INTEGRATION OF AUTOMATED CARGO HANDLING MECHANISM

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CERTIFICATION

This is to certify that this project work titled “INTEGRATION OF AUTOMATED CARGO HANDLING MECHANISM” was carried out by students of the Department of Marine Engineering, Mechanical Engineering and Mechatronics Engineering, Faculty of Engineering, UNIVERSITY OF BENIN, under my supervision. The work meets the standard and requirements for the award of the degree of Bachelor of Engineering (B.Eng.) in Marine Engineering, Mechanical Engineering and Mechatronics Engineering.

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DEDICATION

This project is dedicated to **God Almighty**, whose grace and wisdom guided us throughout this research.

It is also dedicated to our beloved parents for their endless love, prayers, support, and encouragement during the course of my study, I also dedicate the work to our project supervisor Proff Godfery Ariave and finally to the beloved Faculty of Engineering.

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First and foremost, we thank Almighty God for the gift of life, strength, and perseverance that enabled me to complete this project successfully.

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Finally, we appreciate all the authors and researchers whose works were referenced in this study; their contributions to the field of Automated cargo handling mechanism provided the foundation upon which this research was built.

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ABSTRACT

This report presents a comprehensive design and SolidWorks-based modeling of a conceptual container vessel equipped with an integrated robotic cargo-handling crane. The project combines core naval architecture principles with advanced parametric modeling techniques to develop a structurally coherent, hydrodynamically efficient, and operationally automated vessel concept. The aim of the study is to demonstrate how modern CAD tools can be applied to marine engineering design while integrating automation systems that enhance vessel functionality and operational efficiency.

The modeling process covers the systematic construction of the hull, deck arrangement, superstructure, bulwarks, and the robotic crane system using sketches, extrusions, lofts, reference planes, and surface features. Material properties such as mild steel, aluminum alloy, and anti-fouling coatings were applied to approximate real marine construction and enhance visualization accuracy. Design considerations including hydrodynamic efficiency, vessel stability, structural integrity, and safety guided all modeling decisions, particularly the placement and structural support of the onboard robotic crane.

The inclusion of the robotic crane demonstrates the potential for automated cargo operations, reduced human involvement, and improved port efficiency. Rendering and surface finishing techniques further enhance presentation quality, making the model suitable for academic, industrial, and concept-evaluation purposes. Overall, the project showcases the practical application of CAD tools in modern marine engineering and highlights the relevance of integrating advanced automation technologies in contemporary vessel design.

CHAPTER ONE

INRODUCTION

1.1 Background of the study

The marine industry is one of the most important ways by which goods are transferred from different locations, with container vessels as the key backbone of this system. Over time, the maritime industry has improved in meeting demands for faster, safer, and more efficient cargo movement. As the volume of cargoes increases and navigational routes become more complex, traditional cargo handling methods onboard vessels struggle to keep up

While container vessels are primarily built for cargo operations, many still rely on manual labor during these operations. Now, this process not only reduces the working efficiency but also increases the risk of human error and workers being kept in a hazardous environment. On the other hand, many port terminals have accepted the use of automation, possessing advanced technologies such as automated cranes, robotic vehicles, and smart tracking systems. This creates an obvious gap between the high technology efficiency of port-sides of operation, and time-consuming and more laborious processes onboard. The result is a bottleneck in the supply chain that affects turnaround time and overall efficiency.

As industries all over the world evolve into the digital era, there's increasing pressure for ships to evolve into "smart ships." These vessels would integrate automation, artificial intelligence, and real-life monitoring to streamline operations. For cargo vessels, automating the main cargo processes such as loading, unloading, and container storage is an essential starting point. However, implementing these changes requires more than just installing the new equipment. It requires fundamental thinking about how container versions are being designed. Traditional layouts, support structures, power systems, and control frameworks are often not compatible with advanced automation systems.

This project focuses on addressing the challenges by studying how container ships can be redesigned or designed from the start to accommodate integrated automated cargo handling systems. Whether through the use of robotic gantry cranes, Automated Guided Vehicles (AGVs), or smart stowage technologies, the aim is to build vessels that can compare the performance and the efficiency of today's automated port terminals.

Furthermore, this research aligns with wider goals set by international bodies like the International Maritime Organization (IMO), which boost safer, smarter, and more sustainable shipping practices. As port terminal automation and digitalization increase with time, it's only logical that ships that interact with them evolve as well.

By majorly concentrating on ship design, the research aims to point out ways in which automation technologies can be integrated into the physical structure and operational systems of container ships. The main ambition is to help guide a new era in marine operations by improving safety, faster turnaround times, reducing environmental impact, and integrating of intelligent system.

Multiple factors contribute to this challenge:

a. Design Limitations: Most vessels were not designed to support automation. They lack the structural features like space, weight distribution, and mounting areas for robotic cranes, AGVs, and sensor systems. Rebuilding older vessels is usually complex, costly, and technically limited. These design gaps also delay integration with smart port infrastructures. Therefore is essential that when building a ship, from future-ready start should be in mind for future-ready operations.

b. Power System Constraints: Most automation system needs a steady and substantial supply of power. Equipment like robotic cranes, AGVs, and sensor networks requires more power than traditional ship generators can provide. Also, older power-generating systems usually lack the redundancy and load management features needed for automation. Now, to support these improved systems, upgraded power frameworks are critical.

c. Inadequate control System: Automation solely depends on accurate control, real-time monitoring, and intelligent feedback systems. Most older container vessels lack the control devices to manage several automated structures simultaneously. Without integrated monitoring, proper diagnostics, and an adaptive response operating system, it becomes challenging to attain reliable and safe automated operations

d. Onboard Safety Risks: Individual workers promote high risk in cargo operations, such as lashing containers and handling cranes manually. These jobs expose individuals to severe dangers, especially in bad weather or in situations where visibility becomes a challenge. Automating these functions can extremely improve safety by removing workers from dangerous zones and minimizing human error.

e. Lack of Redundancy: Manual operating systems usually have limited or no redundancy, meaning a minute point of failure could stop the operations or lead to a severe incident. Automated allows for essential diagnostics, backup system, and several response protocols that improves reliability and reduce downtime.

1.2 Statement of the Problem

Although port terminal automation has experienced huge progress in recent years, but same doesn’t go for automation on board container vessels. This uneven improvement has led to a major delay in maritime logistics. Ships usually experience this delay while waiting for cargo to be manually loaded or unloaded. This not only slows down sailing schedules but also increases operational costs and reduces fleet efficiency.

1.3 Aims and Objectives of the Study

1.3.1 Aims of the study

The study seeks to demonstrate the application of parametric CAD tools in developing a structurally coherent and hydrodynamically efficient marine vessel. It also aims to integrate an automated robotic cargo-handling crane to enhance vessel functionality and operational efficiency,

by meeting these goals, the research aims to present a forward-thinking ship design model that fully accommodates the demands of next-generation automated cargo handling.

1.3.2 Objectives of the Study

The primary goal of this project is to evaluate and propose targeted design modifications that will enable container ships to support and efficiently operate automated cargo handling systems. The specific objectives are:

a. To pinpoint existing limitations in container ship layouts that hinder the usage of automation technologies.
b. Diagnosing advanced cargo handling systems, like as robotic gantry cranes, AGVs, and smart stowage software to assess their compatibility with onboard environments.
c. To recommend structural and spatial adjustments, including crane rail reinforcements, optimized bay arrangements, and sensor/control placements for smooth equipment integration.
d. To evaluate the power and control system upgrades required to run these systems, including considerations for energy distribution, load balancing, and centralized automation control hubs.
e. To ensure all design recommendations agree with international maritime safety standards, particularly those set by the IMO, and to include redundancy and fail-safe features that improve reliability.

1.4 Scope of the Study

This research is focused on the design and engineering aspects of container vessels, concentrating on integrating automation technologies for the cargo handling system. While the idea of automation is well proven in port terminals, this study is generalized to how these technologies can be modified and applied to the onboard environment.

Key areas covered include:

a. Structural examination of the vessel’s hull, decks, and cargo holds for compatibility with automation equipment.
b. A review of current port terminal automation systems and their possible adaptation for onboard use.
c. Reproduce proposals for structural components like container cell guides, deck arrangements, and crane support
d. Evaluation of onboard energy systems and auxiliary power units used to power the automated component reliably.
e. Integration of control systems and software is essential for real-time monitoring, identifying, and coordinating automation systems.

This study doesn’t focus on the economic cost of automation or the rebuilding of older vessels, although some ideas may be applicable. Rather, the emphasis is on designing new container vessels that are capable of supporting advanced automation from the start.

1.5 Significant of the Study

This study holds significant value for several stakeholders in the maritime sector. As automation dominates the future of global trading and marketing, container vessels must evolve to remain competitive and efficient.

The project offers practical design standards that emphasize the structural and technical requirements of automation, generally for shipbuilders and marine engineers. This design can aid in ensuring that newly built vessels are well prepared for the future of maritime operations.

For shipping companies and vessel operations, automation system aids in the reduction of operational delays, reduction of cost, and increase in safety for both cargo and personnel. Automation also reduces ship idle time in ports, contributing to better and easier utilization and profitability.

From an environmental and sustainability point of view, automation improves cargo handling efficiency, reducing fuel consumption during port stays and emission targets

Academically, the research fills a gap in current literature by addressing the integration of automation in the design phase of container ships, a topic that has not been completely explored. It combines knowledge from naval architecture, automation technology, and system engineering, providing a solid platform for further study and improvement.

CHAPTER TWO

LITERATURE REVIEW

2.1 General Review:

Container shipping has been one of the most impactful backbone of global trade, which make up to about approximately 90% of non-bulk cargo transportation in international shipping, it is recorded by UNCTAD's review of maritime operations in 2023, in 2013 UNCTAD review calls for a proper transition to a more decarbonized shipping industry as well as the integration of digital solutions like AI and block-chain in terms of transaction to improve efficiency as well as sustainability of these vessels during operations.

As global leaders prepare for the next UN climate conference (COP28), UNCTAD advocates for system-wide collaboration, swift regulatory intervention, and stronger investments in innovative technologies and better functioning automated vessels, the report speaks more of the need to balance environmental goals with economic needs but under-scores that the cost of in action far outweighs the required investments.

While most modern container ships rely on port-based cranes for loading and unloading containers, a good number of vessels retain onboard cranes for self-sustaining operations. These ships are crucial in regions with limited port infrastructure, such as developing economies like Nigeria and small island nations.

2.2 Historical Evolution Of Self-Cargo Handling Container Vessels:

The historical evolution of container vessels started in the early 90's and there has been an increase in technological advancement since then, the development of self-cargo handling vessels reflects a significant shift in the maritime logistics of containers particularly aimed at improving port efficiency and reducing reliance on shore based infrastructure, we would be looking into a detailed breakdown of the different evolutions of the use of the container vessels that have placed cargo handling mechanisms which are able to move containers on board vessels in operation.

2.2.1 Early Development (Pre-Containerization and Containerized Era):

Before the use of containers to move cargos that was before the year (1950) cargos was handled as break bulk that is it was transported in individual units which required extensive manual labour for loading and unloading, this was a slow process with high labour costs due to high manpower in operation, this can also lead to cargo damage and theft.

The first containerized vessel was launched in the year 1956, called the Ideal X Malcom Mclean revolutionized shipping by introducing container vessels; however, these vessels relied entirely on port cranes for their port operations while loading or unloading containerized cargos.

2.2.2 The Rise Of Self-Cargo handling Vessels:

In the early days of containerization that is 1960's to about 1990's its use expanded significantly smaller and medium sized ports lacked the infrastructure to handle ship to shore cargo unloading and offloading leading in the need for the automated cargo handling mechanisms on board the vessels which can work independently, this ships were equipped with onboard cranes either boom derricks, gantry cranes, or deck cranes which allowed containers to be loaded without port cranes increasing route flexibility.

Below is a container vessel integrated with cranes to aid in cargo handling on board the vessel.

Figure 1 Self-cargo handling vesssel

As containerization expanded, smaller and medium-sized ports lacked the infrastructure, which led to the dominance of self-cargo handling vessels in feeder routes like intra-Asia and the Caribbean. They also gained dominance in multipurpose cargo operations, container, and break-bulk operations.

According to Nottebom and Rodrigue in 2008, self-gear vessels made up to around 40% of the global container fleet in the 1980s; however, the rise of megaships and highly automated port terminals has since reduced their market share in the economy.

Figure 2 Geared vessel

In parts of Africa, Latin America, and southeast Asia, port infrastructure still lags, many regional routes and terminals lack advanced cranes and modern cargo handling systems, geared vessels are ideal for these markets due to their ability to operate independently of port equipment, which in turn reduces costs and improve turnaround times, examples of these vessels are the older Panamax bulk carriers operating in Africa mineral trades example bauxite and phosphate and smaller geared ships serving regional ports in Southeast Asia.

2.2.3 Roles in Short Sea Shipping, Military and Emergency Logistics:

Geared container vessels with the capacities between 1,000 and 2,500 TEU's are often used in short sea shipping, linking major ports like the Rotterdam and Singapore with smaller terminals, these vessels provide essential flexibility during operation especially when port equipment is limited or unavailable, in Europe short sea shipping has also been promoted as an eco-friendly alternative to road freight under green transport policies.

In military and emergency logistics, geared vessels offer a vital self-sufficiency as they can operate in limited environments without needing functioning ports. In the instance of the US military Sealift Command, it often uses geared ships for quick deployment in conflict zones or humanitarian crises.

These vessels are also used by NGO's for relief operations in natural disasters like hurricanes or floods in regional areas like the Caribbean.

