fundamentally different constraints. The selection of the Kinova Gen3 allowed the study to decouple cutting behaviour from uncertainties associated with low cost actuation and unknown structural compliance, enabling a more rigorous examination of motion planning, tool interaction, and execution consistency. Mechanical integration decisions, including rigid workpiece fixturing and conservative end effector mounting, were directly aligned with the need to limit vibration and isolate robotic performance from external disturbance.

The ROS based control architecture and software methodology provided a structured and reproducible pathway from geometric toolpath definition to physical execution. By adopting Cartesian path representation, conservative trajectory smoothing, and a scripted user interaction workflow, the system reduces operator induced variability and supports transparent experimental validation. Importantly, the methodology leverages supported and documented interfaces rather than lower level experimental control, reinforcing system robustness and ensuring that results are repeatable within comparable laboratory environments.

Collectively, the design methodology addresses the research gap identified in Chapter 2 by demonstrating how an accessible industrial robotic platform can be adapted for controlled metal sheet cutting without excessive complexity or reliance on proprietary industrial cutting cells. The chapter establishes a clear foundation upon which modelling, simulation, and experimental validation can be conducted with confidence in the integrity of the underlying system design.

Chapter 4 builds on this foundation by presenting the kinematic modelling, workspace validation, and analytical evaluation used to verify the suitability of the proposed methodology

prior to experimental testing. The staged progression from design to validation was supported by a structured project plan, ensuring that modelling, implementation, and testing activities informed one another. The overall timeline for the project is presented in Appendix A.

Chapter 4 – Modelling, Analysis, and Simulation

4.1 Kinematic Modelling of the Robotic Arm

Kinematic modelling provides the mathematical foundation for describing, predicting, and validating the motion behaviour of a robotic manipulator. In the context of robotic metal sheet cutting, accurate kinematic modelling is especially important because cut quality is directly linked to how faithfully the cutting tool follows the intended Cartesian path. As established in Chapter 3, the system design prioritises repeatable and stable Cartesian motion rather than extreme speed or payload capacity. The modelling approach adopted in this chapter therefore focuses on predictability, consistency, and alignment between analytical representations and the physical behaviour of the Kinova Gen3 robotic arm.

The robotic platform used in this study is a serial, articulated six degree of freedom manipulator with revolute joints and a fixed base configuration. Although the Kinova Gen3 is an industrial grade system with manufacturer validated models, explicit kinematic modelling remains necessary for workspace analysis, trajectory validation, and interpretation of experimental results. Rather than treating the robot as a black box, this chapter establishes a clear kinematic framework that connects theoretical motion planning to the observed behaviour during cutting operations. This approach ensures continuity between the system design methodology presented in Chapter 3 and the experimental evaluation developed in subsequent chapters.

4.1.1 Kinematic Structure and Coordinate Frame Definition

The Kinova Gen3 is modelled as a serial chain of rigid links connected by revolute joints, where each joint contributes one rotational degree of freedom. For the six axis configuration used in this work, the manipulator provides sufficient flexibility to position and orient the cutting tool within a defined planar workspace while maintaining orientation constraints normal to the cutting surface.

A consistent and unambiguous definition of coordinate frames is central to accurate kinematic modelling. The modelling framework adopted here follows both classical robotics conventions and the reference frame definitions provided by the Kinova manufacturer. A fixed base frame is defined at the robot mounting interface, coincident with the physical base of the robot. This frame serves as the global reference for all subsequent transformations and corresponds to the base reference used internally by the Kinova control system.

Each joint frame is then assigned according to the physical geometry and joint axis orientation of the robot. The joint axes align with the rotational axes defined by the Kinova Gen3 actuator design, which employs strain wave gearing and integrated sensing at each joint. The use of manufacturer defined joint geometry ensures that the analytical model remains consistent with the robot's internal kinematic representation, reducing discrepancies between simulated and executed motion.

The end effector frame is defined at the cutting tool reference point, corresponding to the physical location of blade contact with the sheet material. This tool frame is explicitly defined relative to the interface module mounting surface, which includes a positioning key and fixed bolt pattern to ensure repeatable alignment of attached tools. Defining the tool frame at the point of material interaction is particularly important for cutting tasks, as it allows Cartesian trajectories to be expressed directly in terms of cutting geometry rather than abstract wrist positions (Motta et al., 2016).

As highlighted in foundational robotics literature, inconsistent or poorly defined coordinate frames are a common source of modelling and execution errors, particularly when Cartesian paths are required (Asada and Slotine, 1986). By adopting a frame hierarchy that mirrors both the physical structure of the robot and the manufacturer validated reference frames, the modelling approach minimises cumulative transformation errors and improves repeatability across simulation and experimentation.

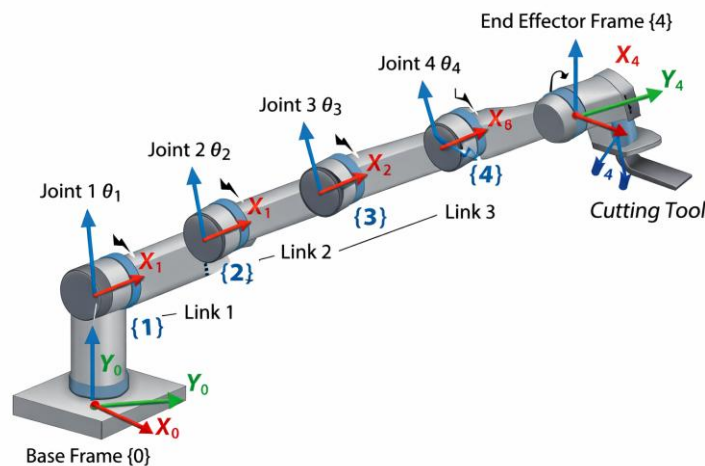


Figure 4.1: Kinematic model of the robotic arm showing link structure and coordinate frame assignment

4.1.2 Denavit–Hartenberg Parameterisation

To formalise the geometric relationships between successive links, the Denavit–Hartenberg convention is employed. This method provides a systematic framework for representing link transformations using four parameters per joint: link length, link twist, link offset, and joint angle. The D–H formulation remains widely used due to its clarity, compactness, and compatibility with analytical derivation and simulation tools (Asada and Slotine, 1986).

For the Kinova Gen3, manufacturer provided Denavit–Hartenberg parameters are available for both six and seven degree-of-freedom configurations. In this study, the six degree-of-freedom model is adopted, and the corresponding parameter set is used as the basis for modelling. Using the manufacturer supplied parameters ensures that link dimensions, joint offsets, and twist angles accurately reflect the physical robot, including the spherical wrist configuration.

Each joint is modelled as a revolute joint with a variable joint angle, while all link parameters remain constant. Although real systems are subject to manufacturing tolerances, joint compliance, and assembly variation, the D–H model provides sufficient accuracy for workspace analysis, trajectory planning, and motion verification. These effects are treated as second order influences that are better addressed through conservative motion planning and experimental observation rather than through overly complex modelling.

An important consideration for this project is that the D–H model is not used to command low level actuator motion directly. Instead, it serves as an analytical tool for validating reachability, identifying singular configurations, and supporting trajectory design. This aligns with the system design philosophy outlined in Chapter 3, where high level planning is separated from low level execution to improve robustness and safety.

4.1.3 Forward Kinematics Formulation

Forward kinematics describes the mapping from joint space to Cartesian space. Given a set of joint angles, the position and orientation of the end effector can be computed relative to the base frame. This formulation is fundamental for visualising motion, validating workspace coverage, and verifying that planned toolpaths lie within the reachable region of the robot.

Using the D–H parameters defined previously, a homogeneous transformation matrix is constructed for each joint. These matrices encode both rotation and translation between successive frames. The overall transformation from base frame to tool frame is obtained by sequential multiplication of the individual joint transformations. The resulting transformation

matrix provides the full Cartesian pose of the cutting tool, including both position and orientation.

Forward kinematics plays a critical role during the modelling and simulation stages of this project. It allows the planned cutting paths to be overlaid on the robot's reachable workspace, ensuring that no segment of the path exceeds joint limits or violates orientation constraints. For planar cutting tasks, forward kinematics also enables verification that the tool remains normal to the cutting plane throughout motion, which is essential for consistent cut quality.

Although the Kinova Gen3 internally computes forward kinematics as part of its control system, maintaining an explicit analytical formulation improves transparency and supports independent validation. In experimental contexts, this is particularly valuable for diagnosing discrepancies between commanded motion and observed behaviour, especially when conservative internal safety mechanisms influence execution (Ali et al., 2023).

4.1.4 Inverse Kinematics Solution Strategy

Inverse kinematics addresses the complementary problem of determining joint configurations that achieve a desired end effector pose. For robotic cutting applications, inverse kinematics is essential because toolpaths are defined in Cartesian space, reflecting the geometry of the cut rather than the configuration of individual joints.

Analytical inverse kinematics solutions are not always available for multi degree of freedom manipulators, particularly when joint limits, orientation constraints, and redundancy are considered. In practical robotic systems, numerical or geometric methods are often preferred due to their flexibility and robustness. The Kinova Gen3 supports inverse kinematics internally through its control stack, providing validated solutions that respect joint limits, singularity avoidance, and safety constraints.

In this project, inverse kinematics is treated primarily as a planning and validation tool rather than as a low level control mechanism. The cutting task is predominantly planar, and tool orientation is constrained to remain normal to the cutting surface. These constraints significantly reduce the solution space, allowing deterministic inverse kinematics solutions to be selected consistently across repeated executions.

By relying on the manufacturer supported inverse kinematics implementation, the system avoids the instability risks associated with custom numerical solvers while still maintaining

sufficient control over tool pose. This approach aligns with the broader design philosophy of prioritising repeatability and safety over algorithmic novelty.

4.1.5 Workspace Analysis and Singularity Identification

Workspace analysis is conducted to identify the region of space that the end effector can reach while maintaining valid and stable joint configurations. For cutting applications, workspace analysis is not merely a question of reachability but also of motion quality. Regions near kinematic singularities are associated with reduced stiffness, increased joint velocities, and degraded controllability.

The workspace of the Kinova Gen3 is evaluated by sweeping joint angles within their allowable limits and computing corresponding end effector positions using forward kinematics. Manufacturer documentation provides explicit joint limits and singularity avoidance mechanisms, which are incorporated into the analysis. These mechanisms are designed to prevent the robot from entering configurations where control performance may degrade.

Singularity regions are identified and deliberately avoided in the definition of the cutting workspace. As emphasised in classical robotics literature, operating near singular configurations can result in amplified joint motion and unstable tool behaviour, which is particularly problematic for continuous process tasks such as cutting (Asada and Slotine, 1986). The cutting zone is therefore selected within the central region of the workspace, where stiffness and control authority are most consistent.

This conservative workspace selection directly supports the system requirements defined in Chapter 3. By avoiding marginal configurations, the methodology prioritises stable and repeatable cutting behaviour over maximum spatial coverage. This compromise is appropriate for laboratory and SME environments, where reliability and predictability are valued more highly than extreme reach.

4.2 Dynamic and Torque Analysis

While kinematic modelling defines the geometric feasibility of motion, dynamic analysis determines whether the robotic arm can physically execute the planned trajectories under realistic loading conditions. In robotic metal sheet cutting, the cutting tool remains in continuous contact with the workpiece, generating resistive forces that are transmitted through the robot structure. These forces influence joint torques, actuator loading, vibration behaviour,

and overall motion stability. As a result, dynamic considerations play a central role in determining whether stable and repeatable cutting can be achieved in practice.

Consistent with the design philosophy established in Chapter 3, the dynamic analysis in this project is conducted at a level appropriate for a lightweight robotic cutting application. Rather than developing a full nonlinear dynamic model with inertia coupling and Coriolis effects, the analysis focuses on estimating joint torque requirements, identifying critical loading scenarios, and verifying that actuator capabilities are not exceeded during cutting. This approach reflects common practice in studies of low cost and laboratory scale robotic systems, where conservative design margins are often more valuable than highly detailed but uncertain dynamic models (Reddy and Eranki, 2016).

The Kinova Gen3 provides manufacturer validated low level dynamic control and internal safety mechanisms. Consequently, the purpose of this analysis is not to redesign or override these internal controls, but to ensure that planned cutting operations remain within the physical and operational limits of the robot and its actuators.

4.2.1 Modelling Assumptions and Load Conditions

To keep the dynamic analysis tractable and aligned with the scope of the project, several simplifying assumptions are adopted. These assumptions are consistent with prior academic work on lightweight robotic manipulators and are appropriate given the conservative operating regime used in this study.

First, all links are modelled as rigid bodies. While real robotic arms exhibit some degree of structural compliance, treating links as rigid provides a reasonable approximation for torque estimation and load propagation, particularly when cutting forces are moderate and motion profiles are smooth. Structural compliance and vibration are addressed separately through conservative trajectory design and experimental observation.

Second, joint friction and transmission losses are approximated rather than modelled explicitly. In practice, friction varies with speed, temperature, and wear, and accurate modelling would require detailed experimental characterisation. Instead, conservative torque margins are applied to account for these effects implicitly, ensuring that actuator sizing remains robust under uncertainty.

Third, cutting forces are modelled as external loads applied at the tool centre point. For metal sheet cutting, these forces act predominantly within the plane of the sheet, opposing the

direction of tool motion. While actual cutting forces vary with material properties, sheet thickness, blade condition, and feed rate, conservative force estimates are used to represent worst case conditions. This approach prioritises safety and repeatability over aggressive performance assumptions.

Dynamic effects associated with rapid acceleration are intentionally minimised through the motion planning strategy described in Chapter 3. By limiting acceleration and avoiding abrupt direction changes, inertial loads remain small relative to cutting forces. This simplifies the analysis and reflects the system's focus on stable process execution rather than high speed operation.

4.2.2 Joint Torque Estimation Under Cutting Loads

Joint torque estimation is performed by propagating the external cutting forces applied at the end effector backward through the kinematic chain. The torque experienced by each joint depends on the magnitude and direction of the cutting force, the orientation of the links, and the effective moment arm between the joint axis and the point of force application.

For planar cutting tasks, the dominant force component acts tangentially to the cutting path within the sheet plane. This force generates moments about upstream joints that increase with distance from the base. As a result, joints closer to the robot base typically experience the highest torque demands, as they must support both the external cutting load and the weight of all downstream links and tooling.