Despite their advantage, geared vessels have declined in global container trades as mega ships dominate long-haul routes, and geared ships face challenges such as high maintenance costs, reduced cargo capacity due to crane space usage, and slower cargo operations compared to advanced port cranes.

While their share in mainstream routes may continue to decline, geared vessels still hold strategic value in the market; future outlook, like modular crane systems, hybrid onboard offshore cranes, and smart cargo handling technologies, could expand their lifespan and relevance.

2.3 Technological Components Of Automation:

The integration of automated cargo handling systems into container ships involves a range of interconnected technologies designed to optimize, secure, and manage cargo operations intelligently. These technologies do more than replace the use of human labour; they also significantly enhance efficiency, safety in operation, as well as responsiveness in shipboard logistics.

Below are the key technological components critical to automation on container ships in operation.

2.3.1 Automated Gantry Cranes (AGC’s)

Automated gantry cranes are central to modern cargo operations. These cranes are programmed to function with minimal human input, relying on preset instructions, sensor feedback, and control algorithms to lift, move, and place containers at their designated position on the vessel or the harbor.

To integrate AGCs into shipboard environments, the vessel's deck design layout must be adapted to support crane tracks, structural reinforcements, and well-connected power cabling routes. Control modules also need to be installed to manage crane operations from a centralized interface.

The advantages of automated gantry cranes include faster turnaround times as automation reduces operational delays, increased safety by eliminating manual handling in dangerous areas, and it also gives a level of improved accuracy thanks to sensor-guided movements and preprogrammed operation.

2.3.2 Automated Guided Vehicles (AGV’s)

AGV’s are self navigating transport vehicles which are used for the moving of containers between ship holds and the quay side, when adapted for on board operations, AGV’s require a well planned internal pathways, docking stations, and communicative protocols that align and synchronize the movements of these vehicles with other systems on board an ashore of the vessels.

Successful AGV integration also depends on redesigning cargo decks to include clear obstacle-free routes, incorporating sensor-based navigation systems, and ensuring compatibility with terminal side systems for seamless coordination.

AVGs greatly enhance operational flow, especially during high labour-intensive operations, and help reduce the dependency on manual labour in tight or hazardous work spaces.

2.3.3 Smart stowage Planning Systems

In proper stowage planning container arrangement is critical to automated operations and smart stowage systems use AI and smart systems to optimize how cargos are loaded and organized, these systems analyze factors such as container placement and destination in the different bulkheads as some containers are 20 ft in size(TEU) while some are 40ft (FEU) in size, this different sizes call for different placement in the vessel.

The key benefits of this include improved stability and weight distribution of the containers on board the vessel, as proper arrangement can easily optimize as well as reduced reshuffling at service ports which can save time and fuel during voyage, this can also serve as a form for better space management in the vessels as to increase the cargo capacity on board.

For the performance of ship-based and port-based systems, they must be able to exchange stowage data in real time, for information to be shared between software platforms and communication interfaces.

2.3.4 Real Time Monitoring And Feedback Systems

Automation cannot function effectively without a strong monitoring system, which continuously tracks equipment status, cargo positions, and environmental conditions. These systems also provide feedback to control centers, enabling quick adjustment and response to any detected faults.

The integration of these systems involves:

a. Installing sensors throughout cargo pathways.
b. Establishing fast, reliable data transmission.
c. Setting up centralized control hubs with diagnostics and visualization tools.

These systems allow for proactive and scheduled maintenance, adaptive performance, and enhanced operational safety by identifying and addressing problems before they escalate into something worse.

2.3.5 Power and Control Requirements

Automated systems have higher power demands than traditional cargo handling systems. In using systems like smart cranes, automated guided vessels, and monitoring systems, they require stable, high-capacity, and well-distributed electrical infrastructure.

There is a need for the following setup in order to have a well-functioning automated system.

a. High-output generators and power distribution units around the vessel.
b. Energy storage solutions like battery banks or hybrid fuel systems.
c. Control systems capable of managing multiple subsystems in real life.

2.4 Design and Technical Specifications Of Onboard Cranes

To successfully integrate onboard cargo handling systems into container vessels, it is essential to structure and operational requirements of the crane systems themselves and their installation requirements. This section details the types of onboard cranes typically used in geared vessels, their unique features, and the technical considerations involved in their installation, as well as functionality.

2.4.1 Deck Mounted Gantry Cranes

Deck mounted gantry cranes are among the most common types found on self cargo handling container vessels, these cranes are typically fixed or rail mounted and they are designed with the lifting capacity ranging from 40 to 50 tons as noted by Ludwig & Heidel in the year 2015, a notable example includes the Leibherr Maritime Crane series, widely recognized for its robust design and efficiency in operation.

Leibherr is a prominent name in the maritime lifting technology, manufacturing cranes used on vessels, harbors, and offshore platforms. Their cranes are engineered to withstand the demanding conditions of the maritime environment while maintaining precision and safety.

Some Vessels design also features side mounted badge systems that can carry the crane structure alongside the hull, while this frees up the deck space for cargo placement, it induces new concerns in regards to vulnerability to piracy and or hijacking, despites these risks the self reliance offered by such designs enable ships to conduct minor cargo operations without external assistance which improves the work time and reduces dependency on port infrastructure.

Images below describe examples of vessels with side-tracked badges and self-mounted cranes in operation at sea.

Figure 3 Image of a badge crane mounted system

As we can see in the above image, the cargo handling systems are mounted on a barge alongside the vessels, which is then used for the heavy lifting. Here is another example of a side-mounted design.

Figure 4 Side mounted design

2.4.2 Swivel Cranes (Hydraulic/Electric)

Swivel cranes are another common type of on-board cargo lifting mechanism operating using hydraulic or electric power or a hybrid of both. These cranes are designed for compact, versatile lifting in cases where space is limited.

In this design, they aid in proper functionality, and the duality allows for a longer span in operation. Below is the breakdown of their features.

Hydraulic Swivel Cranes

a. Powered by hydraulic actuators, which offer strong capacity and fluid motion.

b. Commonly used for heavy-duty lifting in ship building, offshore construction, and industrial maintenance.

Electric Swivel Cranes

a. This operates by electric motors, which are quieter, cleaner, and more energy efficient.

b. It's also ideal for environments that prioritize low emissions and noise reduction.

Key Features of The Swivel Cranes

a. They are built with a 360-degree rotation for flexible load positioning

b. There is a design for a compact structure allowing installation in tight or restricted hull structures

c. Adjustable booms which has a telescopic design for extended reach.

d. It is designed with the having the ability for high load capacity operations typically ranging from 0.5 to over 20 tonnage of container load.

e. It is designed with control options including manual, remote, and well-designed interfaces.

Images below describe examples of hydraulic and electric swivel cranes.

Figure 5 On-shore design of the swivel crane.

There are designs of this crane system mounted on the vessels in operation, which can aid in lifting cargoes on board. Below is a pictorial example.

Figure 6 Swivel crane mounted on a vessel.

2.4.3 Stiffleg Derricks (Traditional Designs)

Stiffleg derricks are one of the earliest forms of onboard lifting equipment used on board vessels, long before the advent of modern mobile or hydraulic cranes. These consist of a rigid vertical mast supported by angled legs, which brought the name (Stiffleg), and it's connected to a pivoting boom.

Characteristics of Stiffleg Derricks

a. It has a fixed installation design, which is typically mounted permanently to the deck of the vessels or a reinforced foundation.
b. It's stable without counterweights, which provides structural support, which in turn eliminates the need for heavy balancing.
c. Its design is based on simple construction procedures, often built from steel or wood in older models with mechanical or manual winches.

Although mostly in operations today, the stiffleg derricks remain relevant in a historical context or for ships operating in isolated or legacy ports with minimal infrastructure.

2.5 Operational Advantages Of Cargo Handling systems On Container Ships

Geared container vessels are ships that are equipped with onboard cargo handling equipment, such as gantry cranes or onboard derricks. These self-sufficient ships are particularly valuable in regions where port infrastructure is limited or underdeveloped, while gearless ships rely entirely on port-based cranes, geared vessels offer room for greater flexibility and operational independence.

Below are the key advantages of geared container ships, supported by maritime industry data and real-world applications.

2.5.1 Ability To Operate In Non-Cranage Ports

Non cranage ports are terminals that lack fixed cargo handling infrastructure such as ship to shore gantry cranes or the straddle cranes, the reason why this is important is based on supporting the emerging markets in developing nations with smaller ports across regions like Africa, Latin America and south Asia where advanced equipments are lacked in operating large gearless vessels noted by (Drewry in 2020).

This, in return, saves costs as vessels with their onboard cranes bypass the need for expensive crane rentals or specialized port services. By not depending on rental equipment availability, these ships can avoid scheduling delays, allowing quicker cargo operations on shore.

2.5.2 Critical Role In Disaster Relief And Emergency Shipping

Geared vessels are particularly useful in crises where port infrastructure may be damaged or non operational, their ability to function without external support makes them ideal for cases where there are emergencies which makes them ideal for humanitarian operations where aid is been delivered to disaster struck regions such as cities or towns been hit by hurricanes, earthquakes or war zones, reaching small or undeveloped ports that are otherwise in accessible to large ships.

In cases of military operations at sea where access to port infrastructure is limited, these designs can aid in the self-operation of these vessels, giving room to operational flexibility in volatile regions.

In various scenarios, geared vessels can act quickly and independently, ensuring the timely delivery of supplies even when traditional port systems are unavailable or overwhelmed.

2.6 Limitation and Research Gaps

While geared container vessels offer notable operational benefits, especially in areas with limited port infrastructure, they also face several technical, economic, and operational drawbacks. These challenges often limit their widespread adoption in mainstream routes where speed, efficiency, and capacity are critical.

Below are listed various limitations and observed gaps in the adoption of these systems.

2.6.1 Reduced Cargo Capacity:

One of the main limitations of incorporating cranes directly into a container vessel is based on the loss of usable cargo space on the deck. We have cases of onboard cranes typically occupying about 5 to 10% of the available deck area, which could otherwise be used for stacking containers on board.

This is also observed in vertical clearance issues when these structures take up air space, which can also reduce stacking heights and, in return, container loading.

For these reasons, ultra large container ships (ULCV) are almost exclusively gearless; their design takes into consideration maximum cargo volume, which would be compromised by adding crane cargo handling systems on board.

2.6.2 Slower Loading and Unloading

This is the situation where the speed of the mounted cargo handling systems, which operate independently of port cranes, in comparison they are relatively slower in operations with the shore-based systems.

Below is a tabular review of this comparison in operational speed.

CRANE TYPES	AVG MOVES PER HOUR	SOURCE
SHIP MOUNTED GEARED CRANES	15- 25 MPH	DREWRY (2021)
MODERN STS (QUAY) CRANES	30- 50 MPH	Port Technology International (2023)

Fewer moves per hour result in longer port delays when the cargoes are being offloaded from the vessel. This is as a result of many geared vessels carrying only one or two cranes, which limits simultaneous operations, and this makes them less competitive in high volume ports where speed is essential in operation.

2.6.3 Operational Inefficiencies

In the operation of these vessels, several inefficiencies arise during actual operations:

a. Sequential Cargo Handling: Limited onboard cranes mean containers are often handled one at a time, unlike at ports where multiple cranes operate simultaneously.
b. Weather Dependency: Onboard crane operations may need to pause in rough seas or high winds, while shore cranes, being land-based, continue with fewer weather disruptions.

These factors considered reduce reliability and slow down the overall adoption of these systems.

2.6.4 Continued Dependency On Yard Equipments

Ships having their cargo handling systems still rely on land-side equipment for cargo movements on shore in cases like:

a. Transporting containers from the ship to the storage yard using trucks and terminal tractors, and this cannot be done except at the port.
b. For the cases of stacking containers on shore, where straddle carriers and reach stackers are used for efficient organizing of yard space.
c. The use of forklifts, which are used for handling light or empty containers.

The dependency weakens the full autonomy that onboard cranes promise, especially in under developed terminals lacking such support equipment.

2.6.5 Higher Maintenance Costs

There is a need for higher cost of maintenance costs when a vessel has its crane system on board in comparison to vessels without the integration of cargo handling systems.

Below is a tabular review of the estimated cost of maintenance of these ships with the onboard cranes.

	Geared Vessels	Non Geared Vessels
Annual Maintenance Costs	\$500K - \$1.2M	\$300K - \$700K
Crane Overhauling	\$200K - \$400K	No crane system
Downtime losses while in Maintenace	5 – 10 days	1 – 3 days

Salt water exposure and constant motion increase the rate of corrosion and mechanical failure, which can result in wear and tear, hence the need for maintenance of these systems.

Cranes involve hydraulic systems, winches, slewing mechanisms, and electronic controls; all these parts do require maintenance, while geared vessels provide unique advantages in certain regions, their cost of maintenance must be well considered, as well as the operational design and long-term functionality.

2.7 Economic and Environmental Considerations

The choice of implementing onboard cargo handling systems on container vessels must vary for both financial and environmental impacts. While geared vessels are mainly for logistical flexibility, especially in areas limited by infrastructure, their operational model brings different economic exchanges and environmental implications.

2.7.1 Cost-Benefit Analysis

In port terminals without adequate handling equipment, geared vessels offer an essential advantage. According to Drewry (2020), operating geared container ships in such locations can reduce overall costs by 20–30%, primarily due to:

a. Eliminated Port Crane Fees: Vessels with installed cranes remove the need for expensive rental or terminal handling charges.
b. Shorter Port Stays: Improved automated ships allow for faster, independent cargo handling operations in low-efficiency ports.
c. Flexibility in Route Planning: Vessels are not limited only to large, well-facilitated terminals, allowing for remote marketing.

However, these savings must be compared with higher maintenance expenses and reduced cargo efficiency capacity, mainly when compared to gearless vessels operating on high-traffic routes.

2.7.2 Emissions and Fuel Efficiency

Automated crane handling systems can contribute positively to environmental goals, mainly when integrated with sustainable design practices:

a. Electric Drive Systems: According to DNV GL (2021), replacing traditional hydraulic crane systems with electric alternatives can reduce CO_2 emissions and improve fuel efficiency during port operations.
b. Reduced Idle Time: Automated cargo handling systems simplify loading and unloading, reducing the time spent running auxiliary engines in port.
c. Cleaner Energy Integration: Vessels installed with battery-assisted crane systems consume less fuel and emit fewer pollutants.

As the marine industry experiences great pressure to meet international emission standards such as the IMO 2030/2050 targets, automation provides a possible path to a more efficient ship design and operation.

2.8. Case Studies

Understanding more about how geared container vessels operate in real life, this section explains two regional case studies that emphasize both the necessity and adaptability of the onboard cargo handling system.

The following examples explain how ships with built-in automation and self-sustaining facilities perform under varying structural and technological conditions.

2.8.1 West African Feeder Routes

Source: UNCTAD (2023)

This case research is on feeder vessel operations serving West African ports like those in Nigeria, Ghana, and Côte d'Ivoire. Most of these terminals experience a lack of a fully advanced port automation system, and many don't have modern STS cranes or AGVs. In such systems, geared container vessels aren't just beneficial, they are also important.

Key Observations:

a. Self-reliance: Vessels with installed cranes onboard can easily load and unload containers without external support, permitting access to smaller, still improving ports.
b. Infrastructure mismatch: Even when vessels are partly automated, port terminals are not equipped to combine with smart or robotic systems, which limits the efficiency from progressing
c. Operational bottlenecks: They are difficulties in synchronizing onboard automation with under-equipped yard logistics, like the manual container stacking and limited transport vehicles.

2.8.2 Intra- Asia Short-Sea Shipping

Source: Notteboom & Rodrigue (2008)

The second case concentrates on the Intra-Asia short-sea shipping network, covering major port cities such as Singapore, Shanghai, and Busan. This section aids thousands of small to mid-size container ships, which must maintain compatibility with a range of automated port terminals.

Key Insights:

a. Terminal Compatibility: Ships are improving with time to integrate with automated port infrastructure, including robotic cranes and automated stowage systems.
b. Energy Optimization: Many vessels are built with energy-efficient power systems to improve automation without compromising fuel performance.

c. Smarter Logistics: Stowage systems onboard are synchronized with port terminal databases, permitting better pre-planning and fast cargo turnover at each port.

These examples demonstrate that in developed port ecosystems, the automation of vessels isn't only achievable but also essential for maintaining speed, consistency, and competitive advantage.

2.9. Future Trends

As the maritime shipping industry continues to improve, geared container ships, regardless of their limited role in mainstream routes, are undergoing some improvements to stay relevant in a technology-driven, environmentally conscious maritime future. Several developments are shaping the future of the marine industry concerning onboard cargo handling and ship design.

2.9.1 Automation and Smart Cranes

One of the most effective developments in the marine industry is the shift toward intelligent crane systems. Manufacturers like Liebherr and MacGregor have introduced cranes with AI-assisted control systems, Remote operation capabilities, and Real-time sensor feedback.

These features enable more accurate, efficient, and safer cargo handling, primarily in high-risk environments.

2.9.2 Hybrid and Electric Crane Systems

To acquire a maintainable target, crane systems are redesigned with hybrid (diesel-electric) or fully electric systems. These systems offer: Lower fuel consumption, Reduced noise and emissions, and improved compliance with IMO 2030/2050 decarbonization goals.

They are specifically efficient in port environmental regulations or emission-restricted zones.

2.9.3 Compact Crane Designs for Smaller Vessels

Movable and lightweight crane systems are being improved to serve feeder vessels and regional container ships, offering: Lower deadweight impact, preserved cargo space, and Simplified installation and maintenance.

This allows smaller ships to maintain flexibility without major capacity losses.

2.9.4 Rising Demand in Emerging Markets

As so many developing regions in the world still lack modern port equipment, the demand for geared ships remains high in Africa, Southeast Asia, and South America. These ships:

a. Expand trade access in remote and underserved locations
b. Encourage port development by stimulating traffic in low-capacity terminals

2.9.5 Digital Integration and Predictive Maintenance

Modern ships are integrating IoT and AI for condition monitoring of crane components and cargo systems. This shift enables: Early fault detection, reduced downtime, and Efficient maintenance scheduling.

Predictive systems also promote safety and reduce the long-term operational expenses of geared components.

2.9.6 Flexible Deck Configurations

Ship designs now highly support modular (movable) crane installations, such as: Rail-mounted gantry cranes, and Telescopic cranes

These adaptable setups allow operations even in more complex or high-stacked container environments.

2.9.7 Sustainable Shipbuilding Materials

Advanced materials like carbon-fiber composites and high-strength steel alloys are now being used in crane components to: Enhance durability, reduce corrosion, and Lower vessel weight

This increases the working period of a vessel and reduces maintenance.

2.9.8 Retrofitting Existing Ships

Older ships are being upgraded with: Modern cranes, Control systems, and Hybrid power units

Retrofitting offers a cost-effective alternative to new builds, extending vessel lifespan and ensuring regulatory compliance.

2.9.9 Geared Vessels in Niche Markets

Geared vessels continue to be vital in: Arctic routes, the Island supply chain, and Military logistics

These markets need vessels that can be operated independently in unpredictable or under-equipped environments.

2.9.10 Regulatory Push and Classification Standards

Organizations like DNV and Lloyd’s Register are increasingly mandating: Smarter safety systems, Standardized load-monitoring protocols, and environmentally friendly crane integration guidelines.

These frameworks are helping modernize geared vessels and align them with global best practices.

Example Technologies:

a. Liebherr CBW Cranes: Use frequency-controlled winches for efficient container/bulk handling.

b. MacGregor Active Heave Compensation: Enhances safety and control during unstable offshore operations.

While geared container vessels may no longer be able to dominate global trade, they attain an essential role in regional logistics, humanitarian aid, and low infrastructure markets. Advances in automation, green technology, and design innovation are helping to restore their relevance and performance. As port independence continues to be an asset in niche environments, geared shops remain an essential part of the maritime future.

CHAPTER THREE
MATERIALS AND METHODS
3.1 OVERVIEW OF THE CONTAINER VESSEL DESIGN PROJECT

Marine technology has come such a long way over the years, completely changing how ships and other seagoing vessels are designed, built and optimized. In the past, ship design was based on physical model scale tanks results under laboratory conditions. But as technology advanced, so did the engineers with tools like Computer-Aided Design (CAD), Solid Works in particular which gave them the ability to visualize Simulate and Evaluate ship designs on a virtual environment way before any physical construction.

This technique provides greater Accuracy in results, Reduced Design errors & Material Costs with Innovate more ideas possible. We have made a report on the design of an assembly of container vessel using Solid Works 3D modeling software. The project's goal is to provide a more distilled, approachable take on the concept of a container ship which are cargo vessels that carry common shipping containers. Indeed, the model reflect some of areas such as hull , deck , cargo holds , superstructure bulwarks, bow and stern represent essential portions of a ship they all produce separately before insert inside hole vessel.

The container vessel model offers an illustrative understanding of structural arrangement and component interaction. The model can also be understood to reflect contemporary marine engineering design principles. The design can be employed as a rudimentary basis for possible work with some of the many automated systems including robotic cranes, linked cargo ships and smart loading and unloading equipment that are current flowing through contemporary technology waves in the maritime industry.

The main objectives of this Solid Works modeling project are as follows:

a. To design a 3D model of a container vessel that reflects accurate marine structural configurations.
b. To develop and assemble individual ship components such as the hull, deck, and accommodation block.
c. To gain practical proficiency in using Solid Works tools like *Extrude, Loft, Shell, Fillet,* and *Mate*.
d. To analyze the vessel’s structure for symmetry, stability, and design aesthetics.
e. To demonstrate how modern marine engineers utilize digital modeling for pre-construction evaluation and design modification.

f. To create a baseline model that could support further research in automation, hydrodynamics, and structural integrity studies.

3.2 DESIGN APPROACH

A container vessel is a specific type of merchant vessel purpose-built to carry intermodal containers with a system of standardized measurement, including the 20-foot equivalent unit (TEU) and 40-foot equivalent unit (FEU). These vessels are designed to be strong, stable, and safe when voyaging the ocean while maximizing space for stowage.

The design of container vessels from the perspective of marine engineering incorporates hydrodynamics, structural integrity, and load distribution. The hull of the container vessel is utilized for buoyancy and resistance to external pressures, while the superstructure is defined for control and life for the crew. The deck, as well as the cargo holds, has to be designed for operations as a platform for stowage and handling.

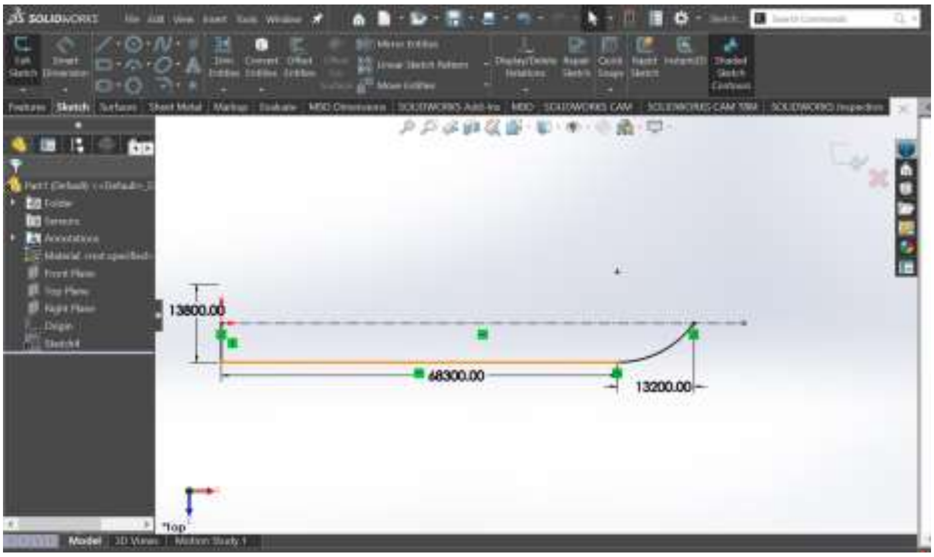
Solid Works can produce the parts to be designed parametrically where dimensions and relationships can be easily manipulated according to the design requirements. Solid Works allows solid modeling to be produced for mechanical components or surfaces to be modeled for rounded structures such as hulls and bows, rendering it useful for marine applications.

3.3 DESIGN METHODOLOGY.

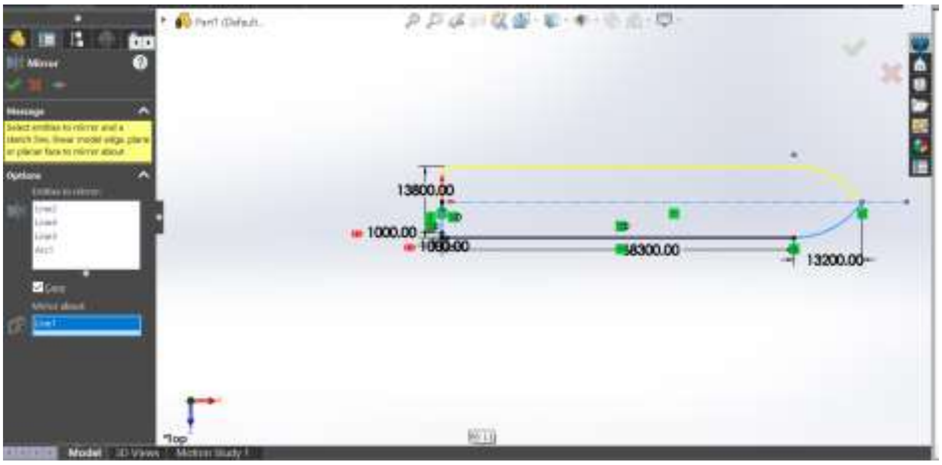
3.3.1 STEP 1

The design process of the container vessel was carried out in a step-by-step structured approach focused on producing an efficient and stable design for the automated cargo aggregate system to be integrated into the vessel.

In the first phase of the design, we began developing a 2D sketch of the vessel's general profile. At this stage, we defined the principal dimensions, particularly the vessel's length overall (LOA), which would be the foundation of all other modeling going forward. The 2D sketch provided an initial representation of the vessel geometry which included the bow shape, stern form, and deck layout.

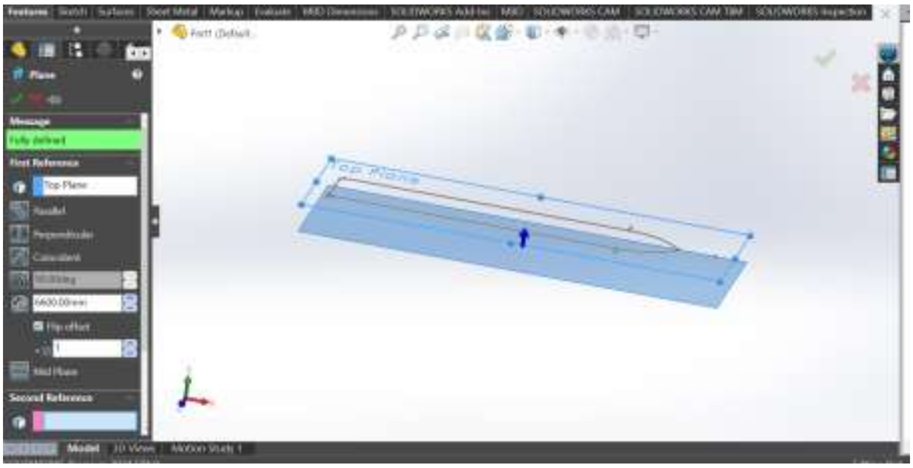


The preliminary sketch assisted with establishing the basic hull shape and overall dimensions of the vessel before moving to the architectural modeling. The design phase also included comparative outlines provided by two differing layout concepts that would guide the construction of a full 3D model for various modeling and analysis purposes later.