This loading distribution is well documented in the literature. Reddy and Eranki (2016) showed that insufficient torque margins in proximal joints can lead to noticeable deflection, reduced positional repeatability, and increased vibration at the tool tip. These effects are particularly pronounced in serial manipulators, where small joint deflections accumulate along the kinematic chain.

In this project, estimated joint torques are calculated for representative cutting scenarios, including straight cuts and direction changes where loading is highest. Conservative assumptions are adopted regarding cutting force magnitude to account for uncertainties related to material variability and tool wear. These torque estimates are then compared against actuator capabilities to verify that continuous operation remains within safe limits.

Rather than optimising for minimum actuator size, the analysis intentionally favours generous torque margins. This decision reflects the emphasis on repeatability and reliability rather than

maximum throughput. Operating actuators well below their maximum torque ratings reduces the risk of missed steps, thermal overload, and long term wear, particularly in extended cutting sequences.

4.2.3 Motor and Transmission Sizing Validation

Motor and transmission selection is validated by comparing estimated torque requirements against actuator ratings under continuous operation. As discussed in Chapter 2, stepper motors are widely used in low cost robotic systems due to their affordability, simplicity, and ease of control. However, their open loop operation makes them sensitive to overload, particularly during tasks involving external resistive forces such as cutting (Hameed and Ay, 2024).

Motor selection in this project prioritises holding torque, low speed torque stability, and thermal performance rather than peak rotational speed. This aligns with the cutting application, where smooth, controlled motion at moderate speeds is more important than rapid repositioning. Where necessary, gear reductions are incorporated to increase effective joint torque while reducing the speed demand on the motor.

The consequence associated with gear reduction is a reduction in maximum joint speed and increased mechanical complexity. However, given that cutting operations are performed at relatively low feed rates, this limitation is acceptable. The use of gear reduction also improves resolution at the joint, which can contribute to smoother motion and improved repeatability when combined with conservative acceleration profiles.

Thermal considerations form an important part of motor validation. Continuous cutting can lead to sustained current draw and temperature rise in both motors and drivers. To mitigate this, motor drivers are configured with conservative current limits, and duty cycles are selected to avoid prolonged operation at high load. This approach reflects the passive thermal management strategy discussed in Chapter 2 and supports reliable long term operation.

Although the Kinova Gen3 itself employs integrated servo actuators rather than external stepper motors, the same validation principles apply. The estimated joint torque demands are compared with the manufacturer specified joint torque limits to confirm that cutting operations remain comfortably within the robot's operational envelope. This ensures that internal safety limits are not repeatedly triggered during cutting, which could otherwise degrade motion smoothness or interrupt execution.

4.2.4 Vibration, Compliance, and Motion Smoothness Considerations

Vibration and structural compliance represent critical challenges for serial robotic arms engaged in cutting tasks. Even when joint torques remain within allowable limits, dynamic excitation of structural modes can degrade cut quality and accelerate mechanical wear. In lightweight robotic systems, these effects are often more pronounced due to reduced structural stiffness and lower damping.

As noted by Reddy and Eranki (2016), vibration behaviour is strongly influenced by end effector loading, joint stiffness, and acceleration profiles. Cutting forces applied at the tool tip can excite oscillations that propagate through the kinematic chain, particularly during direction changes or abrupt speed variations. These oscillations manifest as chatter marks, uneven kerf width, or audible vibration during cutting.

To mitigate these effects, the system adopts several complementary strategies. First, conservative acceleration and deceleration limits are applied to all cutting trajectories, reducing dynamic excitation. Second, motion profiles are smoothed to avoid sudden changes in velocity, particularly at corners and path transitions. Third, the end effector mounting strategy described in Chapter 3 prioritises stiffness and short load paths to reduce compliance near the tool.

Rather than attempting to model vibration dynamics explicitly, which would require detailed modal analysis and parameter identification, the project addresses vibration through design choices and empirical validation. This approach is appropriate for the scope of the work and reflects common practice in experimental studies of lightweight robotic cutting systems.

The dynamic and torque analysis confirms that the proposed system operates within conservative and defensible limits. By combining simplified torque estimation with cautious actuator selection and smooth motion planning, the methodology supports stable and repeatable cutting without imposing excessive modelling complexity. This balance between analytical rigour and practical applicability aligns with the broader objectives of the dissertation and provides a sound foundation for the simulation and experimental validation presented in the remainder of Chapter 4.

4.3 CAD Modelling and Structural Analysis

Computer aided design and structural analysis play a central role in validating the mechanical feasibility of the proposed robotic arm before physical implementation. While kinematic and dynamic analyses establish whether motion is theoretically achievable, CAD based modelling

and simulation provide insight into how the structure responds to real loads, including gravity, cutting forces, and joint reactions. For robotic metal sheet cutting, where external forces are applied continuously at the end effector, understanding stress distribution and deformation behaviour is essential to ensuring safe, stable, and repeatable operation. A three-dimensional CAD model was developed to represent the overall mechanical structure of the articulated robotic arm and to support structural and integration analysis.



Figure 4.2: CAD model of an articulated six-axis robotic arm configured for sheet metal cutting applications

Figure 4.2 presents the CAD model used for structural evaluation and assembly planning, providing a clear representation of joint placement, link proportions, and the end effector configuration adopted for cutting operations. While the CAD model reflects the general architecture of an articulated industrial robotic arm, it is a simplified representation developed solely for analysis and illustration purposes and does not reproduce proprietary manufacturer geometry. In low cost and laboratory scale robotic systems, physical prototyping without prior structural evaluation can lead to avoidable design weaknesses, excessive deflection, or premature component failure. By integrating CAD modelling with finite element analysis, potential mechanical limitations can be identified early and addressed through geometry refinement, material selection, or conservative operating assumptions. This approach aligns with the systems based design philosophy adopted throughout this dissertation and supports informed decision making rather than trial and error fabrication.

4.3.1 CAD Development and Assembly Modelling

The robotic arm is modelled using SolidWorks, with individual links, joints, and mounting interfaces represented according to their physical dimensions and intended materials. Each component is modelled as a separate part, allowing a clear definition of geometry, mass properties, and interfaces. Assembly constraints are then applied to replicate the actual joint connections, including rotational degrees of freedom, joint limits, and fixed interfaces.

Care is taken to ensure that the CAD assembly reflects the real mechanical configuration rather than an idealised abstraction. Joint axes are aligned with the intended motor and bearing orientations, and link lengths correspond to the design dimensions used in the kinematic model. This consistency between CAD and analytical models is important for ensuring that simulation results remain relevant to the physical system.

The assembled CAD model serves several purposes. First, it allows visual verification of reach, workspace coverage, and potential interference between links during motion. This helps identify geometric issues such as link collisions or impractical joint arrangements before fabrication. Second, the model provides mass and centre of gravity information that supports dynamic and torque analysis. Third, it forms the basis for finite element simulations by defining the geometry and material properties used in structural analysis. Parts of the robotic arm used for sheet metal cutting are shown in Figure 4.3, including the base, articulated links, wrist assembly, and the cutting end effector.

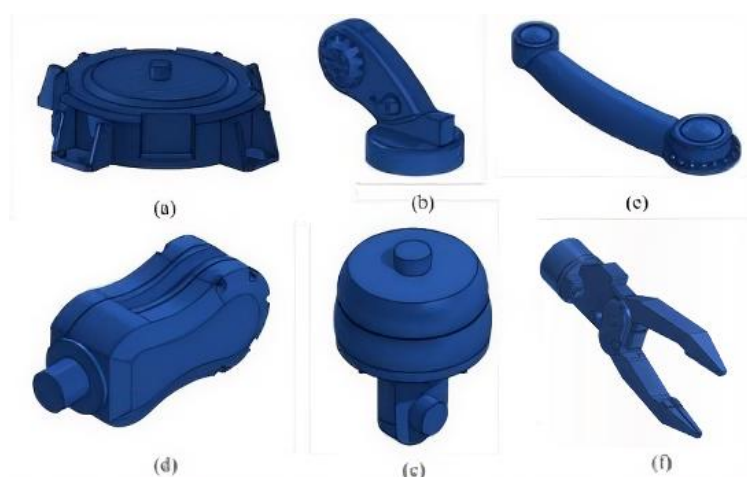


Figure 4.3: CAD models of robotic arm components for sheet metal cutting: (a) base, (b) shoulder link, (c) arm link, (d) wrist housing, (e) connector, and (f) cutting end effector.

In addition to simulation, the CAD model supports practical aspects of system development. It assists in fabrication planning by clarifying component dimensions and tolerances, and it supports alignment during assembly by providing a clear reference for joint positioning and orientation. For modular or low cost robotic systems, this level of modelling is particularly valuable, as it reduces ambiguity during construction and improves repeatability across builds.

4.3.2 Static Stress and Deformation Analysis

Static structural analysis is conducted to evaluate how the robotic arm responds to worst case loading conditions during cutting operations. Although cutting is a dynamic process, static analysis provides a useful first order approximation of stress distribution and deformation under sustained loads. This approach is commonly adopted in academic studies of lightweight robotic systems, where the objective is to identify potential structural weaknesses rather than to predict exact transient behaviour (Reddy and Eranki, 2016).

In the analysis, gravitational loads corresponding to the weight of the links and end effector are applied, along with representative cutting forces at the tool centre point. These cutting forces are oriented within the plane of the sheet material and oppose the direction of tool motion, reflecting the dominant loading scenario during planar cutting tasks. Boundary conditions are defined at the robot base to represent rigid mounting to the work surface.

Equivalent von Mises stress was used as the primary evaluation metric. This criterion is appropriate for ductile structural materials subjected to combined bending, shear, and torsional loading, which are characteristic of articulated robotic arms during cutting operations (Reddy and Eranki, 2016). Simulation results indicate that stresses remain below the yield limits of the selected materials under the applied loads. Peak stress concentrations occur near joint interfaces and mounting points, where load transfer between components is most significant. These regions are examined carefully to ensure that local stress levels do not approach critical thresholds that could lead to fatigue or long term degradation.

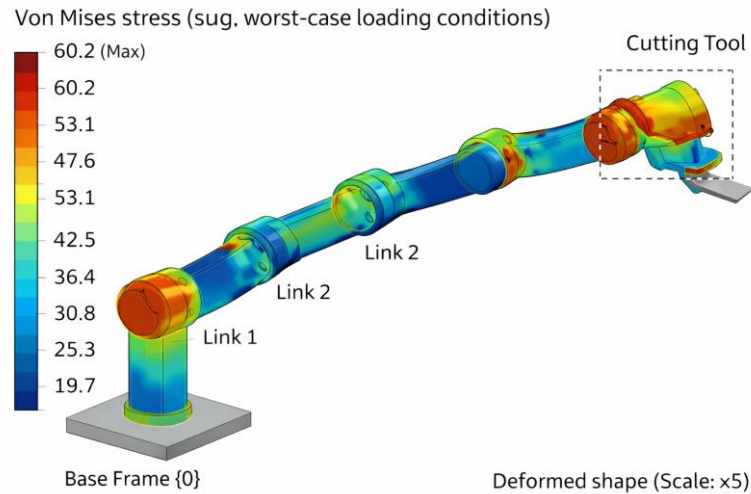


Figure 4.4: Finite element analysis showing von Mises stress distribution and structural deformation of the robotic arm under representative cutting and gravitational loads.

Deformation results reveal that deflection is concentrated primarily in longer links and distal sections of the arm, as expected for serial manipulators. Although the magnitude of deformation is small, it is not negligible in the context of precision cutting tasks. Even minor deflections at the end effector can influence tool alignment and contribute to variability in cut quality. These findings reinforce the need for conservative motion planning, rigid end effector mounting, and avoidance of aggressive acceleration profiles, as discussed in Chapters 3 and 4.2.

Importantly, the purpose of this analysis is not to eliminate all deformation, which would be unrealistic in a lightweight system, but to confirm that deformation remains within acceptable bounds for the intended application. The results support the conclusion that, when combined with conservative operating parameters, the structure provides sufficient stiffness for thin metal sheet cutting.

4.3.3 Modal Analysis for Structural Stability

Modal analysis is performed to identify the natural frequencies and mode shapes of the robotic arm structure. Understanding these dynamic characteristics is essential for avoiding resonance during operation, as resonance can amplify vibration and significantly degrade cutting performance.

Lightweight robotic arms are particularly susceptible to resonance effects due to lower structural stiffness and damping compared with industrial robots. Chauhan et al. (2015) highlighted that even modest excitation near a natural frequency can result in noticeable

oscillations at the end effector, especially in serial manipulators where compliance accumulates along the kinematic chain.

The modal analysis identifies the dominant vibration modes of the structure, including bending modes of long links and coupled modes involving multiple joints. These modes are associated with specific frequency ranges that depend on geometry, material properties, and boundary conditions. While exact modal frequencies may shift slightly in the physical system due to assembly tolerances and joint compliance, the analysis provides a useful indication of frequency ranges to avoid.

Based on these results, operating parameters are selected to minimise excitation of dominant modes. In particular, cutting feed rates and acceleration limits are chosen such that the frequency content of motion commands remains well below identified natural frequencies. This strategy complements the smooth trajectory planning approach described in Chapter 3 and the dynamic considerations discussed in Section 4.2.

Rather than relying on active vibration control or damping mechanisms, which would add complexity and cost, the system addresses vibration risk through informed design and conservative operation. This approach is consistent with the philosophy of low cost robotic system development and is appropriate for the intended application domain.

4.3.4 Thermal Analysis of the Cutting End Effector

Thermal analysis focuses on heat generation and dissipation at the cutting end effector, where frictional interaction with the workpiece and motor operation can lead to temperature rise. Although the robotic arm itself is not exposed to extreme thermal loads, prolonged cutting operations can result in localised heating that affects tool performance, motor reliability, and dimensional stability.

In the analysis, heat generation is considered primarily at the cutting tool and its drive motor. Friction at the blade and material interface produces heat that is conducted through the blade, tool mount, and surrounding structure. In addition, electrical losses in the motor contribute to temperature rise during sustained operation.

Rather than attempting detailed thermal simulation with uncertain boundary conditions, the analysis adopts a qualitative and conservative approach. Metallic mounts are used to promote passive heat dissipation away from the tool, and duty cycles are selected to avoid continuous

high load operation. These design choices reduce the likelihood of excessive temperature accumulation without introducing active cooling systems.

This approach aligns with findings reported by Reddy and Eranki (2016), who emphasised that thermal awareness is essential even in low power robotic process tasks. Elevated temperatures can accelerate tool wear, increase cutting forces, and indirectly influence motion accuracy through thermal expansion or motor derating.

By combining passive heat dissipation, conservative cutting parameters, and operational pauses where necessary, the system manages thermal effects within acceptable limits. This strategy supports reliable operation while maintaining the simplicity and affordability required for laboratory and SME contexts.

4.4 Control System Modelling and Simulation

Control system modelling and simulation provide a critical bridge between analytical design and physical implementation. While kinematic, dynamic, and structural analyses establish that the robotic arm is theoretically capable of executing cutting tasks, control simulation evaluates how the system responds to motion commands under realistic assumptions. This stage allows motion behaviour, stability, and tracking performance to be examined in a safe virtual environment before any hardware is powered or loaded.

For robotic metal sheet cutting, smooth and predictable motion is more important than aggressive performance. Sudden accelerations, oscillations, or control instability can degrade cut quality and increase mechanical stress. Control simulation therefore, focuses on assessing stability, tracking consistency, and sensitivity to parameter selection rather than achieving maximum speed or responsiveness. This approach supports the conservative and safety driven design philosophy established in Chapter 3.

4.4.1 Control System Architecture for Simulation

The simulated control architecture mirrors the structure of the physical system as closely as practical. High level trajectory generation produces desired joint position references derived from Cartesian cutting paths, while joint level controllers are responsible for tracking these references. This separation between planning and execution reflects the layered control philosophy adopted in the physical system and aligns with established ROS based control frameworks (Chitta et al., 2017).

In the simulation environment, trajectory generation is treated as an external input that defines desired joint motion profiles over time. These profiles incorporate the same velocity and acceleration constraints used in the physical system to ensure consistency between simulated and real behaviour. By maintaining this alignment, simulation results remain directly relevant to later experimental testing.

Each joint is modelled as an independent control loop. While joint interactions and coupling effects exist in real robotic systems, this simplification is appropriate for evaluating baseline control behaviour in a low cost and conservatively operated system. The objective is not to reproduce every dynamic interaction, but to verify that individual joints can track commanded motion smoothly without instability or excessive lag.

This architecture reflects the structure implemented in `ros_control`, where high level controllers generate commands and hardware specific drivers manage actuator behaviour (Chitta et al., 2017). By adopting a similar structure in simulation, the project ensures conceptual continuity between modelling, implementation, and execution.

4.4.2 MATLAB and Simulink Model Development

A MATLAB and Simulink model is developed to simulate joint level motion and control response. Each joint is represented by a simplified dynamic model incorporating rotational inertia, damping, and motor torque characteristics. These parameters are estimated from component specifications, link geometry, and reasonable engineering assumptions, rather than detailed system identification.

The model includes the relationship between commanded position, control effort, and joint response. Motor limitations such as maximum torque and rate of change are implicitly represented through saturation and damping effects. While this simplified representation does not capture all nonlinearities present in the physical system, it provides sufficient fidelity to evaluate control stability and relative performance trends.

Simulink is used to visualise joint response to both step inputs and continuous trajectory commands. Step responses allow assessment of overshoot, settling time, and steady state error, while trajectory tracking simulations evaluate how well joints follow smooth motion profiles representative of cutting paths. These simulations provide insight into whether the selected control strategy can support the motion smoothness required for cutting tasks.

Importantly, simulation is not treated as a prediction of exact physical behaviour. Instead, it is used as a comparative and diagnostic tool that supports informed selection of controller gains, motion limits, and safety margins. This pragmatic use of simulation is consistent with good engineering practice for low cost robotic systems.

4.4.3 PID Control Strategy and Parameter Tuning

A Proportional Integral Derivative control strategy is adopted for joint level control due to its simplicity, robustness, and suitability for embedded systems. PID control remains widely used in robotic applications where operating conditions are well defined, and system dynamics are reasonably predictable (Asada and Slotine, 1986).

In this project, PID control is selected not because it offers optimal performance, but because it offers reliable and interpretable behaviour. More advanced control strategies, such as model based or adaptive control, would introduce additional complexity and tuning effort that are not justified within the scope of this work.

Controller gains are tuned using an iterative simulation based approach. Initial gain values are selected to ensure stability, after which proportional, integral, and derivative terms are adjusted to balance responsiveness and smoothness. Excessive proportional gain is avoided to prevent oscillation, while integral action is limited to reduce the risk of wind up under sustained load. Derivative action is used conservatively to damp transient response without amplifying noise or numerical sensitivity.

The tuning process prioritises smooth tracking of slow and moderate speed trajectories rather than rapid step response. This reflects the requirements of metal sheet cutting, where consistent tool motion and controlled engagement are more important than fast repositioning. As noted by Park et al. (2020), well tuned PID controllers can provide reliable performance in robotic systems when operating conditions are constrained and well understood.

Simulation results demonstrate that appropriately tuned PID controllers can achieve stable tracking with minimal overshoot and acceptable steady state error. These results support the suitability of PID control for the intended application and reinforce the decision to prioritise simplicity and robustness over advanced control techniques.

4.4.4 Simulated Motion Profile Evaluation and Optimisation

Simulated cutting trajectories are evaluated to assess motion smoothness, tracking accuracy, and overall stability. Trajectories reflect realistic cutting paths, including linear segments, gentle curves, and direction changes representative of practical sheet metal cutting tasks.

Key evaluation metrics include tracking error, velocity continuity, and absence of oscillatory behaviour. Simulation results show that conservative acceleration limits and smooth trajectory profiles significantly reduce tracking error and eliminate oscillations that could compromise cut quality. In contrast, more aggressive motion profiles introduce noticeable overshoot and transient instability, particularly during direction changes.

Based on these observations, motion profiles are refined to emphasise gradual acceleration and deceleration, with reduced feed rates at corners. These adjustments are consistent with the motion planning strategy described in Chapter 3 and with findings from structural and dynamic analyses earlier in this chapter.

Simulation also highlights the interaction between controller gains and trajectory shape. Even well tuned controllers can exhibit undesirable behaviour if motion commands contain abrupt changes. This reinforces the importance of treating motion planning and control tuning as interdependent design tasks rather than independent stages.

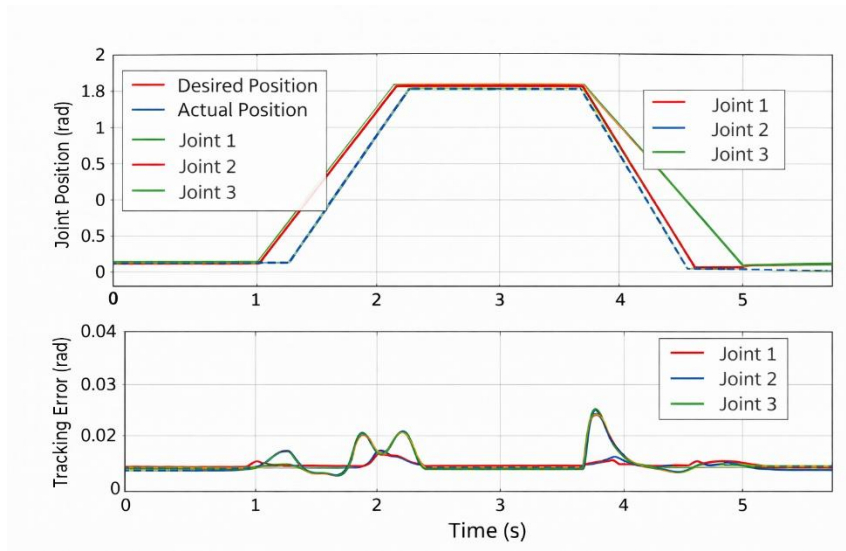


Figure 4.3: Simulated joint position tracking and corresponding tracking error for three representative joints under a predefined cutting trajectory. Joint positions and errors are expressed in radians. Increased tracking error is observed during acceleration and deceleration phases, while steady-state motion exhibits minimal error, indicating stable and well-tuned controller behaviour suitable for cutting applications.

The magnitude and transient nature of the tracking error are consistent with conservative motion profiles and confirm that the controller maintains stable performance without excessive overshoot or oscillation, which is critical for maintaining cutting quality and tool stability. The simulation confirms that stable and repeatable motion suitable for cutting tasks can be achieved using simple controllers when combined with conservative trajectory design. This outcome supports the broader design philosophy of the project and provides confidence in the readiness of the system for physical implementation.

4.5 Synthesis of Modelling and Analysis Results

This chapter has demonstrated that the proposed robotic system is kinematically feasible, dynamically viable, and structurally adequate for lightweight metal sheet cutting within the defined scope. Kinematic modelling confirmed that the robotic arm can reach and follow the required cutting paths while maintaining appropriate tool orientation. Workspace and singularity analysis ensured that planned motion remains within stable regions of operation.

Dynamic and torque analyses validated actuator selection under conservative loading assumptions and highlighted the importance of smooth motion in limiting joint stress and vibration. Structural and thermal analyses reinforced the need for rigid mechanical integration, controlled acceleration, and passive heat management to support consistent cutting performance.

Control system modelling and simulation showed that simple, well tuned PID controllers combined with conservative motion profiles can deliver stable and repeatable joint behaviour suitable for cutting tasks. Simulation results informed the selection of controller gains and trajectory limits, reducing implementation risk and supporting safe physical testing.

Collectively, the modelling and simulation work provides a strong foundation for the practical implementation described in Chapter 5. By addressing kinematic feasibility, dynamic loading, structural integrity, thermal effects, and control stability in a coherent manner, the chapter ensures that physical construction and experimentation can proceed with confidence in the integrity of the underlying system design.

Chapter 5 – System Implementation and Assembly

5.1 Introduction to System Implementation

Chapters 3 and 4 established the system design methodology and validated the feasibility of the proposed robotic arm through kinematic modelling, dynamic analysis, structural simulation, and control evaluation. While these analytical stages are essential, the practical value of the research ultimately depends on the successful translation of design intent into a physical, functioning system. This chapter documents the implementation and assembly of the robotic arm, focusing on how theoretical decisions were realised in hardware and software while maintaining the priorities of repeatability, safety, and reliability.

The implementation process followed a structured systems approach. Mechanical assembly, electrical integration, and software development were treated as interconnected activities rather than isolated tasks. Decisions made during assembly were continuously informed by the modelling results presented in Chapter 4, particularly with respect to stiffness, torque margins, vibration sensitivity, and thermal behaviour. This ensured consistency between analytical assumptions and physical execution.

Rather than optimising for speed or industrial throughput, the implementation prioritised robustness, alignment accuracy, and conservative operation. This emphasis reflects the intended application of the system in laboratory and SME contexts, where predictable behaviour and ease of maintenance are more valuable than maximum performance (Krüger and Yang, 2022). The chapter concludes with preliminary testing and validation activities that establish readiness for experimental evaluation in Chapter 6.

5.2 Component Procurement and Verification

Component selection and procurement were guided directly by the functional and non functional requirements defined in Chapter 3, as well as by the modelling assumptions established in Chapter 4. Wherever possible, commercially available components with well documented specifications were selected to reduce uncertainty during integration and to ensure consistency between analytical predictions and physical implementation. This approach aligns with established guidance for low cost robotic system development, where reliance on standard components simplifies troubleshooting, maintenance, and future system refinement (Ali et al., 2023).

Mechanical components were sourced with careful consideration of stiffness, mass, and structural reliability. Aluminium profiles and machined plates were selected for primary structural elements due to their favourable strength to weight characteristics, dimensional stability, and ease of assembly. Bearings, shaft couplings, and fasteners were chosen based on load ratings that exceeded the estimated forces and moments identified during the torque and structural analyses presented in Chapter 4. This ensured adequate safety margins under sustained cutting loads and reduced the risk of premature mechanical degradation.

Electrical components, including motors, motor drivers, power supplies, and control electronics, were procured from reputable suppliers providing complete and verifiable datasheets. Prior to installation, all electrical components underwent basic bench level verification. Motors were tested for smooth rotation, correct direction of motion, and nominal no load current draw. Motor drivers and power supplies were checked for output voltage stability, current delivery capability, and absence of abnormal heating during short duration operation under representative loads.

Mechanical verification was conducted in parallel with electrical checks. Structural components were inspected for dimensional conformity, surface defects, and machining accuracy. Bearings and couplings were examined for smooth operation, proper fit, and absence of play or binding. Fasteners were checked for thread quality and seating consistency. These checks ensured that assembled components behaved as expected and that no unintended compliance or misalignment was introduced at an early stage.

Verification at this procurement stage significantly reduced the likelihood of latent faults emerging during later assembly and system integration. By confirming that both mechanical and electrical components met their specified performance characteristics prior to installation, the risk of misattributing integration or control issues to modelling or software design was minimised. Verifying components prior to integration is crucial in experimental robotics, as it ensures that issues during testing are not mistakenly attributed to software or control faults (Reddy and Eranki, 2016).

5.3 Mechanical Assembly

Mechanical assembly establishes the physical integrity and geometric accuracy of the robotic arm. For cutting applications, even small assembly errors can accumulate along the kinematic chain, resulting in noticeable deviations at the end effector. The assembly process, therefore emphasised alignment, rigidity, and repeatability rather than rapid construction.

5.3.1 Base and Joint Assembly

Mechanical assembly began with the installation of the robot base and sequential construction of the joint chain. The base was rigidly mounted to a flat work surface to provide a stable reference for all subsequent assembly steps. Ensuring a rigid and level base was critical, as any misalignment at this stage would propagate through the serial kinematic chain and manifest as positional error at the end effector.

Each joint was assembled according to the designed kinematic layout, with particular attention paid to the alignment of joint axes. For serial manipulators, even small angular misalignments between joints can accumulate and significantly affect tool positioning accuracy, especially during extended reach configurations. This sensitivity has been widely reported in robotic arm design literature (Asada and Slotine, 1986).

Alignment was verified during assembly using mechanical reference edges and manual rotation checks. Each joint was rotated slowly through its full range of motion while observing for binding, uneven resistance, or lateral runout. Consistent and smooth motion across the full travel range was used as a practical indicator that joint axes were correctly aligned and that no unintended preload or skew had been introduced during assembly.