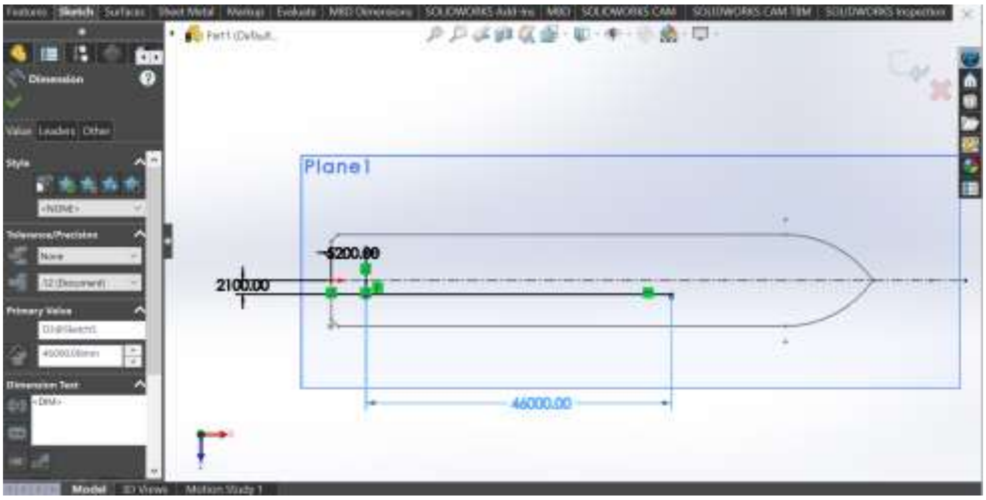
3.3.2 STEP 2:

Following the completion of the primary 2D Sketch representing the vessel structure, the next action is to in use the Reference Geometry tool in SOLIDWORKS, which allows you to create a reference plane that is below the original base plane. This new plane will allow you to have a working surface that represents the ground or base level of your vessel model. By having a second plane established, now you are able to create a second 2D sketch, that will create depth into your model, which then transitions it from a simple outline to an actual three-dimensional vessel structure.



3.3.3 STEP 3:

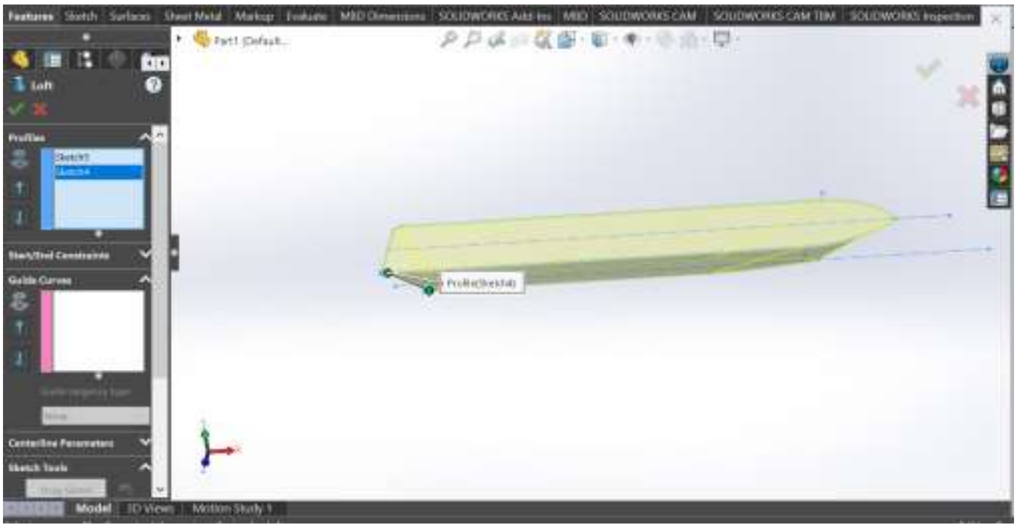
After the reference plane has been established through the Reference Geometry tool, the next step is to create a second 2D sketch on this newly created plane. This second sketch will be used as the basis for defining the lower part of the vessel. The Mirror Tool in SOLIDWORKS will be used to mirror the elements of the sketch about the same reference midpoint line, creating a symmetrical and geometrically correct 2D outline of the vessel that captures the deck configuration on top and the depth of the hull below. The mirror creates a complete sketch that can be used as the geometry for developing the 3D modeling and surfacing.



3.3.4 STEP 4:

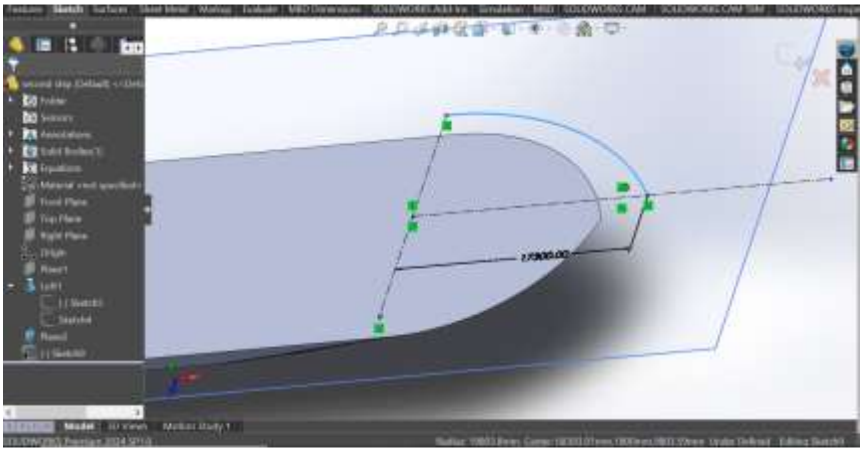
After you finish your 2D sketch, the next part is to convert the design into a 3D model by utilizing the Loft Tool within SOLIDWORKS. The Loft Tool is used to create a smooth continuous 3D surface connecting the profiles that are designed on the top reference plane and the references that were designed on the lower reference plane. Once you select the corresponding sketch profiles to loft, the Loft Tool will transition to allow profiling to happen in order to establish the hull curvature of the vessel, and it’s vertical geometry. It allows you to accurately control the depth of your hull, contour, and shape the vessel as it transitions from upper and lower sections structurally, while being hydro dynamically efficient and aesthetically

coherent. The 3D lofted body will be the initial designed structure before further detailing and design iterations.

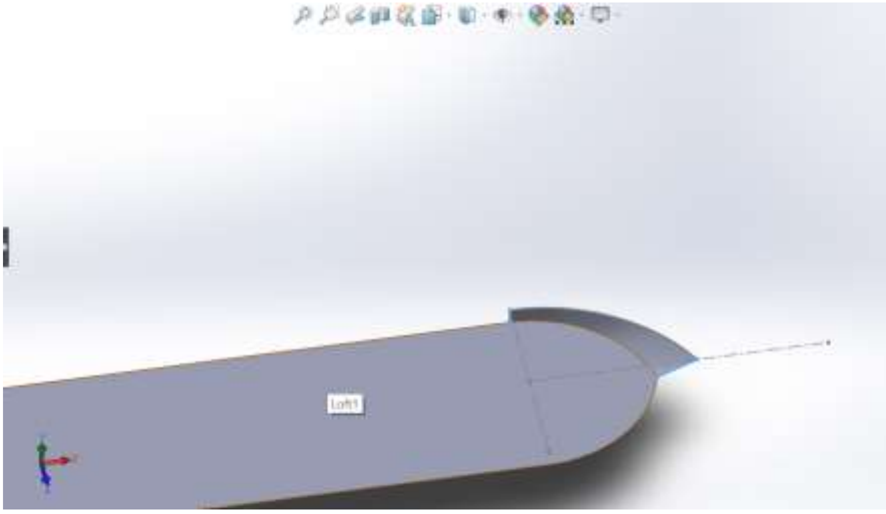


3.3.5 STEP 5

Once the lofting process has established the main hull form, the next step is to specify some bow restrictions and modify the top deck curvature to obtain the profile that is desired for your vessel. In this stage of the process, the Reference Plane Tool will be employed to create a new plane above the level of the deck, which will act as the working surface for an additional 3D sketch. On this new plane, you will use the 3D Sketch function, mainly with Line and Spline tool, to establish the curvature of the bow front at the front end of the vessel.

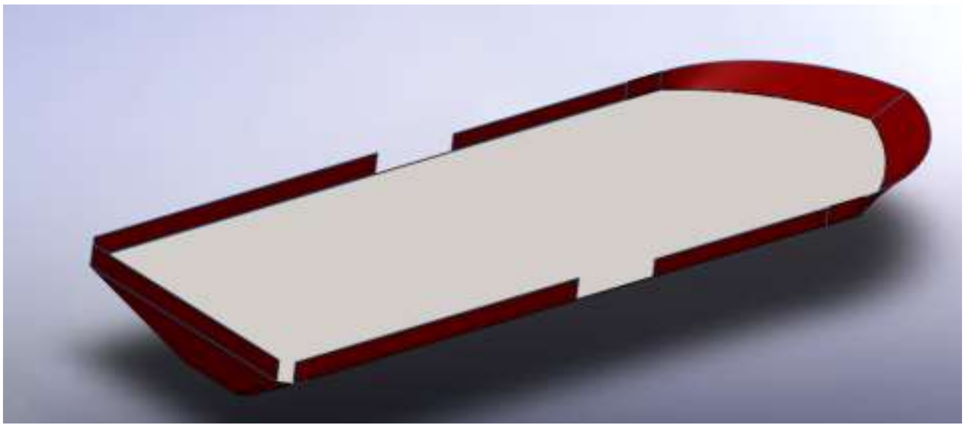


The curvature that you will create will ultimately shape the hydrodynamic contour of the bow and collectively assist larger water with resistance and a more efficient flow. Ultimately, the design that you establish will frame the forward hull's geometrical shape into the deck structure of the vessel, while achieving practical and visually appealing aspects to the overall geometry of the vessel.



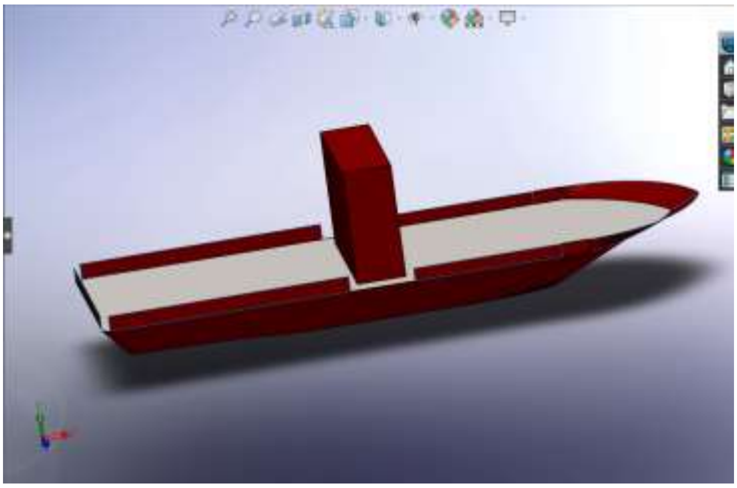
3.3.6 STEP 6

At this point in time, design restrictions and safety constraints are formally imposed throughout the deck organization of the marine craft. This step implements that the model meets all marine design standards and safety regulations on ship-build constructions. In SOLIDWORKS, fixing tool sets such as geometric relations, dimensioning, and boundary conditions are applied to secure the location, alignment, and proportioning of the components of the deck. This stitching step limits the chances of unintended deformation in later modeling practices and standardizes the integration of the geometry of the ship and the components of the deck. Implementing these deck restrictions develops assurance that the design is both structurally sound and safe a framework to launch into detailing, outfitting, and stability investigations.

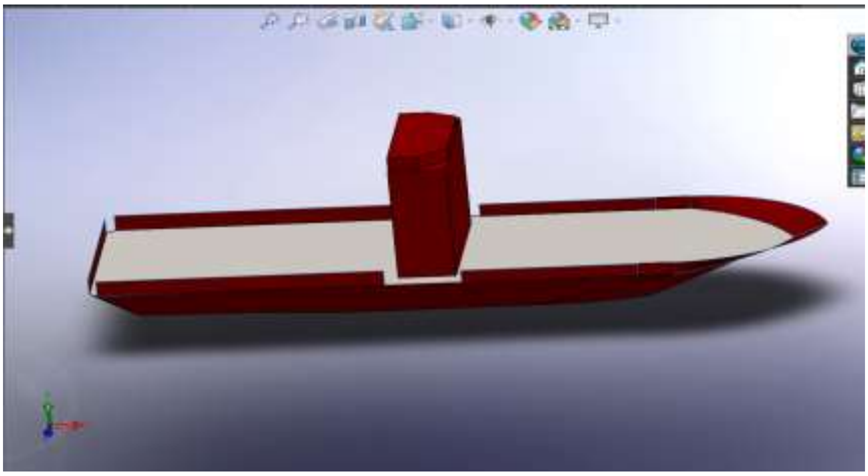


3.3.7 STEP 7

At this point, the placement and structure of the navigation bridge will be addressed as this is the vessel’s primary command and control station. Due to the need for stability, visibility, and generally accepted principles of general arrangement in contemporary container vessels, bridges are located at the midship position in particular. This location will provide stable weight distribution on the vessel while granting control of navigation and the vessel in various sea states.



Using SOLIDWORKS, the Boss-Extrude Tool will be applied to create the height of the bridge, and the bridge must rise above the main deck height enough to provide an unobstructed line of sight for navigational duties. The parameters of the extrusion will be defined to replicate the height value of a realistic bridge for the model scale of the vessel. This step in the modeling process will ensure the functional and visual integration of the bridge's integrity into the outline of the vessel while also complying with its operational standards and expectations concerning the maritime industry.

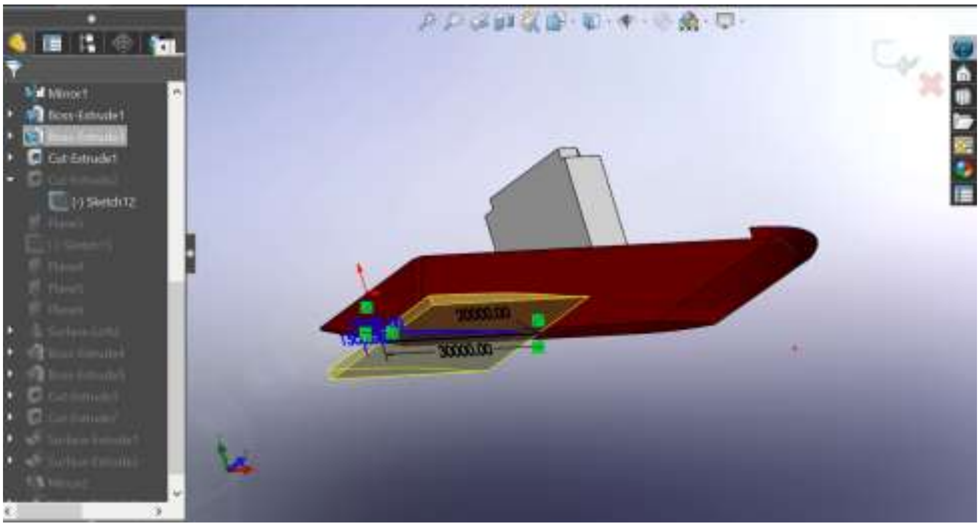


Further design of the bridge.

3.3.8 STEP 8.

The hydrodynamic form of the hull requires further optimization at the lower back section of the vessel. In SOLIDWORKS, with the Boss-Extrude Tool, an appropriately formed contour is created to define the parameters of the stern of the vessel. This extruded shape dictates the geometry needed in order to shape the stern, which is needed for streamlining and to create a design which will reduce drag for the vessel to successfully glide through the water surface with as little resistance as possible.

The back of the vessel is carefully modeled to minimize the amount of turbulence generated by fluid flow moving from areas of the vessel, midship, to the stern. This is important so that the vessel operates with the best propulsion efficiencies and for overall performance of the vessel. At the same time, this not only adds to the aesthetic refinement of the vessel, but also allows the vessel to guarantee it achieves a working design by applying basic principles of naval architecture and hydrodynamics of the design.

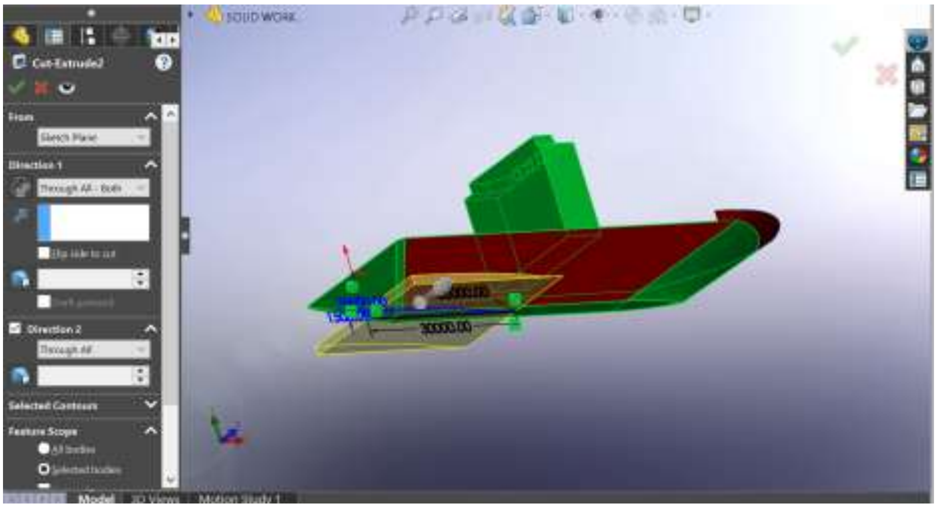


3.3.9 STEP 9:

After extruding the stern section, the Cut-Extrude Tool (also known as the Cut Restriction Tool) is used to modify and finish the previously created geometry. This step is essential to provide the appropriate streamlining effect for efficient hydrodynamic performance. Controlled cutting is

used to remove unnecessary excess material from the extruded body to create a clean taper shape that adheres to the vessel's flow lines.

Each cut will be executed with reference drawings and geometric limitations in mind in order to facilitate transition from midship to aft section hull curvature. This step increases the vessel's ability to reduce drag, increase directional stability and maintain efficient propulsion while underway. The completed streamlined shape increases performance while achieving the minimum required design criteria for marine efficiency and stability.



From: Sketch Plane

Direction 1: Through All - Both

Direction 2: Through All

Selected Contours

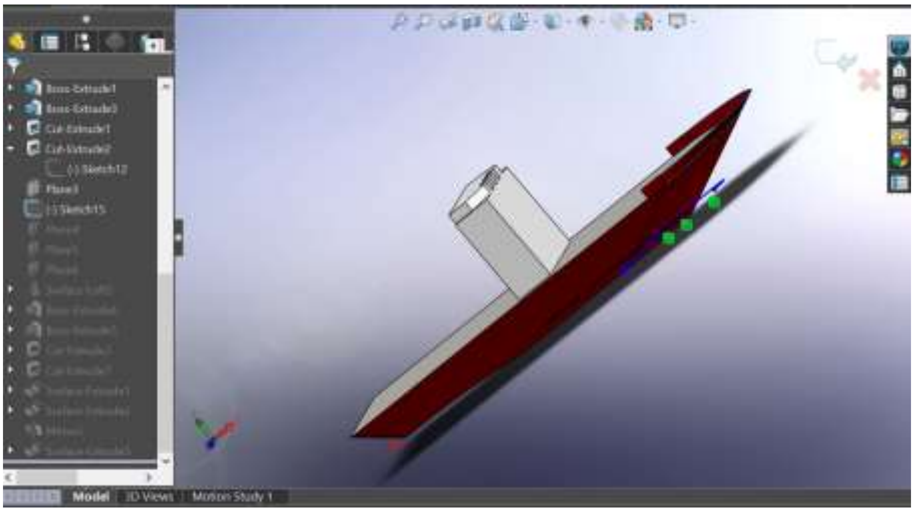
Feature Scope

3.3.10 STEP 10

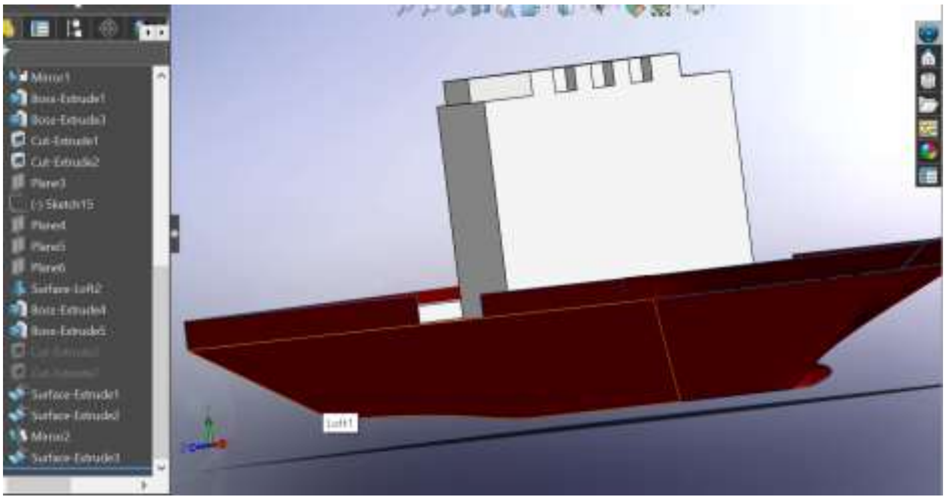
At this point, the attention of the sketch design shifts to the bow portion of the boat, which will continue to provide basic shape to determine the boat's hydrodynamic performance and wave-piercing performance. It is at this stage that the 2D sketch will be created on the assigned reference plane. Using the Three-Point Arc Tool in SOLIDWORKS, the bow's basic curvature

will be created, outlining the hull's forward contour, which will define the basic shape of our bow's streamlined geometry.

Next, two reference planes will be created one at the hull's bottom and the other, higher up to assign the necessary profiles for the Loft Tool. The Loft Feature will then be used to connect the two planes together, creating our 3D bow form, smooth and continuous. This form and connection method will help transition the bow while maintaining the hull body, flow line, and hydrodynamic balance. The shape established by process will also significantly address water resistance to reduce drag and allow for optimal vessel efficiency for grinding and forward motion.



The bulbous bow was then built fully in order to give resistance to the flow of the vessel through the fluid.

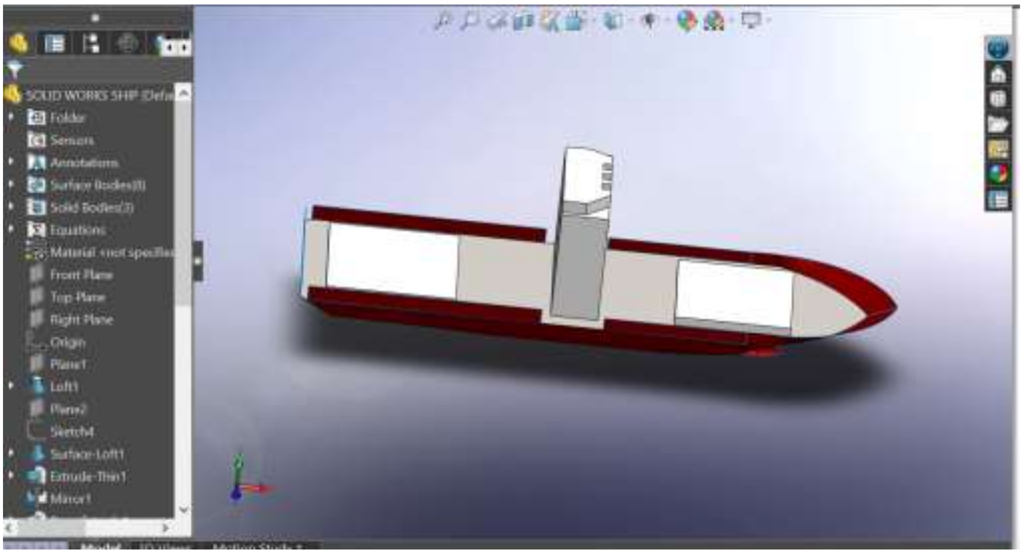


3.3.11 STEP 11

To design the container cargo holds, the Rectangular Tool is used to create the overall form and limits of each hold. The initial hold is positioned at the bow of the vessel, purposefully aligned to accommodate the allocation of containers and accommodation. The dimensions of each hold are specified to conform to standard container dimensions while allowing sufficient spacing for loading, unloading and securing the containers.

After the fore-hold, the same process continues at the corresponding aft section of the vessel. Again, the Rectangular Tool is used to shape the hold's geometry and to ensure that it meshes correctly with the hull of the vessel while maintaining required clearances for structural supports and maintain access. This is followed by the application of the Center Rectangular Tool to position the holds correctly in relation to the centerline of the vessel, promoting symmetry and balance.

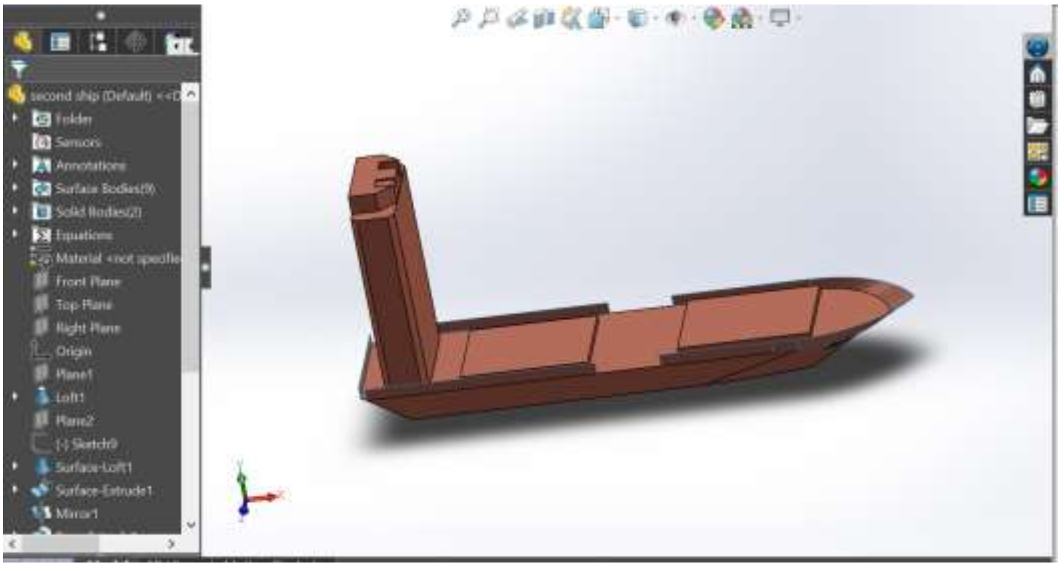
This layering, additive construction process ensures that not only is the cargo hold size appropriately established, but that their location maintains maximizing the capacity. Each hold is designed with specific emphasis set on the container isolation, weight location, and accessibility for an efficient way to load and unload for automation or manual cargo operations.