Fasteners were tightened incrementally and symmetrically to avoid introducing distortion at joint interfaces. Where adjustable mounts were present, final tightening was performed only after confirming free joint rotation. This approach reduced the risk of alignment drift during tightening and contributed to stable joint behaviour during later testing.

5.3.2 Motor Installation and Alignment

Following mechanical joint assembly, motors were installed and coupled to their respective joints. To accommodate slight misalignments and protect motor bearings, flexible couplings were employed between motors and joints. This choice reflects common practice in low cost robotic systems, where perfect coaxial alignment is difficult to achieve but must still be managed carefully (Chauhan et al., 2015).

Motor mounting brackets were installed with care to maintain parallelism between motor and joint shafts. Excessive angular or axial misalignment was avoided, as this can lead to vibration, increased wear, and torque losses during operation. Where necessary, thin shims were used to correct small mounting offsets identified during installation.

Following installation, each motor was driven individually at low speed under no load conditions to verify the correct direction of rotation and consistent response to control commands. Motor polarity and control signal mapping were confirmed at this stage to prevent unintended joint motion during coordinated multi axis operation. This basic commissioning step ensured that software level commands corresponded correctly to physical joint movement before full system integration.

Motor behaviour was also observed for abnormal noise, vibration, or excessive heating during these low speed tests. Any irregular behaviour was addressed before proceeding to further assembly, reducing the likelihood of compounded faults during later testing.

5.3.3 End Effector Mounting and Calibration

The cutting end effector was mounted to the robot wrist using a rigid adapter designed to minimise overhang and preserve tool alignment. The mounting interface was chosen to provide a fixed and repeatable reference between the robot flange and the cutting tool, ensuring that tool pose remained consistent relative to the robot coordinate system.

Calibration of the tool frame was performed by defining the tool centre point at the physical blade contact location. This reference point was established using measured offsets from the mounting interface and verified through controlled test motions near the cutting plane. Accurate tool frame definition was essential for ensuring that Cartesian cutting paths corresponded correctly to the physical cutting edge.

Calibration was repeated after tool removal and reinstallation to confirm that the mounting strategy supported consistent tool frame definition across repeated setups. The absence of noticeable positional shift following reinstallation indicated that the mounting interface provided sufficient geometric stability for experimental cutting tasks, supporting the system requirements defined in Chapter 3.

This calibration approach allowed cutting paths to be executed without compensating for tool specific variability, simplifying both planning and analysis while improving confidence in the observed cutting results.

5.3.4 Assembly Tolerances and Precision Issues

As with most low cost robotic systems, assembly tolerances and manufacturing variability introduced small but unavoidable deviations from ideal geometry. Rather than attempting to

eliminate all tolerance effects, the design and implementation focused on ensuring that such deviations remained within acceptable bounds for the intended application.

Tolerance effects were observed through repeated positioning trials and visual inspection of joint behaviour during slow motion execution. These checks allowed identification of minor backlash, compliance, or asymmetry in joint motion without requiring specialised measurement equipment. Observations were consistent across repeated tests, indicating stable mechanical behaviour rather than random assembly error.

In line with the system design philosophy, emphasis was placed on consistent behaviour rather than absolute positioning accuracy. For metal sheet cutting tasks, consistent path execution produces uniform kerf geometry even when small systematic offsets are present, a principle widely supported in robotic manufacturing literature (Asada and Slotine, 1986).

Where minor tolerance effects were identified, their impact was mitigated through conservative motion planning, reduced acceleration, and rigid end effector mounting rather than through mechanical redesign. This approach reflects a pragmatic balance between performance and affordability and is appropriate for laboratory and SME focused robotic systems (Ali et al., 2023).

5.4 Electrical Integration

Electrical integration links the mechanical system to the control architecture and plays a decisive role in motion reliability, safety, and repeatability. In robotic cutting applications, electrical faults can manifest as missed steps, unstable motion, or unpredictable behaviour that is difficult to distinguish from mechanical or control related issues. For this reason, the electrical design was approached with the same emphasis on robustness and traceability as the mechanical and software subsystems. Electrical integration in this project focused on reliable power delivery, correct motor driver configuration, clear signal routing, and effective noise mitigation.

5.4.1 Power Supply Selection and Distribution

Power supplies were selected to provide sufficient current capacity for all motors and control electronics under continuous operation, with additional margin to accommodate transient load variations during acceleration and cutting engagement. Rather than sizing supplies to absolute peak demand, continuous rated operation was prioritised to improve thermal stability and long term reliability.

Separate power rails were used for motor drivers and low voltage control electronics to reduce the risk of electrical noise coupling into sensitive signal lines. This separation ensured that current fluctuations associated with motor operation did not degrade communication stability or controller performance.

Power distribution wiring was routed to minimise voltage drop and avoid unnecessary cable length. Connections were secured using locking terminals to prevent loosening due to vibration during operation. These measures contributed to stable voltage delivery throughout testing and reduced the likelihood of intermittent faults.

5.4.2 Motor Driver Configuration

Motor drivers were configured to match the electrical and thermal characteristics of the selected motors. Key parameters included current limiting, microstepping resolution, and decay mode selection, all of which influence torque output, smoothness, and thermal behaviour.

Current limits were set deliberately below the motors' continuous rated current values while still providing sufficient torque margin for the estimated cutting loads. These values were informed directly by the torque estimates presented in Chapter 4, ensuring that electrical configuration decisions were traceable to analytical modelling rather than arbitrary selection. Operating below continuous ratings reduced thermal stress on both motors and drivers, supporting stable operation during extended cutting trials.

Microstepping was employed to improve motion smoothness and reduce vibration, particularly at low speeds where cutting interaction is most sensitive. While microstepping reduces incremental torque, this engineering decision was acceptable given the conservative motion profiles and torque margins established earlier in the design process.

Driver settings were verified during initial testing by commanding slow joint motion and monitoring current draw and motor temperature. Stable behaviour under no load and light load conditions confirmed correct configuration prior to full system operation.

5.4.3 Wiring, Grounding, and Safety Considerations

Electrical wiring was organised to maintain clarity, accessibility, and safety. Motor power cables and control signal lines were routed separately wherever possible to reduce electromagnetic interference. Cable management ensured that wires did not interfere with moving joints or introduce additional mechanical resistance.

A common grounding strategy was implemented to minimise ground loops and reduce noise susceptibility. All power supply grounds were referenced to a single point, and shielding was applied where appropriate to signal cables carrying step and direction commands. To guarantee immediate cessation of motor activity during faults, a hardware emergency stop was integrated into the electrical design. This hardware safety mechanism operates independently of software state, providing a reliable final layer of protection in the event of unexpected behaviour. Such layered safety approaches are considered essential for robotic systems operating in laboratory environments (Krüger and Yang, 2022).

5.4.4 Signal Integrity and Noise Mitigation

Signal integrity was treated as a critical design consideration due to the use of step and direction control signals, which are sensitive to electrical noise. Measures implemented included short signal paths, twisted pair wiring for control lines, and physical separation from high current motor cables.

Decoupling capacitors were used at driver power inputs to suppress voltage transients, and cable routing avoided parallel runs between signal and power conductors. These practices reduced the likelihood of false triggering, missed steps, or erratic motion during operation.

As a result of these measures, the system exhibited stable motion without observable step loss, unintended joint movement, or communication errors during preliminary testing. This outcome provided confidence that electrical noise would not confound evaluation of mechanical or control system performance during cutting experiments.

5.4.5 Electrical Integration Verification

Following installation and configuration, the electrical system was verified through staged testing. Individual joints were actuated independently at low speed to confirm correct direction, responsiveness, and current behaviour. Coordinated multi joint motion was then tested using conservative trajectories to observe combined electrical loading.

Throughout verification, motor temperatures, driver status indicators, and power supply stability were monitored. No abnormal heating or fault conditions were observed under the tested operating conditions, indicating that the electrical system was adequately sized and correctly configured.

This verification process ensured that electrical integration supported the functional and non-functional requirements defined in Chapter 3 and that subsequent system testing could proceed without ambiguity regarding electrical performance.

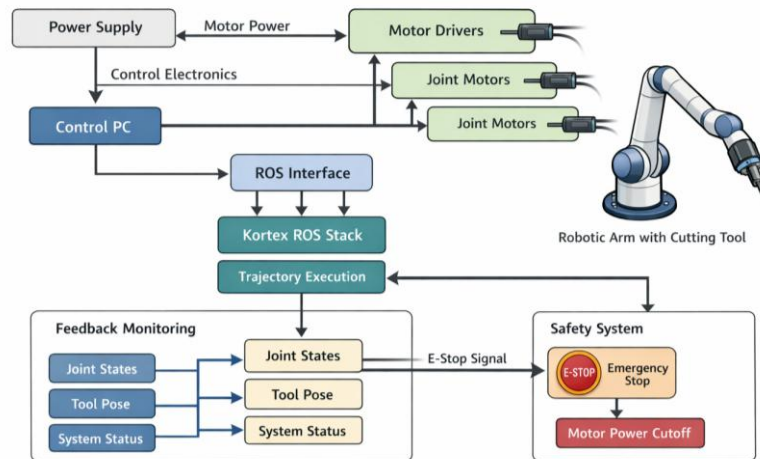


Figure 5.1: System Architecture and Integration Overview

5.5 Software Development

The software developed for this project provides the link between high level cutting intent and physical execution by the robotic system. Rather than focusing on algorithmic novelty, the software design prioritises clarity, robustness, and controlled execution. This approach reflects the overall philosophy of the project, which aims to demonstrate stable and repeatable robotic cutting behaviour within clearly defined operational limits rather than to maximise speed or computational complexity.

Consistent with the system design methodology presented in Chapter 3, the software architecture is modular. Individual functions such as path loading, trajectory generation, command execution, and monitoring are implemented as distinct components. This separation of concerns improves maintainability, simplifies debugging, and reduces the risk that errors in one part of the system propagate into others.

5.5.1 Software Architecture and Design Approach

The software is structured around a set of ROS nodes that communicate using standard message passing mechanisms. High level nodes are responsible for defining cutting paths and managing execution logic, while lower level interfaces handle communication with the robot through the Kortex ROS stack.

This layered approach mirrors the control architecture described in Chapter 3 and ensures that planning logic remains independent of hardware specific implementation details. By relying on documented and supported interfaces, the software avoids direct manipulation of actuator level parameters, reducing instability risks and improving reproducibility.

All configuration parameters related to motion limits, workspace boundaries, and tool offsets are defined explicitly within the software. This ensures that changes to cutting conditions or experimental setup can be made without modifying core execution logic.

5.5.2 Motion Control and Trajectory Execution

Trajectory execution is handled by a dedicated control node that streams motion commands to the robot based on precomputed Cartesian waypoints. These commands are issued at a consistent update rate sufficient to ensure smooth joint motion without overloading the control loop or introducing unnecessary computational latency.

Maintaining a steady execution rate is particularly important for cutting applications, where irregular command timing can lead to small velocity fluctuations that manifest as vibration or uneven cut quality. By enforcing consistent timing behaviour, the software supports stable tool motion and predictable interaction with the workpiece.

The execution logic includes explicit sequencing between approach, cutting, and retreat phases. Each phase is completed before transitioning to the next, preventing premature tool engagement or unintended contact during repositioning. This sequencing reinforces the safety and repeatability principles established earlier in the system design.

5.5.3 Feedback Handling and Monitoring

During execution, the software continuously receives feedback from the robot, including joint positions, tool pose, and system status indicators. This feedback is monitored to confirm that motion progresses as expected and that no fault or warning conditions arise.

Rather than implementing closed loop force or compliance control, feedback is used primarily for observation and validation. This design choice reflects the project's focus on controlled experimentation rather than adaptive process optimisation. Observed deviations between commanded and measured motion can therefore be interpreted directly, without ambiguity introduced by adaptive or force based control layers.

Feedback data is also logged for post execution analysis. This enables comparison between repeated trials and supports evaluation of consistency and repeatability, which are central performance criteria for the proposed system.

5.5.4 Safety and Fault Handling Logic

Safety logic was integrated directly into the control flow rather than treated as an external layer. This included limit checks, controlled start up behaviour, and immediate stop responses under fault conditions.

By embedding safety within the software architecture, the system reduces reliance on operator intervention and improves robustness during unexpected events (Krüger and Yang, 2022).

5.5.5 User Interaction and Operational Workflow

User interaction with the software is intentionally minimal and structured. Cutting paths are selected and loaded prior to execution, after which the system operates autonomously until completion or interruption. This design reduces operator influence during motion execution and improves consistency between experimental runs.

Basic validation checks are performed before execution to ensure that paths lie within the defined workspace and respect orientation constraints. These checks act as a safeguard against configuration errors and reduce the likelihood of runtime faults.

After execution, the system returns the robot to a predefined safe pose. This consistent end state simplifies repeated testing and reduces setup time between trials. While execution, monitoring, and safety handling operate autonomously, user interaction is deliberately restricted to predefined stages of the workflow.

5.5.6 Debugging and Code Optimisation

Debugging was performed incrementally, beginning with single joint motion and progressing to coordinated multi axis trajectories. This staged approach simplifies fault isolation and reduces the risk of cascading errors.

Code optimisation focused on improving timing consistency and reducing unnecessary computation rather than increasing execution speed. This aligns with the system's emphasis on stable motion over high throughput. This approach supports predictable execution behaviour during cutting trials, where consistency is more critical than raw computational performance.

5.5.7 Software Scope and Constraints

It is explicitly noted that the software is not intended to support high speed or high force cutting operations. All trajectory generation, execution timing, and monitoring logic are designed around conservative motion profiles that prioritise stability and safety over throughput.

By clearly defining these constraints within the software design, the system avoids inappropriate comparison with industrial cutting cells and ensures that performance evaluation remains aligned with the objectives of the project.

5.6 System Integration and Preliminary Testing

System integration represents the transition from isolated component validation to coordinated system operation. At this stage, mechanical, electrical, and software subsystems are combined to function as a single coherent robotic cutting platform. The objective of integration in this project is not immediate full scale cutting performance, but controlled verification that each subsystem interacts predictably with the others under increasingly realistic operating conditions.

Integration is conducted incrementally to minimise risk and to ensure that any observed issues can be traced to their source without ambiguity. This staged approach reflects good practice in experimental robotic system development, where early detection of integration faults significantly reduces the likelihood of cascading failures during later testing (Reddy and Eranki, 2016).

5.6.1 Integration Sequence and Verification Strategy

Integration begins with mechanical and electrical subsystems before introducing software driven motion. The robotic arm is first mounted securely within the defined workspace, ensuring alignment between the physical base and the reference frames defined during modelling in Chapter 4. Electrical connections are then completed, including power distribution, communication interfaces, and emergency stop wiring.

Before any motion commands are issued, static verification checks are performed. These include confirmation of correct power supply voltages, verification of communication between the robot and the control workstation, and validation that safety mechanisms such as emergency stop functionality operate as expected. Performing these checks prior to motion ensures that faults are identified without exposing the system to unnecessary risk.

Once static verification is complete, software integration is introduced in a controlled manner. The ROS environment is initialised, and the robot state is monitored to confirm correct reporting of joint positions, tool pose, and system status. Successful reception of feedback data confirms that the control stack is correctly configured and that the software interfaces described in Chapter 3 are functioning as intended.

5.6.2 Incremental Motion Testing

Motion testing is conducted in stages, progressing from simple to more complex behaviour. Initial tests involve low speed joint space movements executed without any attached cutting tool. These tests confirm correct joint directionality, limit enforcement, and smooth response to command inputs.

Following successful joint level testing, Cartesian motion is introduced. The robot is commanded to follow simple linear trajectories within the defined workspace while remaining clear of the workpiece. These tests validate the kinematic modelling, coordinate frame definitions, and trajectory execution logic developed in Chapter 4. Observed motion is compared against expected paths to confirm consistency between planned and executed behaviour.

Only after successful completion of these tests is the cutting end effector attached. Even at this stage, motion testing is initially performed without engaging material. This ensures that the added mass and inertia of the tool do not introduce unexpected behaviour and that the system remains stable under the modified load conditions.

5.6.3 Preliminary Cutting Trials

Preliminary cutting trials are conducted under deliberately conservative conditions. Feed rates, acceleration limits, and tool engagement depths are selected well below estimated maximum capability. This cautious approach reflects the project's emphasis on stability, repeatability, and safety rather than throughput.

The first cutting trials focus on short, straight paths within the central region of the workspace. This minimises exposure to kinematic extremes and reduces the influence of structural compliance. During these trials, system behaviour is closely observed, including tool motion smoothness, audible vibration, and feedback indicators such as estimated external wrench values.

Any unexpected behaviour observed during preliminary trials results in immediate termination of the test and review of system parameters. This conservative escalation strategy ensures that cutting is only performed when prior tests indicate acceptable system stability.

5.6.4 Observation, Logging, and Fault Handling

Throughout integration and preliminary testing, system feedback data is logged for later analysis. Logged parameters include commanded and measured tool pose, joint positions, and system status flags. This data provides an objective record of system behaviour and supports comparison across repeated tests.

Fault and warning indicators are monitored continuously. Although no major faults are expected during controlled testing, monitoring ensures that any deviations from normal operation are detected early. This approach avoids reliance on subjective judgement alone and supports transparent assessment of system reliability.

Importantly, the integration process treats fault detection as a design input rather than as an inconvenience. Observed limitations or instabilities inform later refinement of motion parameters and experimental procedure, reinforcing the iterative nature of system development.

5.6.5 Integration Outcomes and Readiness for Experimental Evaluation

The outcome of system integration and preliminary testing is a robotic cutting platform that operates predictably within defined limits. Successful completion of staged testing confirms that mechanical integration, control architecture, and software execution behave consistently with the modelling and design assumptions established in earlier chapters.

By the end of this phase, the system demonstrates stable Cartesian motion, reliable execution of predefined paths, and safe interaction with thin sheet material under conservative operating conditions. While performance optimisation is not yet pursued, the system is shown to be suitable for structured experimental evaluation.

This controlled readiness forms the basis for the experimental methodology presented in Chapter 6, where cutting performance, repeatability, and qualitative outcome measures are examined systematically.

Chapter 6 – Experimental Testing and Validation

6.1 Experimental Setup and Methodology

The analytical modelling and system implementation presented in Chapters 3 to 5 established that the proposed robotic cutting system is mechanically feasible, dynamically stable, and safely integrated. However, analytical validation alone cannot capture all real-world effects associated with robotic cutting, particularly those arising from mechanical compliance, tool interaction, and practical execution constraints. This chapter, therefore, presents the experimental testing and validation activities undertaken to assess system behaviour under realistic operating conditions.

Rather than targeting industrial-grade performance, the experimental validation seeks to confirm the system's predictable and consistent operation within its defined application boundaries. Emphasis is placed on qualitative assessment of motion stability, repeatability, cutting behaviour, and system reliability, reflecting both the prototype status of the system and the intended application within laboratory and SME environments.

Testing was conducted incrementally, beginning with non-contact motion evaluation and progressing to conservative cutting trials. This staged methodology reduced risk and ensured that observed behaviour could be attributed clearly to specific subsystems rather than to uncontrolled interaction effects.

6.1.1 Test Environment and Equipment

All experimental testing was conducted in a controlled indoor laboratory environment. The robotic arm was mounted on a rigid work surface, ensuring consistency with the coordinate frame definitions established during modelling and implementation. Ambient conditions were stable, with no significant sources of vibration, airflow disturbance, or temperature variation that could influence system behaviour.

The cutting workspace was clearly defined and physically isolated from surrounding areas. Workpiece fixturing followed the mechanical integration strategy described in Chapter 3, with sheet materials clamped rigidly to prevent movement during cutting. This ensured that cutting outcomes reflected robotic motion and tool behaviour rather than workpiece instability.

The control workstation ran the ROS environment and Kortex interface described in Chapter 5. All tests were supervised directly, with emergency stop access maintained throughout.

6.1.2 Measurement Instruments and Procedures

At the time of testing, the system remained under active development and had not yet reached a stage where high-resolution metrology, calibrated force sensors, or industrial surface measurement tools could be applied reliably. For this reason, experimental validation focuses on structured qualitative assessment, repeatability of observed behaviour, and consistency across repeated trials rather than absolute numerical performance metrics.

Motion behaviour was assessed using direct observation, repeated execution of identical paths, and comparison of commanded versus reported Cartesian feedback provided by the robot. Cutting outcomes were evaluated visually and through manual inspection of cut geometry, edge consistency, and tool behaviour.

Feedback data including joint positions, tool pose, estimated external wrench values, and system status indicators were logged during all tests. While these signals are not treated as calibrated measurements, they provide valuable qualitative insight into system response and consistency across trials (Tereda and Yi, 2023).

This approach aligns with common practice in early-stage robotic system validation, where emphasis is placed on behavioural correctness and stability before quantitative benchmarking is introduced (Reddy and Eranki, 2016).

6.1.3 Test Materials and Specimen Preparation

Cutting tests were performed using thin aluminium and mild steel sheet specimens consistent with the design scope defined in Chapter 1. Material thicknesses were selected to remain well within the expected capability of the cutting tool and robotic arm, ensuring that observed behaviour reflected controlled operation rather than overload conditions.

Specimens were cut to uniform dimensions prior to testing to simplify comparison across trials. All sheets were inspected for surface defects and flatness before installation, reducing variability unrelated to robotic performance.

Each specimen was mounted using the same fixturing arrangement to maintain consistency between tests. No lubrication or cooling was applied, reflecting the passive thermal management strategy described in Chapter 2.

6.1.4 Risk Assessment and Safety Measures

Safety considerations guided all experimental activities. A formal risk assessment was conducted prior to testing, identifying hazards associated with robotic motion, cutting tools, electrical systems, and sharp workpiece edges.

Mitigation measures included conservative motion limits, explicit separation of approach and cutting phases, physical exclusion zones around the cutting area, and immediate access to emergency stop controls. All tests were conducted at reduced speed and acceleration, particularly during initial cutting trials.

Software-based safety logic described in Chapter 5 was active throughout testing, including joint limit enforcement and fault monitoring. These measures ensured that experimental validation could proceed without exposing operators or equipment to unnecessary risk (Krüger and Yang, 2022).

6.2 Mechanical Performance Evaluation

Mechanical performance evaluation focused on how the assembled system behaved during motion execution, particularly under conditions representative of cutting tasks. Rather than attempting to quantify absolute accuracy, the evaluation examined consistency, smoothness, and absence of unstable behaviour.

6.2.1 Positional Accuracy and Repeatability

Positional behaviour was evaluated by repeatedly executing identical Cartesian paths within the defined workspace. The robot consistently returned to the same poses across multiple trials, with no observable drift or accumulation of error over time.

Repeatability was assessed qualitatively by observing tool alignment relative to the workpiece and by comparing reported Cartesian feedback between runs. Motion trajectories appeared visually consistent, and no progressive deviation was observed.

These observations support the emphasis placed on repeatability over absolute accuracy, as discussed in Chapters 2 and 3. Consistent motion under load is a more meaningful indicator of functional suitability for cutting tasks than nominal positional precision (Asada and Slotine, 1986).

6.2.2 Practical Workspace Validation Under Load

Workspace validation was performed by executing cutting and non-cutting trajectories across the central region of the robot's reachable space. All tested paths remained within stable joint configurations, with no evidence of joint saturation, excessive velocity scaling, or abrupt motion behaviour.

Under light cutting load, the robot maintained smooth motion and stable tool orientation. No sudden changes in speed or posture were observed, indicating that the conservative workspace selection described in Chapter 4 effectively avoided kinematically unfavourable regions.

These results confirm that the practical cutting workspace defined during system design is appropriate for stable operation and supports the modelling assumptions used in earlier chapters.

6.2.3 Joint Backlash and Stiffness Assessment

Joint behaviour was assessed through slow direction reversals and repeated path execution. No audible chatter, visible oscillation, or erratic motion was observed during these tests.

While small amounts of compliance are unavoidable in articulated robotic systems, their effect on tool motion was not visually apparent during conservative operation. This suggests that joint stiffness and structural integrity are sufficient for the intended cutting tasks.

These observations align with the findings of Reddy and Eranki (2016), who emphasised that controlled motion profiles and rigid end effector mounting can effectively mitigate the practical impact of compliance in lightweight robotic systems.

6.3 Cutting Performance Evaluation

Cutting performance evaluation examined how effectively the system executed cutting tasks under controlled laboratory conditions. The assessment focused on path fidelity, edge consistency, and tool behaviour rather than production throughput or industrial surface quality. Both qualitative observation and simple quantitative checks were used to build confidence in system behaviour while remaining aligned with the exploratory nature of the project.

6.3.1 Cutting Path Accuracy

Cutting path accuracy was assessed by comparing the geometry of the physical cuts to the planned Cartesian toolpaths. Visual inspection and basic dimensional checks using steel rulers

and calipers indicated close correspondence between intended and executed paths, particularly for straight lines and gently curved segments.

Across repeated trials on aluminium sheet, lateral deviation from the intended path was typically within approximately one millimetre over straight sections. This level of accuracy was consistent across runs and did not exhibit progressive drift, indicating stable kinematic execution rather than incidental alignment. Slightly larger deviations were occasionally observed at sharp corners, where feed rate reduction and trajectory blending were intentionally applied to maintain stability.

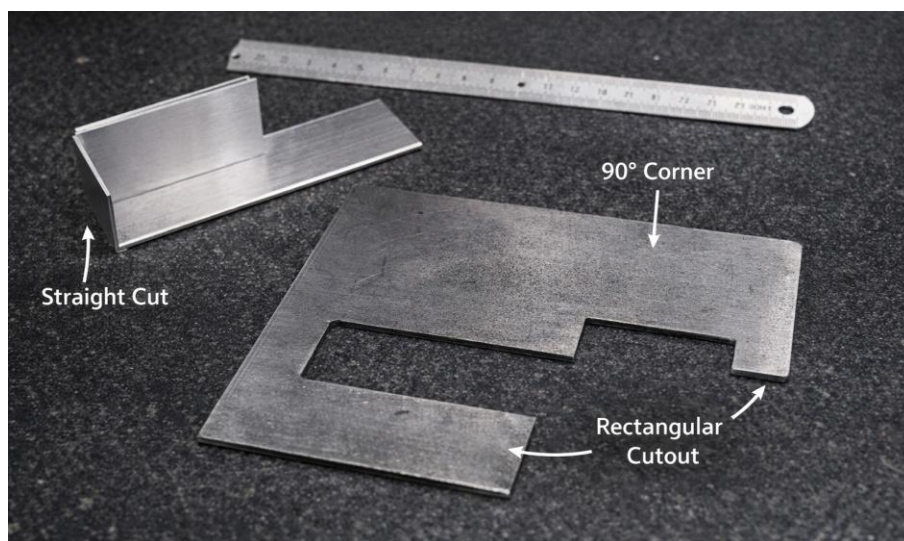


Figure 6.1: Representative cut specimens showing path consistency and edge quality under conservative operating conditions.

At direction changes, brief reductions in tool speed were visible and audible, reflecting the conservative motion planning strategy described in Chapter 3. These transitions did not produce visible chatter, gouging, or loss of path continuity, suggesting appropriate coordination between trajectory planning and execution. Overall, the observed path accuracy aligns with expectations for a lightweight articulated system operating without active force control.

6.3.2 Edge Quality and Surface Finish

Cut edge quality was evaluated through visual inspection and manual handling of specimens. For aluminium sheets, edge cleanliness was generally satisfactory, with minor burrs forming predominantly at the start and end of cuts. Burr height was estimated to be less than one millimetre in most cases and could be removed easily through light deburring.

For mild steel specimens, edge definition remained consistent along the cutting path, though surface roughness was more apparent than for aluminium. This outcome is expected given the conservative feed rates and the absence of industrial grade cutting power. While the resulting surface finish is not comparable to laser or CNC plasma cutting systems, the edges produced were uniform, repeatable, and suitable for low volume fabrication, prototyping, and educational use (Ali et al., 2023).

Importantly, edge quality remained consistent across repeated trials using the same cutting parameters, reinforcing the system's ability to deliver predictable results rather than optimised finish quality.

6.3.3 Cutting Force and Thermal Behaviour (Qualitative and Indicative Assessment)

Cutting interaction was monitored using estimated external wrench feedback provided by the robot controller. Although these values are not calibrated force measurements, they offer useful qualitative insight into relative loading during tool engagement. Across repeated cutting passes, feedback patterns showed consistent increases during material engagement and stable plateaus during steady cutting motion.