This concludes the step-by-step process of constructing the vessel. A second vessel was developed, considering a different general arrangement with the accommodation located at the aft of the vessel, to explore varied design considerations and how it would impact the overall vessel layout and functionality.

The second vessel which was considered due to its bridge placement.

The process of building the container ship has been outlined step-by-step, as discussed above. A second ship was built similarly to the process used for the first, with one key difference in the arrangement of important components in the second ship: the bridge was located aft of the mid-point of the ship, while the container cargo holds were positioned directly in front of the bridge system. Exploring an alternative arrangement was perceived as an opportunity to consider a second design option and examine how a different configuration of the vessel's layout could affect the general functionality and operational efficiency. By developing these two designs, lessons could be learned about the best placement of accommodation spaces and cargo holds for performance purposes.



A secondary vessel which was built to integrate the positioning of the bridge.

The topic integration of automated cargo handling on container vessel allows for the design of a robotic crane that would be integrated on the container vessel built above.

3.4 MATERIAL PROPERTIES AND SURFACE FINISHES

Despite being a conceptual model in Solid Works of the vessel rather than a ship that has been built, realistic material properties were assigned to each major main hull part of the vessel to approximate a real standard of marine construction. The material selection in Solid Works was based on the functional properties of strength, corrosion resistance, optimal weight and hydrodynamic capabilities. Not only do these materials enhance the structural fidelity of the model, but they will support simulation studies in the future with respect to stress analysis, buoyancy, and hydrostatic stability.

a. Hull Material:

   The hull that contains the primary load-bearing and watertight structure of the vessel was modelled with mild steel (shipbuilding-grade steel). In reality, marine-grade steels, such as AH36 or DH36, would be real materials used to build the hull because of their high tensile strength, ductility and fatigue and corrosion resistance properties. These steels also welded easily, so large hull plates could be welded together without losing a considerable amount of structural integrity.

b. Material for the deck and bulwarks:

   The deck and bulwarks were also given the properties of mild steel material. This is the standard in shipping construction as the deck and bulwarks would be constructed using the same material grade as the hull to ensure similar mechanical performance and corrosion protection. The deck was selected for material based on its strength and rigidity characteristics to support the concentrated loads of containers, cranes, and machinery on the deck.

c. Superstructure Material:

The superstructure settings, which are above the main deck and connect the navigation bridge and accommodation block, were modeled in Solid Works using an aluminum alloy material. In shipbuilding practice, lightweight aluminum alloys (for example AA5083 or

AA6061) are often used for superstructures since they help to lower the vertical center of gravity and enhance stability and sea keeping performance.

d. Protection Coatings and Paint Systems:

1. To be representative of a real marine surface treatment, a protective coating system was simulated with changes to color and texture.
2. We coated the underwater part of the hull red, as you would for anti-fouling paint. Anti-fouling coating systems are specially designed to minimize vessel bio fouling and prevent the growth of marine organisms, such as algae and barnacles, from growing on the hull to increase hydrodynamic efficiency with reduced fuel consumptions.
3. We gave the deck a grey finish, representing the anti-skid, corrosion-resistant steel plating that is typically used in operational areas.

The superstructure received a light grey coating, illustrating the heat reflective marine paint that lowers interior temperature and enhances the visual uniformity.

3.5 DESIGN CONSIDERATIONS OF THE VESSEL

The construction of the vessel model in SolidWorks incorporated several critical engineering and functional considerations to ensure its virtual representation reflected realistic principles of shipbuilding. The design of seakeeping, stability, required strength, safety, and overall appearance were made with thoughtful consideration to the vessel's hydrodynamic performance. The critical engineering and functional considerations of the design are detailed below.

a. Hydrodynamic Efficiency :

In order to achieve smooth motion through the water, the hull form made with a fine-entry bow as well as curved contours along the hull. This improves hydrodynamic drag by allowing efficient flow of water along the hull's surface, resulting in reduced resistance and improving fuel efficiency in real world implementation. Additionally, the shape reduces wave-making resistance, improving seakeeping and boat maneuverability through variable sea states.

b. Stability:

   The center of gravity of the vessel was purposely lowered by distributing structural mass vertically and along the longitudinal axis. The hull and deck are both modeled with heavier weight steel material properties, while lighter weight aluminum was used for the superstructure. This promotes transverse and longitudinal stability, preventing the vessel from rolling excessively (port-to-starboard), or pitching excessively (fore-aft). These ideal characteristics will promote stability when loaded and/or operating under realistic conditions.

c. Structural Integrity:

   The model aims to be robust and durable over time by using continuous surfaces with aligned joints, and reinforcing sections with analogous real world shipbuilding methods. These features will also lessen structural weak points and relieve stress concentrations, particularly in areas of connection like the deck to hull connection and bulwark connections. The model has prioritized a consistent surface transition through all sections, which promotes the model’s ability to withstand operational stresses in any future simulation studies.

d. Safety:

   Safety during operations was addressed by incorporating bulwarks on the edges of the deck, preventing crew or equipment from slipping overboard. In reality of ship design, bulwarks are an important safety feature for keeping people on board in difficult sea conditions as well as protecting the vessel from splashes of seawater. Having bulwarks in the model adds functional authenticity, and observe safety requirements in amritime design protocols.

e. Aesthetic Authenticity:

   The model also was given consideration for visual accuracy and quality of presentation. The size and dimensions of the vessel were captured proportionally, along with a realistic appearance of color, and the surface finish reflecting levels of marine construction. These all assure the model has visibility within the learning environment, with scope for presentation (beyond education purposes) in technical documentations and possible future industry presentations or concept demonstrations, therefore it holds an educational and professional purpose.

3.6 ROBOTIC CRANE BUILD STEP BY STEP PROCESS.

3.6.1 LINK 1.

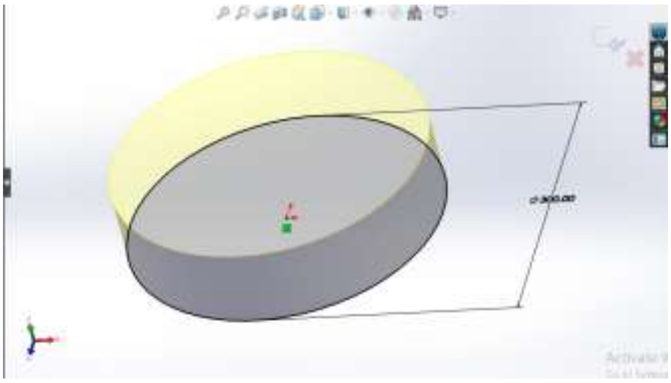
3.6.1.1 STEP 1.

We started with the base of the robotic arm where we stated the various processes involved in the build.

We start the design with the base measurement.

Note: All measurements are recorded in MM (Millimeters), the measurement is 300mm in diameter where we went forward and used the Boss extrusion tool to give the sketch its thickness in depth.

As we can see there is a level of thickness and depth that is given to the original sketch, the data for the boss-extrude is detailed below.

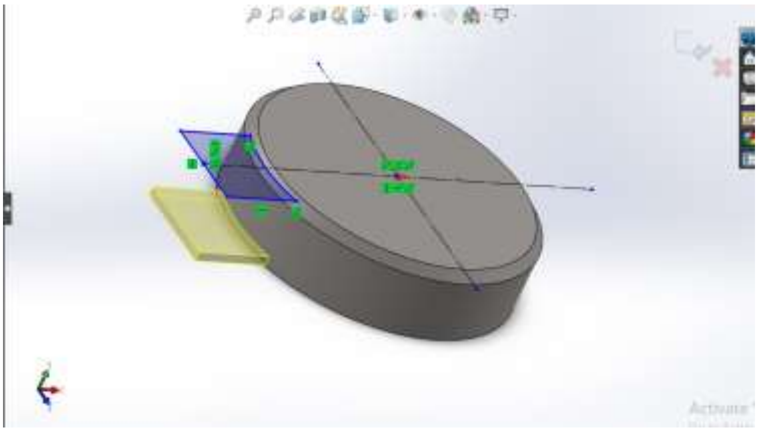


The base of the robotic crane

After the extrusion has been carried out, we then chamfered the top surface of the extrusion so as to give a good finishing.

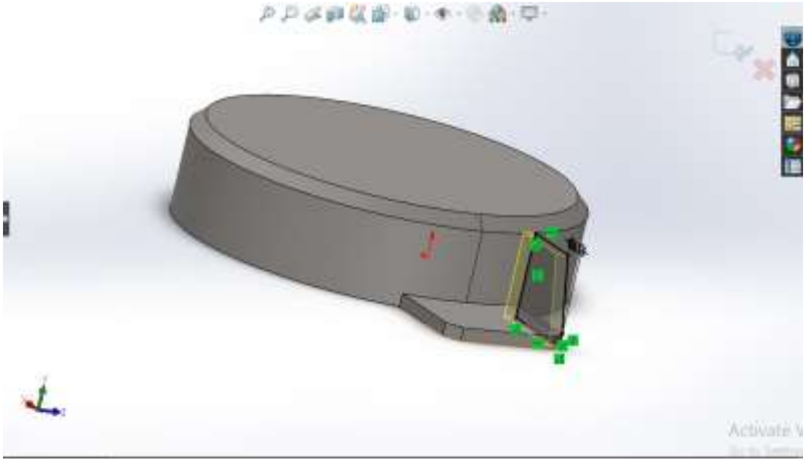
3.6.1.2 STEP 2

The next process that was carried out was the design of the side extension of the base of the crane that gives room to the base been bolted to the floor of where it would be mounted upon, the side extension is then extruded to a certain plane below the base in order to give the right design.



View of the extrusion casted below the top plane to the level below for the next design phase.

The subsequent phase in designing the vessel involved the side design and extension - an essential modification that occurred after the main hull structure was completed. This phase focused on refining the lateral profile of the vessel to ensure structural balance and an optimal hydrodynamic design.

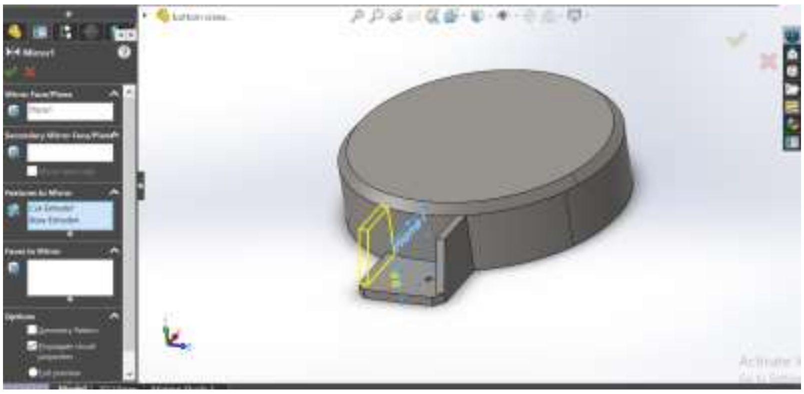


The side extension was added to enhance the vessel’s overall beam stability and aesthetic matching, particularly around the midsection where the curvature of the hull transitions into the deck plating. This design consideration provides for a more hydrodynamic body with less drag resistance and optimizes buoyancy distribution.

In this process, often with great precision, dimensional adjustments were made using Solid Works Extrude Boss/Base tool. The side attachment was extruded inward approximately 10 mm creating a reduced intervening ship side. This inward extrusion enabled several engineering benefits:

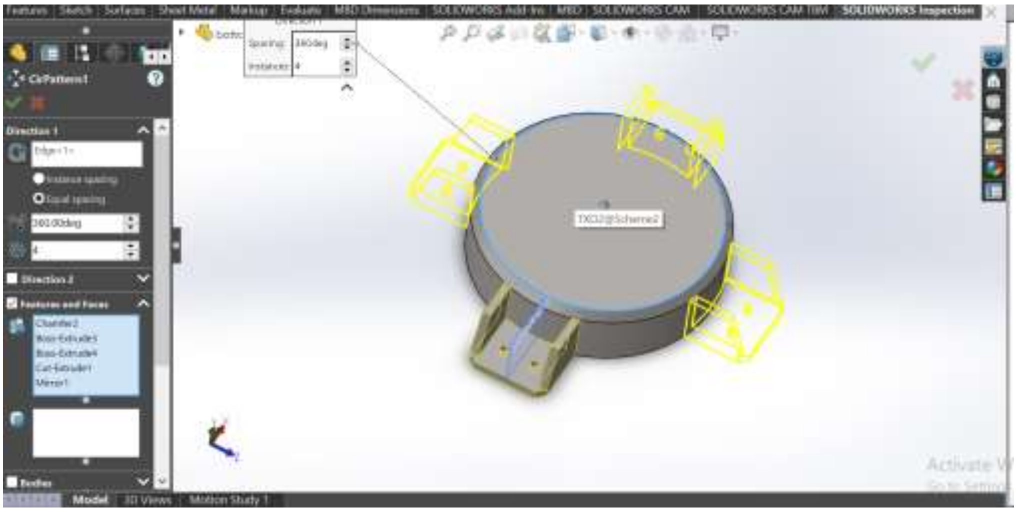
3.6.1.3 STEP 3

The next step in the design process was to mirror the side extension of the robotic arm to achieve structural symmetry and avoid duplicating modeling effort. Instead of creating the whole opposing side again manually which may result in dimension error puts a misalignment the Mirror Tool in SolidWorks was used to accurately and precisely mirror the design about a plane of reference.