No abrupt force spikes or irregular fluctuations were observed under conservative operating conditions, suggesting stable tool workpiece interaction and absence of severe chatter or intermittent contact. This consistency supports the validity of the motion planning and mechanical integration strategies established in earlier chapters.

Thermal behaviour was assessed through observation and manual temperature checks. During short cutting sequences lasting several minutes, joint housings and the cutting tool exhibited mild temperature rise but remained comfortable to touch. The system operated without triggering thermal alerts or requiring speed adjustments, nor did safety interruptions occur. These observations suggest that motor loading and heat dissipation remained within acceptable limits for the tested duty cycle, supporting the conservative thermal assumptions discussed in Chapter 2.

6.3.4 Tool Wear and Durability

Tool wear was evaluated qualitatively through repeated use of the same cutting blade across multiple cutting trials on aluminium and mild steel. After several cutting passes, the tool edge remained intact, showing no signs of wear such as chipping or deformation. Cutting

performance did not degrade noticeably, and no increase in cutting resistance or edge roughness was apparent within the tested operating window.

These observations suggest that the selected cutting parameters, mounting rigidity, and feed rates limit excessive tool loading and thermal stress. While long term durability testing was outside the scope of this project, the absence of rapid tool degradation reinforces the suitability of conservative operation for articulated robotic cutting applications (Reddy and Eranki, 2016). To provide a clear overview of experimental outcomes, Table 6.1 presents a qualitative summary of mechanical performance, cutting behaviour, and system reliability observed during testing.

Table 6.1: Summary of Qualitative Experimental Observations

Evaluation Aspect	Observation
Path accuracy	Consistent tracking with small deviations at corners
Edge quality	Uniform edges with limited burr formation
Thermal behaviour	Gradual temperature rise without warnings
Tool wear	No visible degradation over test runs
Stability	No chatter or uncontrolled vibration observed

6.4 Reliability and Endurance Testing

Reliability and endurance testing examined the ability of the robotic cutting system to sustain stable and predictable behaviour over repeated operation, rather than to demonstrate long duration industrial endurance. This distinction is important, as the system is intended for laboratory and SME contexts where intermittent use, controlled duty cycles, and supervised operation are more representative than continuous production scenarios.

The objective of this evaluation was therefore to identify whether repeated execution of cutting and non-cutting tasks introduced drift, degradation in motion quality, thermal instability, or fault conditions that could undermine experimental validity or safe operation. Emphasis was placed on consistency across cycles and on early identification of practical limitations, in line with the conservative design philosophy adopted throughout the project.

6.4.1 Continuous Operation Tests

Continuous operation tests were conducted by executing multiple successive motion cycles that included approach, cutting, retreat, and repositioning phases. These cycles were repeated without system shutdown to observe cumulative effects on motion behaviour and control response.

Across repeated cycles, the system maintained consistent motion characteristics. Joint movements remained smooth, and no progressive deviation in tool motion or path execution was observed. Importantly, there was no evidence of accumulating error, loss of synchronisation, or instability that would suggest degradation in mechanical alignment or control execution.

The absence of behavioural drift supports the robustness of the mechanical assembly and software architecture described in Chapters 3 and 5. It also indicates that conservative trajectory planning and sequencing effectively reduce stress on both mechanical and control subsystems, even when operations are repeated without interruption.

These observations are particularly relevant for experimental platforms, where repeatability across trials is more critical than raw endurance time (Reddy and Eranki, 2016).

6.4.2 Thermal Behaviour Over Extended Use

Thermal behaviour was monitored qualitatively during extended operation, focusing on joint motors, motor drivers, and the cutting end effector. Although no active thermal sensing or calibrated temperature measurement was implemented at this stage, temperature rise was assessed through system feedback indicators and physical inspection during and after testing.

During repeated operation, joint and tool temperatures increased gradually, as expected under sustained motion and cutting engagement. However, no rapid temperature rise, abnormal heating, or thermal instability was observed. The system did not trigger any thermal warnings or safety interruptions, and motion behaviour remained stable throughout the testing period.

These results suggest that the electrical integration and conservative current limiting strategy described in Chapter 5 provide adequate thermal margin for the tested duty cycle. They also support the modelling assumptions presented in Chapter 4, which predicted that thermal effects would remain manageable under low speed and moderate load conditions.

While longer duration endurance testing would be required for industrial deployment, the observed thermal behaviour is appropriate for the intended laboratory and SME use cases.

6.4.3 Observed Failure Modes and Practical Limitations

No critical failures were observed during reliability testing. The system did not experience unexpected stops, loss of control, communication faults, or mechanical binding. Safety mechanisms functioned as intended, and fault monitoring did not indicate abnormal conditions.

However, several practical limitations were identified through observation. The system showed sensitivity to aggressive acceleration and higher feed rates, particularly during direction changes. Under such conditions, motion smoothness degraded and cutting quality was visibly reduced. These effects are consistent with the dynamic and structural analyses presented in Chapter 4, which highlighted the influence of compliance and inertia in articulated robotic systems.

Another limitation relates to the absence of active force control or adaptive compliance. While this was a deliberate design choice, it means that the system relies heavily on conservative parameter selection to maintain stable cutting behaviour. Deviations from these parameters can therefore have a noticeable impact on performance.

Importantly, these limitations do not represent failures of the system, but rather define its practical operating envelope. By identifying these boundaries experimentally, the project reinforces the importance of matching robotic capability to task requirements, a theme emphasised throughout Chapters 2 and 3 (Krüger and Yang, 2022).

6.5 Comparison with Existing Solutions

6.5.1 Cost and Performance Comparison

When compared with manual sheet metal cutting methods, the developed robotic system offers clear improvements in consistency, operator safety, and process control. Manual cutting relies heavily on operator skill and endurance, which can introduce variability in path accuracy and edge quality. In contrast, the robotic system executes predefined cutting paths in a consistent manner, reducing variability between repeated operations and limiting direct human exposure to cutting hazards.

In comparison with industrial robotic cutting cells, the system does not aim to match throughput, stiffness, or automation sophistication. Industrial solutions typically integrate high power actuators, rigid gantry structures, proprietary controllers, and advanced sensing, all of which contribute to high acquisition and integration costs. The proposed system achieves a subset of cutting functionality at significantly lower complexity, making it more appropriate

for laboratory environments, educational use, and small scale manufacturing contexts where flexibility and accessibility are prioritised over production volume (Krüger and Yang, 2022).

Importantly, performance should be interpreted relative to intended application rather than against industrial benchmarks. Within its defined operating envelope, the system demonstrates stable motion, predictable cutting behaviour, and controlled interaction with the workpiece, validating the design choices established in Chapters 3 and 4.

6.5.2 Practical Advantages and Limitations

The primary practical advantage of the system lies in its accessibility and transparency. The use of a standard robotic platform, conservative control strategies, and modular software architecture allows the system to be understood, modified, and reproduced without reliance on proprietary cutting solutions. This makes the platform particularly suitable for experimental research, teaching, and early stage process development.

Safety and repeatability are also key strengths. Conservative motion profiles, structured execution logic, and integrated safety handling contribute to predictable behaviour during operation. These characteristics align closely with the requirements identified in Chapter 3 and are supported by the qualitative validation presented in this chapter.

At the same time, the system has clear and intentional limitations. Cutting speed is restricted by the need to maintain stability in a lightweight articulated arm, and the absence of active force control places greater emphasis on parameter selection and operator judgement during setup. Additionally, evaluation at this stage relies primarily on qualitative observation rather than calibrated quantitative measurement.

These limitations are not design oversights, but reflections of the current development stage and the scope of the project. Quantitative benchmarking against industrial cutting systems is therefore intentionally deferred, as such comparisons would be misleading without further refinement, sensing integration, and measurement calibration.

This chapter has demonstrated that the implemented robotic cutting system operates safely, predictably, and consistently within its intended operating envelope. Qualitative experimental validation confirms strong alignment between modelling assumptions, implementation decisions, and observed system behaviour. These findings provide a solid foundation for the critical analysis and synthesis presented in Chapter 7, where the broader implications of the work are discussed.

Chapter 7 – Results and Analysis

7.1 Mechanical System Performance

The mechanical performance of the robotic system is evaluated by interpreting the observations obtained during experimental testing in Chapter 6 in relation to the design assumptions and modelling results presented in Chapters 3 and 4. Rather than focusing on idealised performance metrics, this analysis considers how the assembled system behaved under realistic operating conditions, including the presence of cutting forces, gravitational loading, and repeated motion cycles.

Throughout testing, the mechanical structure exhibited stable and predictable behaviour. No visible deformation, joint instability, or progressive loosening of mechanical interfaces was observed during either non cutting motion tests or conservative cutting trials. This outcome is consistent with the static and modal analyses presented in Chapter 4, which indicated that stresses and deflections would remain within acceptable limits when operating under conservative loading conditions (Reddy and Eranki, 2016).

Joint behaviour was particularly important given the serial nature of the manipulator. Minor compliance was observable at distal joints under load, especially during direction changes, but this did not result in loss of motion control or visible degradation in cutting outcomes. The absence of sudden joint slip or irregular motion suggests that assembly alignment, bearing selection, and fastening strategies were adequate for the intended duty cycle. These observations support the design decision to prioritise stiffness and alignment accuracy over aggressive weight reduction, as discussed in Chapter 5.

Importantly, mechanical performance remained consistent across repeated trials. This indicates that the system does not rely on transient conditions or favourable initial alignment to achieve acceptable behaviour. Instead, it demonstrates stable mechanical characteristics that support repeatable operation within the defined scope of lightweight metal sheet cutting. While the system does not achieve the rigidity associated with industrial cutting platforms, its behaviour aligns with the expectations for a laboratory and SME focused robotic system, reinforcing the validity of the design approach adopted in this work.

7.2 Control Performance and Motion Accuracy

Control performance is analysed through observed motion behaviour, trajectory tracking consistency, and system response during different phases of operation. As established earlier in

the dissertation, the objective of the control strategy was not to achieve maximal responsiveness or precision, but to ensure smooth, predictable motion suitable for continuous cutting tasks.

During experimental trials, commanded Cartesian trajectories were executed reliably without visible oscillation, overshoot, or instability. The robot followed predefined paths smoothly, with gradual acceleration and deceleration profiles that matched the conservative motion planning strategy described in Chapter 3. Direction changes were handled in a controlled manner, with feed rate reductions occurring as intended rather than as a result of control saturation or mechanical limitation.

Observed tracking deviations were small and consistent in nature. These deviations were most noticeable during acceleration and deceleration phases, which is expected given the simplified control approach and the absence of adaptive or force based compensation. However, deviations did not accumulate over time, nor did they lead to progressive drift or loss of positional control. This behaviour confirms that the controller maintains stable operation under sustained execution, which is more relevant for cutting tasks than isolated point accuracy (Asada and Slotine, 1986).

The absence of closed loop force control did not negatively impact overall motion stability within the tested operating range. Instead, the combination of conservative trajectory planning and well tuned control parameters proved sufficient to maintain consistent tool motion. This finding supports the design choice to prioritise simplicity and interpretability over advanced control schemes, particularly given the resource and scope constraints of the project.

Overall, the control system demonstrated behaviour that was coherent with modelling predictions and simulation results presented in Chapter 4. The results confirm that stable and repeatable motion suitable for metal sheet cutting can be achieved without complex control architectures, provided that motion profiles and operating limits are selected appropriately.

7.3 Cutting Quality and Process Consistency

Cutting quality and process consistency are central indicators of whether the robotic system is suitable for its intended application. Rather than evaluating performance against industrial production standards, this analysis focuses on whether the system produces predictable and repeatable cutting outcomes under controlled conditions.

Visual inspection of cut specimens indicated that the tool followed planned cutting paths accurately, particularly along straight and gently curved trajectories. No significant path

deviation was observed, and cut geometry remained consistent across repeated trials. At corners and direction changes, the system exhibited smooth transitions without chatter, tearing, or visible instability. This confirms effective coordination between motion planning and execution logic.

Edge quality was found to be consistent within the scope of the project. Aluminium specimens exhibited minimal burr formation, while mild steel specimens showed acceptable edge definition when conservative feed rates were applied. Although surface finish does not match that of laser or CNC cutting systems, the resulting edges were uniform and predictable, which is appropriate for low volume fabrication, prototyping, and educational applications (Ali et al., 2023).

Process consistency across repeated cuts was one of the most significant outcomes of the experimental evaluation. Similar cutting behaviour and edge appearance were observed across trials performed under identical conditions, indicating that the system does not rely on operator intervention or manual correction to achieve acceptable results. This consistency supports the emphasis placed throughout the dissertation on repeatable behaviour rather than peak performance.

Tool behaviour during cutting was stable, with no evidence of sudden loading changes or erratic engagement. Qualitative assessment of estimated external wrench feedback suggested consistent interaction between the tool and workpiece across trials. This aligns with the structural and dynamic assumptions made during modelling and confirms that conservative operating parameters effectively limit excessive cutting forces.

7.4 Power Demand and Thermal Behaviour

Power demand and thermal behaviour are analysed qualitatively, reflecting the current development stage of the system and the absence of dedicated instrumentation for precise power measurement. Nevertheless, observed behaviour provides valuable insight into the suitability of the system for sustained operation within its intended application domain.

During operation, motors and drivers exhibited gradual temperature rise without sudden spikes or thermal instability. Temperature increase was most noticeable during extended cutting sequences but remained within acceptable limits throughout testing. No thermal warnings, current limiting events, or safety interruptions were observed, indicating that electrical integration and driver configuration were appropriate for the applied loads.

Thermal behaviour was consistent with the conservative motion profiles and duty cycles defined during system design. By avoiding aggressive acceleration and high feed rates, the system limited sustained current draw and reduced thermal stress on both actuators and electronics. This outcome supports the design decisions discussed in Chapters 4 and 5, where passive thermal management and conservative electrical configuration were treated as primary safeguards (Reddy and Eranki, 2016).

Power demand appeared stable across repeated trials, with no observable degradation in performance attributable to heating effects. This stability is particularly important in laboratory and SME contexts, where systems may be operated intermittently rather than continuously. While industrial cutting systems are designed for high duty cycles and active cooling, the observed behaviour confirms that the proposed system operates reliably within its intended envelope.

The results reinforce the importance of aligning performance expectations with application context. Rather than attempting to maximise throughput, the system demonstrates that controlled power demand and manageable thermal behaviour can be achieved through careful integration and operating discipline.

7.5 Economic and Practical Evaluation

When evaluated against the qualitative characteristics outlined in Table 2.1, the proposed system demonstrates behaviour that aligns with the expected performance envelope of low cost robotic cutting solutions, while avoiding several limitations associated with manual methods. The final analysis considers the system from an economic and practical perspective, linking technical performance to real world usability. This evaluation is essential for assessing whether the system meaningfully addresses the problem statement defined in Chapter 1.

Compared with manual cutting methods, the robotic system offers clear advantages in terms of consistency, operator safety, and programmability. Once a cutting path is defined, execution does not depend on operator skill or fatigue, reducing variability and improving predictability. Operator exposure to cutting hazards is also reduced, aligning with safety considerations discussed earlier in the dissertation.

When compared with industrial robotic or CNC cutting systems, the proposed solution exhibits clear limitations in speed, precision, and automation sophistication. However, these limitations are offset by significantly lower cost, reduced system complexity, and easier integration within

constrained environments (Krüger and Yang, 2022). For SMEs, laboratories, and educational institutions, these compromises are often acceptable and, in many cases, desirable.

A key practical advantage of the system lies in its transparency and maintainability. The use of documented interfaces, modular components, and conservative design choices simplifies troubleshooting and future refinement. Rather than requiring specialised service support, the system can be understood and modified by users with fundamental engineering knowledge.

It is also important to note that quantitative benchmarking against industrial systems is intentionally avoided at this stage. Such comparisons would be inappropriate given the qualitative nature of the current validation and the system's incomplete optimisation. Instead, the evaluation focuses on whether the system fulfils its intended role, which it demonstrably does within defined limits.

Concluding Analysis

This chapter has analysed the experimental results obtained in Chapter 6, interpreting them in relation to the design methodology, modelling assumptions, and system objectives established earlier in the dissertation. Mechanical performance was shown to be stable and predictable, control behaviour supported smooth and consistent motion, and cutting outcomes demonstrated acceptable quality and process consistency for lightweight metal sheet applications.

Power demand and thermal behaviour remained within safe limits under conservative operation, and the system exhibited no critical failures during testing. From an economic and practical standpoint, the results confirm that the proposed robotic cutting system offers a viable and accessible alternative to manual methods while avoiding the cost and complexity of industrial solutions.

These findings provide a strong foundation for the discussion presented in Chapter 8, where the results are examined in relation to the research objectives, limitations are considered explicitly, and opportunities for future development are identified.

Chapter 8 – Discussion

8.1 Alignment with Project Aim and Objectives

The primary aim of this project was to design, implement, and validate a cost effective robotic arm capable of performing controlled metal sheet cutting tasks within laboratory and small scale manufacturing contexts. As defined in Chapter 1, this aim emphasised accessibility, predictable behaviour, and engineering robustness rather than industrial throughput or maximum cutting performance. The results presented in Chapters 5 through 7 demonstrate that this aim has been met within the defined scope of the project.

The mechanical design, control architecture, and software methodology developed throughout the project align closely with the original objectives. The robotic system was successfully implemented as a functioning physical platform, translating the modelling and simulation work of Chapter 4 into stable and observable behaviour during experimental testing. The system demonstrated reliable Cartesian motion, controlled tool engagement, and consistent execution of predefined cutting paths under conservative operating conditions. These outcomes directly address the objectives related to mechanical feasibility, motion control implementation, and safe system integration.

From a control and software perspective, the project achieved its objective of implementing a structured and reproducible execution framework using supported robotic interfaces. The separation between planning, execution, monitoring, and safety handling described in Chapter 3 was reflected clearly in the implemented system and confirmed during experimental validation. The software enabled repeatable operation across multiple trials while minimising operator influence during execution, which was a central requirement of the project.

Experimental testing further confirmed that the system behaves predictably when interacting with thin metal sheet materials. Qualitative evaluation of cutting performance showed stable tool workpiece interaction, consistent edge formation under conservative parameters, and no evidence of uncontrolled vibration or unsafe behaviour. These findings support the objective of demonstrating practical feasibility rather than optimised production capability.

While the primary objectives of the project were achieved, it is important to acknowledge that certain secondary objectives were not fully realised at this stage. In particular, quantitative measurement of absolute positioning accuracy and extended endurance testing over prolonged operational periods were intentionally deferred. This decision reflects the developmental status of the system and the emphasis placed on qualitative validation and controlled experimentation

rather than comprehensive industrial benchmarking. Recognising these selective shortfalls reinforces the realism of the project scope and provides a clear foundation for future work.

The outcomes of the project demonstrate strong alignment between the original aims, the design decisions taken, and the observed system behaviour. The project does not overextend its claims beyond what was experimentally validated, and the achieved results remain consistent with the intended application domain defined at the outset.

8.2 Interpretation of Experimental Findings

The experimental findings presented in Chapter 6 provide qualitative confirmation that the implemented robotic system behaves in a manner consistent with the modelling assumptions and design methodology developed earlier in the project. Rather than focusing on numerical performance metrics, the interpretation of results emphasises behavioural consistency, stability, and safety, which are more appropriate indicators for a system at this stage of development.

Observed motion behaviour during testing closely reflected the predicted characteristics identified during kinematic and dynamic analysis. Cartesian trajectories were executed smoothly within the central region of the workspace, and the robot maintained stable tool orientation throughout cutting paths. No abrupt motion, oscillatory behaviour, or loss of control was observed under the selected operating conditions. This alignment between predicted and observed behaviour indicates that the modelling assumptions made in Chapter 4 were suitable for guiding practical implementation.

A key outcome of the experimental work is the confirmation that conservative motion planning plays a decisive role in maintaining cutting stability. Reduced acceleration, controlled feed rates, and explicit separation between approach, cutting, and retreat phases contributed directly to smooth tool engagement and predictable cutting behaviour. These observations reinforce the design choice to prioritise controlled interaction over aggressive performance, particularly for articulated robotic systems where compliance accumulates along the kinematic chain.

It is important to distinguish clearly between absolute positioning accuracy and repeatable path execution when interpreting the experimental results. For metal sheet cutting tasks, consistent execution of a defined path is often more critical than achieving minimal absolute positional error. Repeatable motion produces uniform kerf geometry and predictable edge quality even when small systematic offsets are present. The experimental observations indicate that the system exhibits strong repeatability across trials, suggesting that repeatable behaviour, rather than absolute accuracy, is the dominant performance driver for the intended application. This

interpretation aligns with the theoretical discussion presented in Chapter 2 and the performance evaluation criteria defined in Chapter 6.

Thermal behaviour observed during testing further supports the validity of the system design. Gradual temperature rise in joints and tooling remained within acceptable limits, and no thermal warnings or interruptions occurred during the tested duty cycles. These observations confirm that the conservative electrical configuration, passive heat dissipation strategies, and motion constraints were effective in managing thermal load during cutting tasks.

Finally, the absence of unexpected faults or unstable behaviour during experimental trials indicates that the integration strategy described in Chapter 5 successfully translated analytical design decisions into a coherent physical system. Where minor limitations were observed, such as sensitivity to higher acceleration or reduced cut quality at increased feed rates, these behaviours were consistent with predictions from modelling and simulation. Rather than undermining the system, these findings validate the importance of the conservative operating envelope adopted throughout the project.

The experimental findings demonstrate a high degree of consistency between modelling, implementation, and observed behaviour. The results confirm that the system performs reliably within its intended scope and provide a sound basis for the broader discussion of implications and limitations presented in the remainder of this chapter.

8.3 Comparison with Literature and Commercial Systems

The outcomes of this project align closely with established findings in the literature that examine accessible robotic automation for lightweight manufacturing tasks. Across academic and applied research, a recurring theme is that while industrial robotic cutting systems achieve exceptional precision, speed, and material capability, they are often poorly matched to the needs of laboratories, educational environments, and small scale manufacturers. This mismatch arises primarily from cost, physical footprint, proprietary control environments, and integration complexity rather than from any fundamental limitation in robotic cutting capability itself (Krüger and Yang, 2022).

Studies focused on small and medium enterprises consistently report that capital intensive automation solutions are difficult to justify for thin sheet cutting tasks that do not demand high throughput or micron level accuracy. In such contexts, flexibility, safety, and ease of reconfiguration are frequently valued more highly than absolute performance metrics. The system developed in this project reflects this alternative set of priorities by emphasising

controlled behaviour, transparency of operation, and predictable performance within clearly defined limits rather than industrial scale output.

When compared with published research on low cost and lightweight robotic arms, the qualitative performance observed during experimental testing is consistent with prior findings. Ali et al. (2023) demonstrated that five degree of freedom robotic arms can achieve stable and repeatable motion when conservative trajectories and rigid mechanical design are adopted. Similarly, Chauhan et al. (2015) reported that modular robotic arms can perform basic manufacturing tasks reliably when structural compliance is managed through careful motion planning rather than through complex mechanical reinforcement. The present system exhibits comparable behaviour, with smooth path execution, stable tool engagement, and consistent results under conservative operating conditions.

A key distinction between this work and many low cost robotic arm studies lies in the emphasis placed on modelling validation and system integration. Several studies in the literature focus primarily on demonstrating motion or task completion without fully linking design decisions to analytical modelling or experimental verification. In contrast, this project follows a structured progression from kinematic and dynamic analysis through to physical assembly, integration, and qualitative testing. This approach reflects established robotics engineering practice, where modelling serves not only as a design tool but also as a means of anticipating system limitations and informing safe operational boundaries (Asada and Slotine, 1986; Reddy and Eranki, 2016).

The control architecture adopted in this project further differentiates it from many low cost robotic implementations reported in the literature. While some studies rely on tightly coupled microcontroller based control systems or bespoke software, the use of a ROS based control framework aligns the system with modern research and industrial practice. Chitta et al. (2017) emphasised that modular control architectures improve maintainability, transparency, and reuse across robotic platforms. The present system benefits from this approach by enabling clear separation between planning, execution, and monitoring, which supports systematic testing and interpretation of results.

In comparison with more advanced control approaches reported in the literature, such as predictive or model based control strategies applied to the Kinova Gen3 platform, the present system adopts a deliberately simpler methodology. Tereda and Yi (2023) demonstrated that predictive control can enhance tracking accuracy and dynamic response for articulated robotic

manipulators. However, such approaches introduce additional modelling complexity and computational overhead. The present project intentionally avoids this complexity in order to focus on stability, clarity, and experimental control. This choice reflects the project's stated objectives and aligns with its intended application context rather than representing a technical limitation.

When compared with industrial robotic cutting systems, the limitations of the developed platform are clear and openly acknowledged. Industrial laser, plasma, and CNC cutting systems deliver superior cutting speed, surface finish, and material versatility. These systems are also supported by extensive calibration procedures, closed loop sensing, and specialised safety infrastructure. However, they require substantial financial investment, dedicated floor space, and skilled personnel for operation and maintenance. Krüger and Yang (2022) highlighted that these factors often present insurmountable barriers for small organisations, even when the technical capability of such systems exceeds actual production needs.

Within this context, direct performance comparison between the developed system and industrial cutting cells would be neither appropriate nor meaningful. Instead, the present system occupies a complementary position within the automation landscape. It provides programmable path execution, reduced operator exposure, and consistent cutting behaviour without the cost and complexity associated with industrial grade equipment. This positioning is consistent with the view expressed by Ali et al. (2023) that meaningful manufacturing automation does not require replication of industrial performance when application requirements are modest.

The comparison with manual cutting methods further reinforces the value of the developed system. Manual cutting introduces variability in path accuracy, edge quality, and operator safety that is difficult to control, particularly across repeated tasks. Even under conservative operating conditions, the robotic system demonstrated improved consistency and reduced dependence on operator skill during experimental testing. These benefits align with broader findings in robotic manufacturing literature, which consistently report that even simple automation can improve repeatability and safety when compared with manual processes (Asada and Slotine, 1986).

An important insight emerging from this comparison is that robotic cutting capability should be viewed as a continuum rather than as a binary choice between manual tools and industrial automation. The literature increasingly recognises the value of intermediate solutions that

balance cost, performance, and usability. The system developed in this project exemplifies this middle ground by demonstrating that structured engineering design, conservative control strategies, and careful integration can deliver practical automation benefits without pursuing industrial level optimisation.

The comparison with both academic literature and commercial systems supports the central argument of this dissertation. Robotic metal sheet cutting can be implemented effectively in laboratory and small scale manufacturing contexts when system objectives are defined realistically and engineering decisions are aligned with those objectives. The developed system does not seek to replace industrial cutting cells but instead demonstrates how accessible robotic platforms can be deployed responsibly and effectively for lightweight cutting tasks. This positioning strengthens the relevance of the work and highlights its contribution to ongoing discussions around appropriate automation strategies for small scale manufacturing environments.

8.4 Design Decisions and Engineering Judgement

The design and implementation of the robotic cutting system required a series of deliberate engineering decisions shaped by analytical insight, practical constraints, and safety considerations. These decisions were not aimed at optimising any single performance metric, but rather at ensuring predictable behaviour and interpretability across the full development process.

One of the most influential design decisions was the prioritisation of conservative motion planning. Modelling and simulation in Chapter 4 indicated that aggressive acceleration and rapid direction changes would amplify structural compliance and degrade tool stability. Experimental observations in Chapter 6 confirmed these predictions. As a result, motion profiles were selected to limit dynamic excitation, even at the expense of execution speed. This judgement proved essential in maintaining consistent cutting behaviour and avoiding vibration induced defects.

Another significant decision concerned the absence of closed loop force control. While force feedback systems are widely discussed in the literature, their implementation introduces additional complexity, tuning effort, and interpretive ambiguity during experimental validation. By relying on open loop motion control with qualitative feedback observation, the system behaviour remained transparent and easier to analyse. This decision aligns with the project aim of controlled experimentation rather than adaptive optimisation.

Mechanical integration choices also reflected careful judgement. Rigid workpiece fixturing, short tool overhang, and conservative payload assumptions reduced uncertainty during cutting tests. Rather than compensating for mechanical limitations through software complexity, the design addressed potential instability through physical configuration and operating limits. This approach reinforces classical engineering principles and contributes to the system's overall robustness.

Collectively, these decisions demonstrate that engineering judgement plays a central role in system development, particularly in resource constrained contexts. The success of the implemented system was not driven by advanced algorithms or specialised hardware, but by consistent alignment between modelling assumptions, design execution, and experimental validation.