To begin mirroring the side extension of the robotic arm, a Plane was created first using two reference points within the model. The reference points were selected from the centerline axis of the robotic arm assembly, likely at the base joint and the top linkage joint. By casting a wane through the two reference points, a perfect mirror plane was created in-line with the arm's centerline to ensure geometric accuracy during the geometric replication.

In this step we would work on using the tool called the circular pattern to replicate this one extension into different points in the base to have a more complete structure.

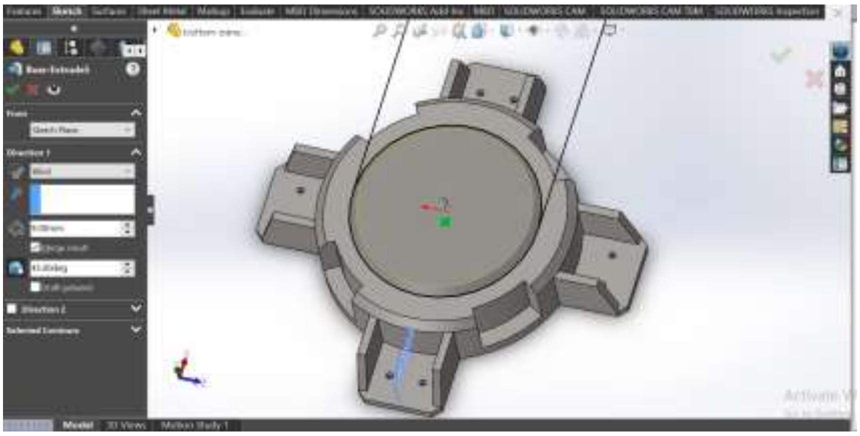


3.6.1.4 STEP 4

This operation was implemented to enrich the visual and functional detailing of the robotic arm by cutting various sections out of its side cut areas for mechanical fittings, material weight, and dynamic efficiency of the component. The side cut extrusion issue is one of the most important finishing touches in mechanical modeling as it possesses implications for both external visual styling, as well as the internal balance of the structures, that can become fixed with motions.

The depth of the cut, that has been measured and echoed in the data section below, was exactly taken from the thickness of the material, the loading-bearing bearings, and desired design intent of the arm. The cut has been extruded to the accurate depth thus created an exact indentation to fulfill the subsequent functions for the following objectives of determining engineering objectives.

Component Accommodation: The extrusion produced the necessary clearance for a sensor, servomotor and control cables to be placed and fitted within the arm's frame internally.

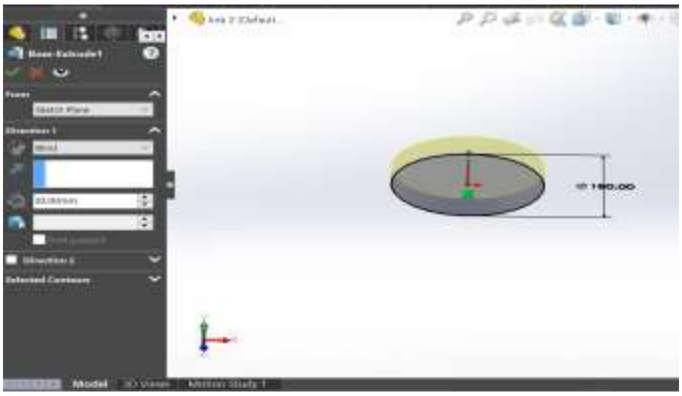


3.6.2 LINK 2.

3.6.2.1 STEP 1:

Starting the process we give the below pictured diameter to the next part we are going to create working from the Top plane sketch, after the diameter has been inputted we then boss extrude the circular surface of which we just drew in other to give it a particular depth.

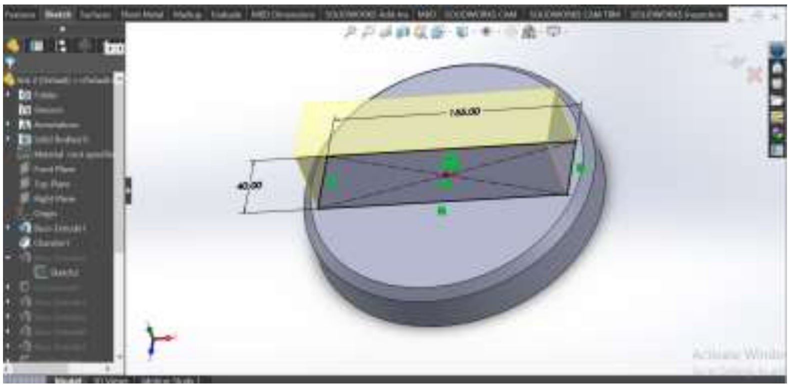
The depth and thickness was given 30mm to specify what is needed for the link 2 build which is then continued in the next process.



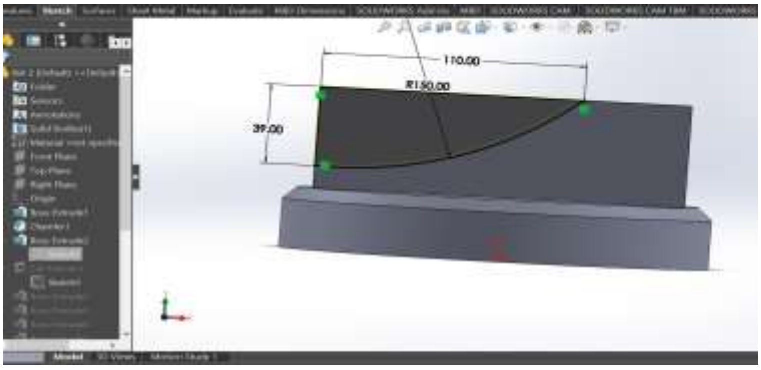
3.6.2.2 STEP 2

On the newly created surface we then take out the rectangular tool which is then placed on the surface and then with smart dimension it is then placed on the surface and then it is extruded to a certain thickness, with the length and bredth specified in the design of the rectangular top as seen in the picture above.

The extrusion is then placed to give the rectangular surface a certain depth of about 50mm which is the required depth needed.

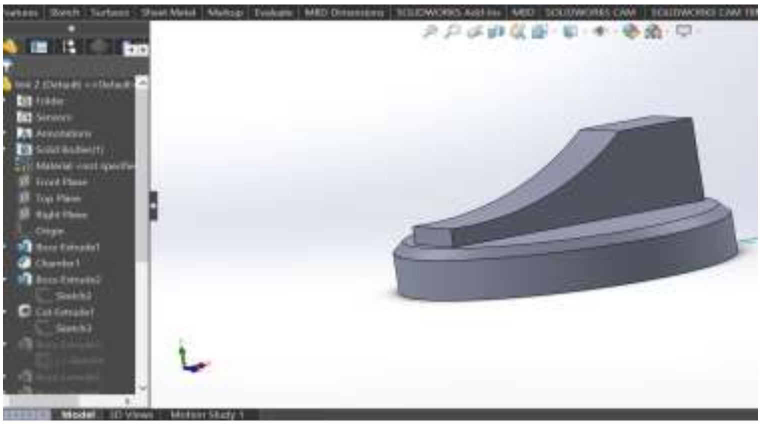


We then go forward to cut extrude a part of the rectangular surface which is a needed part of the design phase, in order to cut extrude the shape we need the shape has to be drawn on the surface of the design which is the part that would then be later extruded.



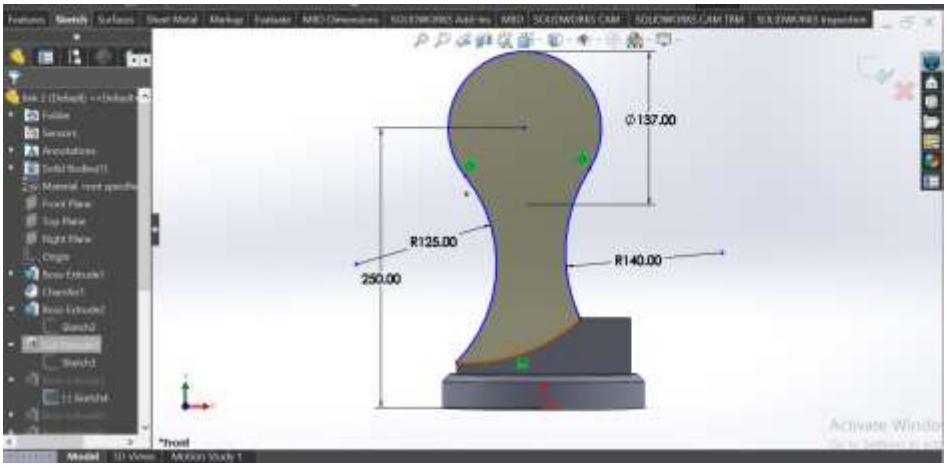
The three point arc tool is then pulled out and used to place the shape by the side of the rectangular surface which is then cut extruded out, the preview will be shown below.

This is the preview of the cut extrude option that was placed into the design of the rectangular block and this is the effect of the cut extrude we just did.



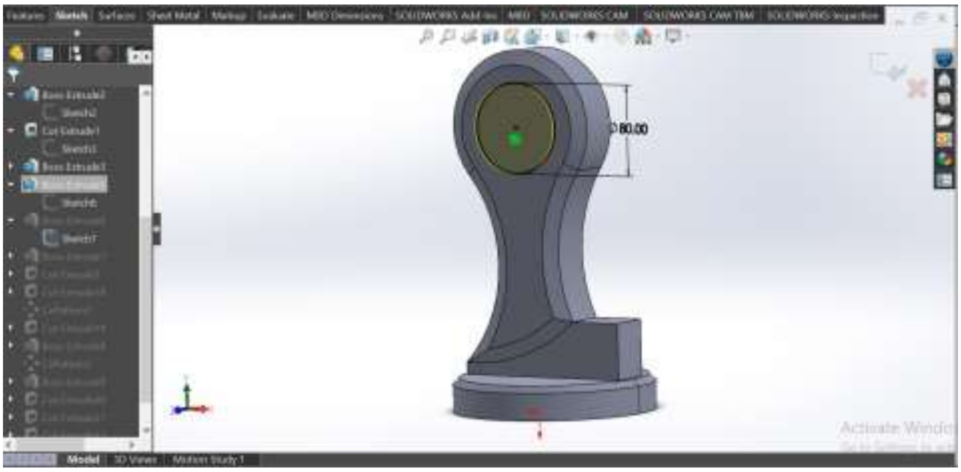
3.6.2.3 STEP 3

The next step is to show the design of the shape to be mounted on the part that was just cut extruded above, the shape was created using the circular tool as well as the three point arc that was part of the build, to give the required smoothness in connection the tangent tool was used, then the shape was then extruded to give it a certain thickness using the boss extrude.



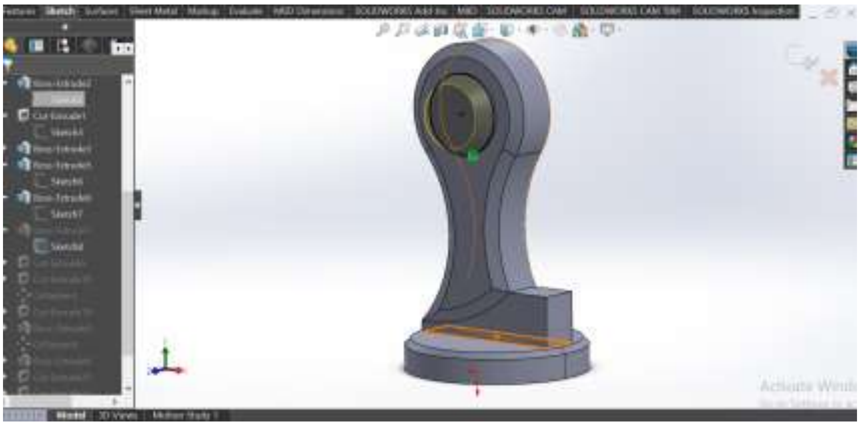
As seen the boss extrude was placed on the shape to give it a certain design flow.

On the new shape that was built a circular shape is casted on it which is then used to build a side screw design, the circle is given a certain diameter and an extruded surface.



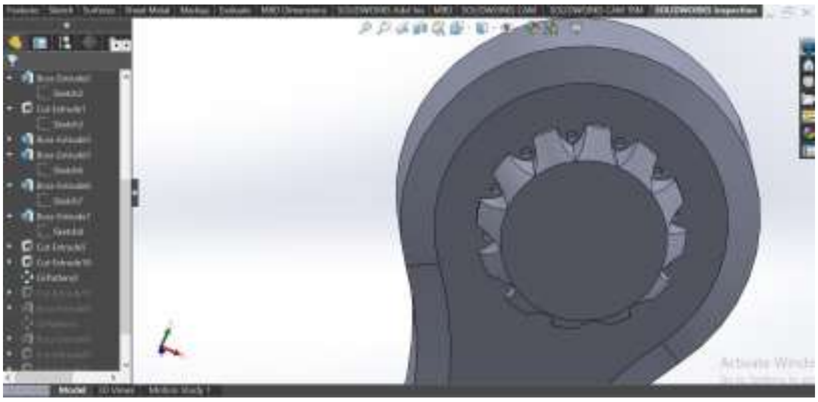
3.6.2.4 STEP 4

Let go into the design of the side screw from the circular surface that was built, the process is as follow, the circular surface was then offset to give out the second circle on top the first one, the new shape is then boss extruded to a certain angle of 25deg of about 25mm.