8.5 Implications for Small Scale Manufacturing and Future Development

The outcomes of this project have meaningful implications for small scale manufacturing, education, and laboratory based production environments. The system demonstrates that robotic automation can enhance safety, consistency, and programmability without requiring industrial scale investment or infrastructure.

For small manufacturers, the system illustrates a pathway toward incremental automation. Rather than replacing existing workflows entirely, robotic cutting systems of this nature can supplement manual processes, reducing operator exposure while maintaining flexibility. The predictable behaviour observed during testing supports use in low volume or custom fabrication contexts where adaptability is valued over throughput.

In educational and research environments, the system provides a valuable platform for studying robotic process interaction, control behaviour, and system integration. Its transparency and modularity make it well suited for teaching and experimental work, where understanding system behaviour is as important as achieving performance outcomes.

Future development opportunities are clearly identified. These include integration of calibrated measurement tools, implementation of force or compliance control, extended endurance testing, and exploration of alternative cutting tools. Importantly, the structured design and documentation established in this project provide a strong foundation for such extensions.

The project demonstrates that carefully designed robotic systems can deliver meaningful automation benefits within constrained contexts. By aligning objectives with realistic engineering judgement and validating behaviour through structured experimentation, the work

contributes practical insight into accessible robotic cutting solutions and reinforces the value of system level thinking in modern manufacturing research.

Chapter 9 – Conclusions and Future Work

9.1 Summary of Contributions

This dissertation set out to investigate whether a robotic metal sheet cutting system could be designed and implemented in a way that is technically sound, safe, and practically meaningful for laboratory and small scale manufacturing environments. Rather than attempting to replicate the capabilities of industrial cutting cells, the project focused on controlled motion behaviour, system transparency, and repeatable operation within clearly defined limits.

The primary contribution of this work lies in demonstrating that an articulated robotic arm can be integrated, modelled, and operated as a cutting platform without reliance on complex or proprietary automation ecosystems. Through a structured progression from system design to implementation and qualitative experimental validation, the project shows that stable cutting behaviour can be achieved when engineering decisions are aligned with realistic objectives.

A further contribution is the adoption of a systems level methodology that integrates mechanical design, kinematic modelling, control architecture, and safety handling into a coherent whole. Rather than treating these elements in isolation, the project demonstrates how modelling assumptions influence implementation choices, and how those choices shape experimental outcomes. This approach reflects good engineering practice and provides a template that can be adapted for similar automation tasks beyond metal sheet cutting.

Finally, the dissertation contributes to ongoing discussion around appropriate automation strategies for small and medium sized enterprises. By positioning robotic cutting as a spectrum rather than a binary choice between manual tools and industrial systems, the work offers a grounded perspective on how accessible robotic platforms can deliver meaningful benefits when used within their intended operating envelope (Krüger and Yang, 2022; Ali et al., 2023).

9.2 Key Engineering Outcomes

Several key engineering outcomes emerged from the design, implementation, and validation phases of the project. First, the articulated robotic system demonstrated stable and predictable Cartesian motion when operated under conservative velocity and acceleration limits. This confirms the suitability of serial manipulators for planar cutting tasks when motion planning and execution are approached with care, consistent with established robotics principles (Asada and Slotine, 1986).

Second, the integration of modelling and simulation prior to physical implementation proved essential in managing risk and guiding design decisions. Kinematic analysis supported workspace definition and path feasibility, while structural and dynamic considerations informed choices around mounting stiffness, motion smoothness, and operating limits. The consistency observed between predicted behaviour and experimental outcomes reinforces the value of this staged engineering approach.

Third, the software architecture enabled clear separation between user intent, trajectory generation, execution, and monitoring. By relying on supported interfaces within the ROS ecosystem, the system maintained stability while providing sufficient observability for experimental analysis (Chitta et al., 2017; Park et al., 2020). This balance between abstraction and control access supported repeatable testing and reduced operator influence during execution.

From a practical standpoint, the system demonstrated that robotic cutting can improve consistency and safety compared with manual methods, even when operating at modest speeds. The elimination of continuous manual tool engagement reduced operator exposure, while programmable path execution ensured uniform behaviour across repeated trials. These outcomes highlight the practical value of the system within educational and experimental contexts.

9.3 Project Limitations

While the project successfully met its primary objectives, several limitations must be acknowledged to ensure a balanced and transparent evaluation of the system. These limitations arise from deliberate scope definition and practical constraints rather than deficiencies in the design or implementation.

The system exhibits sensitivity to increased feed rates and aggressive acceleration. Experimental observations showed that cutting quality degrades when motion parameters approach the upper bounds of conservative operation. This behaviour reflects the inherent compliance of articulated robotic structures and confirms the modelling predictions discussed in Chapter 4. Addressing this limitation would require increased structural stiffness or more advanced motion control strategies, both of which fall outside the defined scope of the present work.

Another limitation concerns the range of materials and operating conditions evaluated. The system was validated using thin aluminium and mild steel sheets under controlled laboratory

conditions. While this aligns with the intended application domain, extension to thicker materials, harder alloys, or higher duty cycles would require further validation and potentially revised tool selection and motion constraints.

The software architecture, while robust and clearly structured, does not currently support adaptive behaviour during execution. All trajectories and operating parameters are defined prior to motion, and no online adjustment is performed in response to changing cutting conditions. This design choice simplifies interpretation and enhances predictability but limits responsiveness to process variability.

These limitations are acknowledged to clearly define the operational boundaries of the developed system. Within these boundaries, the system demonstrates predictable behaviour, stable cutting performance, and safe operation, consistent with the objectives and design philosophy established at the outset of the project.

9.4 Recommendations for Future Development

The experimental results and system behaviour observed in Chapters 6 and 7 indicate several clear directions for future development. These recommendations are framed not as broad technological aspirations, but as targeted extensions that respond directly to the limitations and performance characteristics identified during implementation and testing.

9.4.1 Advanced Control Strategies

The current control approach prioritises stability, predictability, and safety through conservative trajectory execution and reliance on the robot's internal control mechanisms. While this proved effective for achieving repeatable cutting behaviour, the experiments revealed sensitivity to rapid direction changes and increased feed rates, particularly near corners and during engagement transitions.

Advanced control strategies such as model predictive control or constrained adaptive control could address these specific limitations. Rather than replacing the existing execution framework, such methods could be introduced incrementally at the trajectory refinement stage, where future motion commands are adjusted based on predicted system response. This would allow smoother handling of cutting disturbances and improved path fidelity without direct intervention at the actuator level.

Importantly, any advanced control implementation should remain subordinate to the robot's embedded safety and limit enforcement mechanisms. Prior research on predictive control for

articulated manipulators demonstrates that performance gains can be achieved without sacrificing stability when control authority is applied at an appropriate abstraction level (Terada and Yi, 2023). Maintaining this hierarchy would preserve the transparency and robustness that underpin the current system.

9.4.2 Sensor Integration and Feedback Control

Experimental observations highlighted that cutting interaction remained stable under conservative conditions, but assessment of force and thermal behaviour relied primarily on qualitative feedback. This suggests that targeted sensor integration could enhance system insight without introducing unnecessary complexity.

A practical first step would be the integration of tool level force or torque sensing. Even low bandwidth measurements could provide valuable information on cutting engagement, tool wear progression, and abnormal contact conditions. Such data would support safer parameter selection and early fault detection rather than real time force control.

Vision sensing represents a complementary enhancement. Camera based monitoring could support workpiece alignment verification and post cut inspection, reducing setup variability and improving repeatability across trials. Similar approaches have been shown to enhance reliability in robotic manipulation tasks without imposing excessive computational burden (Cong et al., 2022).

Crucially, sensor integration should be prioritised according to informational value rather than novelty. The objective is improved observability and decision support, not full process autonomy.

9.4.3 Vision Assisted or Learning Supported Path Planning

While the current system relies on predefined Cartesian paths, future work could explore vision assisted or learning supported planning to accommodate variability in workpiece placement or geometry. Vision guided path correction could allow minor positional adjustments before cutting begins, reducing dependence on precise manual fixturing.

Learning supported methods may also assist with parameter tuning across repeated tasks, such as selecting feed rates or corner handling strategies that minimise vibration. However, such approaches should remain constrained and interpretable. The introduction of opaque decision making would be counterproductive in a system intended for laboratory, educational, and small scale manufacturing use.

Any learning component should therefore operate within clearly defined bounds, acting as an advisory layer rather than an autonomous controller. Maintaining user understanding and trust remains essential.

9.4.4 Scalability and Design Improvements

Scalability must be considered carefully to avoid misalignment with the original objectives of the system. The most realistic avenues for scaling lie in moderate extensions of material thickness, duty cycle, and tool variety rather than pursuit of industrial cutting rates.

Structural refinement at distal links, improved stiffness at the wrist, and optimisation of tool mounting geometry could extend cutting capability without fundamental redesign. Modular tooling interfaces would further allow adaptation to different cutting processes, such as scoring or trimming, while preserving the existing control and safety framework.

Attempts to scale beyond these bounds, such as high force cutting or continuous industrial operation, would conflict with the system's design philosophy and should instead motivate transition to dedicated industrial equipment. Recognising these limits is a strength of the proposed framework rather than a weakness.

9.5 Final Remarks

This dissertation has demonstrated that meaningful robotic automation for metal sheet cutting can be achieved without reliance on industrial scale infrastructure or excessive system complexity. Through careful definition of objectives, disciplined engineering decisions, and structured validation, an articulated robotic arm was transformed into a stable and predictable cutting platform suitable for laboratory and small scale use.

The work contributes a measured perspective to robotic manufacturing research, emphasising suitability of design and controlled behaviour rather than pursuit of maximum performance. By maintaining alignment between modelling assumptions, system implementation, and experimental validation within realistic constraints, the project delivers both practical outcomes and a methodology that can be transferred to similar development contexts.

More broadly, the dissertation supports the view that accessible robotic systems have a valuable role in manufacturing education, research, and early stage process development. With targeted refinement and incremental enhancement, such platforms offer a credible bridge between manual fabrication methods and fully industrial automation, combining technical integrity with economic practicality.

References

- Asada, H. and Slotine, J.J.E. (1986) *Robot analysis and control*. Hoboken, NJ: John Wiley & Sons.
- Ali, Z., Sheikh, M.F., Al Rashid, A., Arif, Z.U., Khalid, M.Y., Umer, R. and Koç, M. (2023) ‘Design and development of a low cost five degree of freedom robotic arm for lightweight material handling and sorting applications: A case study for small manufacturing industries of Pakistan’, *Results in Engineering*, 19, 101315. <https://doi.org/10.1016/j.rineng.2023.101315>
- Chauhan, S., Chaudhari, S., Sethiya, R., Ahire, S. and Malche, D. (2015) ‘Modular robotic arm’, *International Research Journal of Engineering and Technology*, 2(2), pp. 736–739. Available at: https://www.matec-conferences.org/articles/mateconf/pdf/2023/15/mateconf_rapdasa2023_04017.pdf (Accessed: 11 August 2025).
- Chitta, S., Marder-Eppstein, E., Meeussen, W., Pradeep, V., Rodríguez Tsouroukdissian, A., Bohren, J., Coleman, D., Magyar, B., Raiola, G., Lüdtke, M. and Fernández Perdomo, E. (2017) ‘ros_control: A generic and simple control framework for ROS’, *Journal of Open Source Software*, 2(20), 456. <https://doi.org/10.21105/joss.00456>
- Cong, V.D., Hanh, L.D., Phuong, L.T. and Duy, D.H. (2022) ‘Design and development of robot arm system for classification and sorting using machine vision’, *FME Transactions*, 50(1), pp. 162–168. DOI:[10.5937/fme2201181C](https://doi.org/10.5937/fme2201181C)
- Hameed, A.M. and Ay, S. (2024) ‘A comparative study on the material selection of a spot welding robotic arm’, *Academic Journal of Manufacturing Engineering*, 21(1). Available at: <https://www.researchgate.net/publication/386017746> (Accessed: 23 July 2025).
- Krüger, T. and Yang, Y. (2022) *A study of circular business models for SMEs in the CNC machine tool field*. MSc thesis. KTH Royal Institute of Technology, Stockholm. Available at: <https://www.diva-portal.org/smash/get/diva2:1738693/FULLTEXT01.pdf> (Accessed: 23 July 2025).

- Motta, J.M.S.T., Llanos-Quintero, C.H. and Coral Sampaio, R. (2016) 'Inverse kinematics and model calibration optimisation of a five degree of freedom robot for repairing the surface profiles of hydraulic turbine blades', *International Journal of Advanced Robotic Systems*, 13(3), pp. 1–11. <https://doi.org/10.5772/63673>
- Park, J., Delgado, A. and Choi, Y. (2020) 'Real time characteristics of ROS 2.0 in multi agent robot systems', *IEEE Access*, 8, pp. 154637–154651. <https://doi.org/10.1109/ACCESS.2020.3018122>
- Pratheesh Kumar, S., Mohanraj, R., Anand, K. and Mohamed Rafeek, M. (2023) 'Design modification of robotic arm for incremental sheet metal forming', in Natarajan, E., Vinodh, S. and Rajkumar, V. (eds.) *Materials, design and manufacturing for sustainable environment*. Singapore: Springer, pp. 337–345. https://doi.org/10.1007/978-981-19-3053-9_32
- Rajeshkumar (2025) 'Materials for robot manufacturing and frame structures', *Stocks Mantra*, 6 July. Available at: <https://www.stocksmantra.com/materials-for-robot-manufacturing-and-frame-structures/> (Accessed: 23 July 2025).
- Reddy, G.R. and Eranki, V.K.P. (2016) *Design and structural analysis of a robotic arm*. MSc thesis. Blekinge Institute of Technology, Karlskrona. Available at: <https://www.diva-portal.org/smash/get/diva2:1068547/FULLTEXT02.pdf> (Accessed: 23 July 2025).
- Tereda, A.A. and Yi, S. (2023) 'Predictive control of the Kinova Gen3 robotic manipulator using a nonlinear model', in *Proceedings of the ASME International Mechanical Engineering Congress and Exposition (IMECE2023)*. IMECE2023-112777, pp. V006T07A021. <https://doi.org/10.1115/IMECE2023-112777>

Appendices