On the middle part of the above shape, we designed an extruded surface which was designed using the three point arc which was then mirrored to the other side of the construction line that is seen in the sketch.

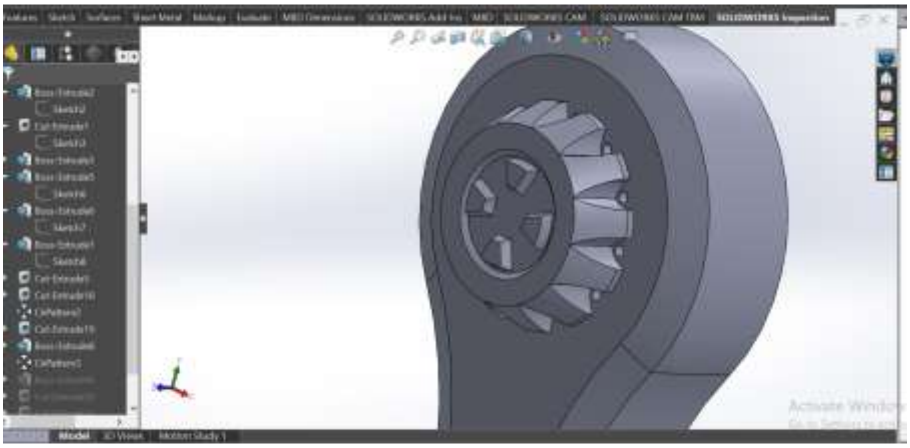
The above extrude is the patterned to the other part of the shape to avoid building every part which is a crucial part of design.



As we can see from the above picture the previous made sketch was then patterned to speed up the design process and still give design accuracy.

After that a circular shape is then placed in which is then cut extruded to about 3mm in depth after which the shape seen below is built on the circular surface.

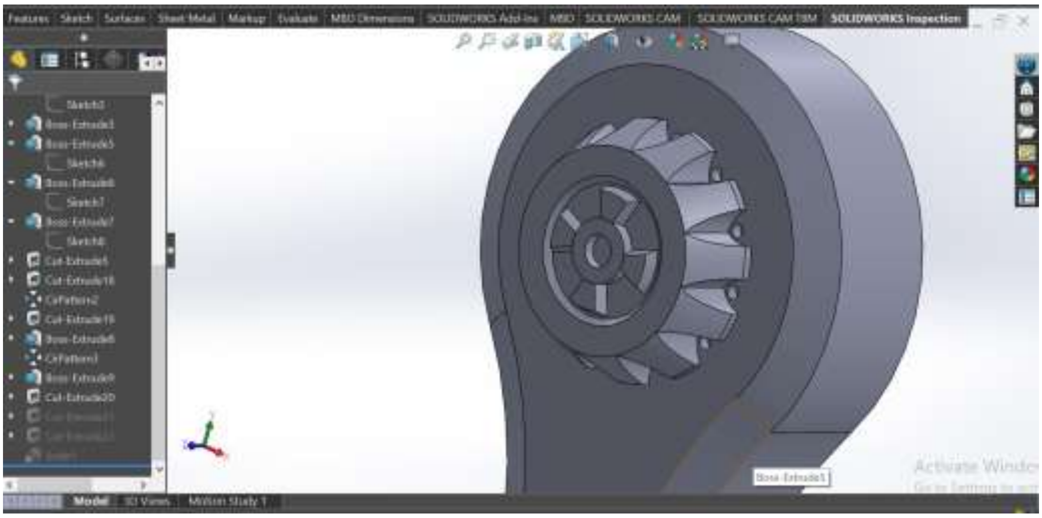
The shape is then circular patterned in order to give the same result but in a quicker neat design phase.



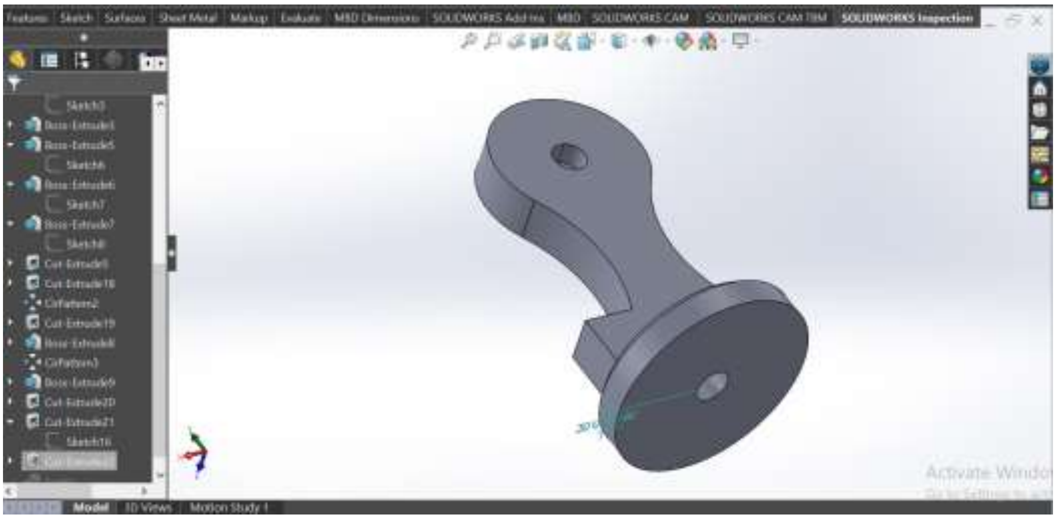
As seen above the shape was successfully patterned to the other parts of the above shape.

3.6.2.5 STEP 5

In the final phase of the construction of link 2, we then go forward in putting the beauty in the above shape that was made using the circular cut extrude tool.



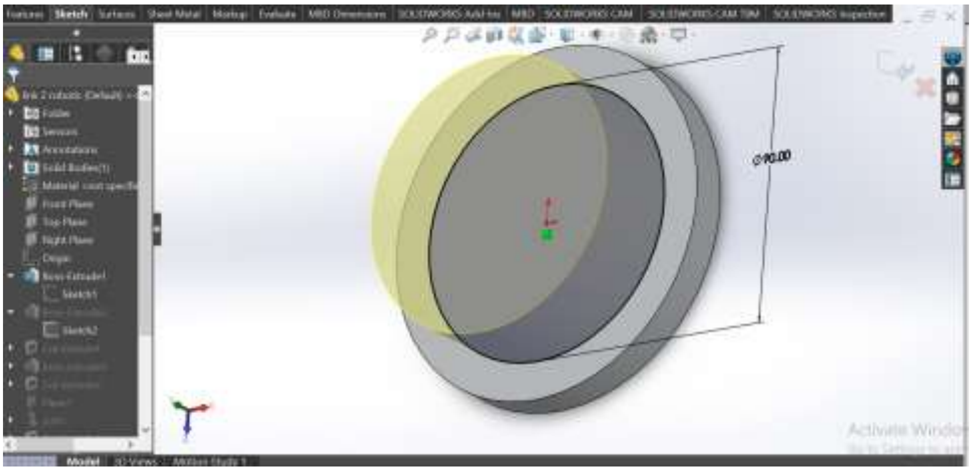
On the final note we then create the cut extruded hole below the link two will then be mated to the link one and link three as seen below.



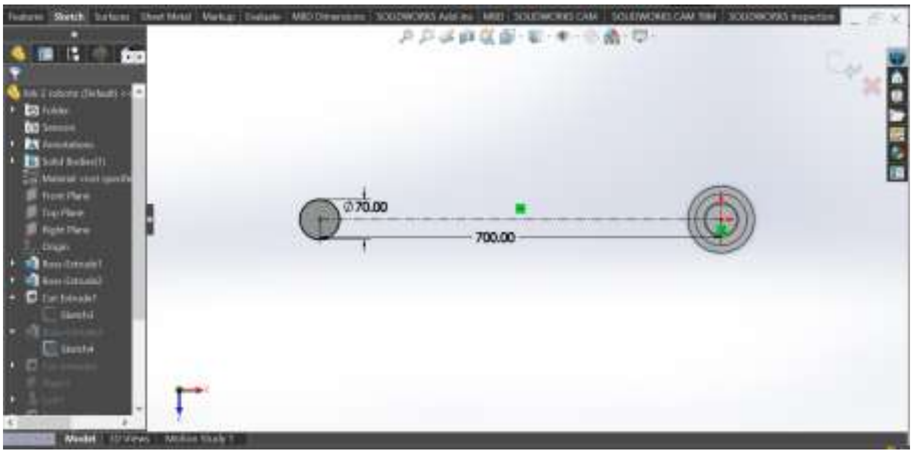
3.6.3 LINK 3

3.6.3.1 STEP 1

To start of the design of the link three we kick off using the circulal tool which is given a certain extruded pattern also a certain boss extruded shape, after the first design pattern we then sketch a second circular shape on the first which is later on then extruded to a certain depth.



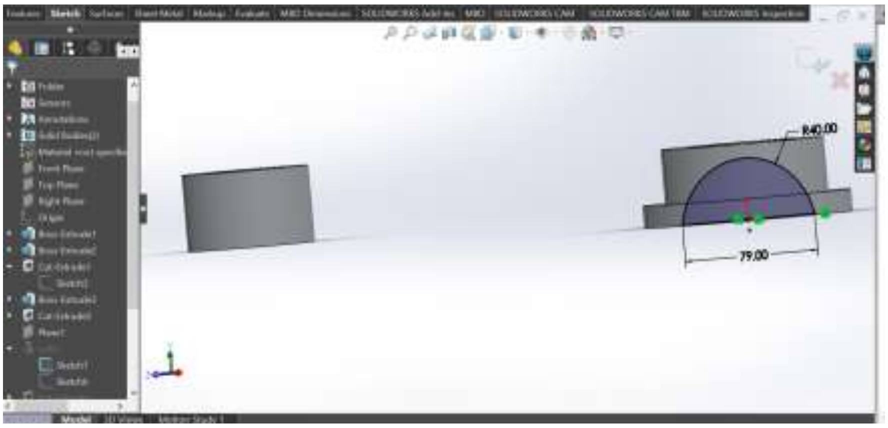
3.6.3.2 STEP 2.



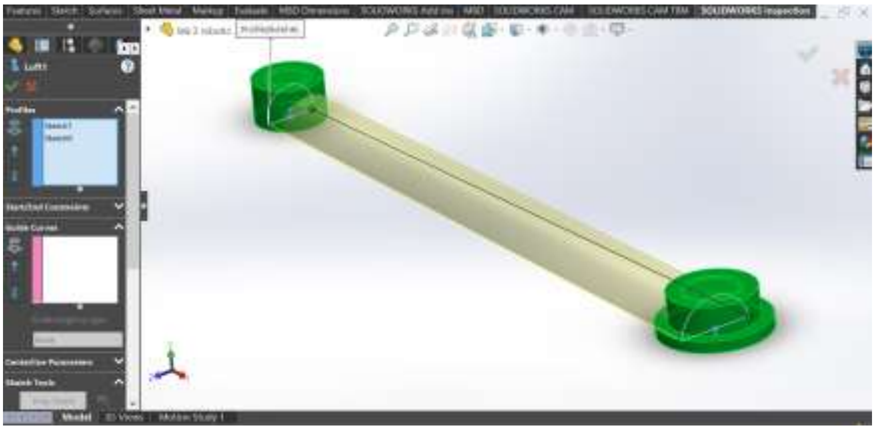
In the above sketch we used the centerline to give a certain distance as seen above, at the end of the line a circular shape was still sketched which was then extruded.

As seen above the circular shape at the end of the shape was extruded, after this a cut extrude was placed on top of the shape.

In the next process the two shapes which is separated by a certain distance is then lofted to give the connectivity needed which will be seen below, before the loft tool is used the desired shape to be lofted will first be sketched out .

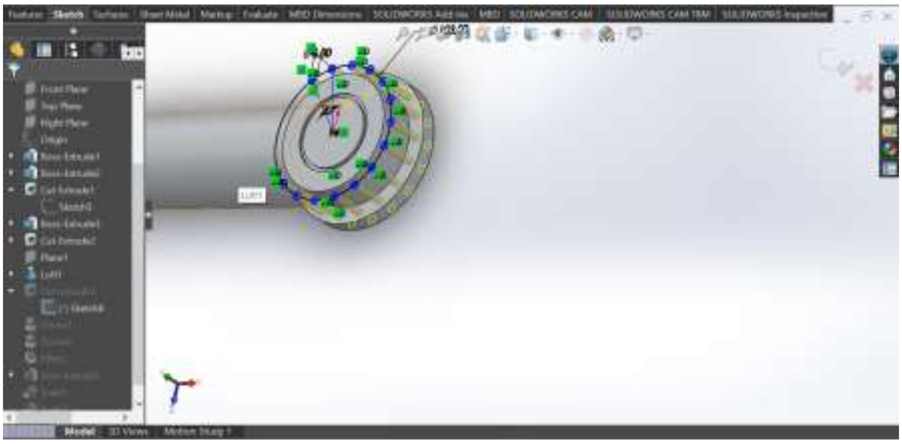


The desired shape which is a semi-circle, it is drawn on both surface to be connected to as would be seen in the preview mode, the shape has successfully been lofted between the two shapes that was drawn out.

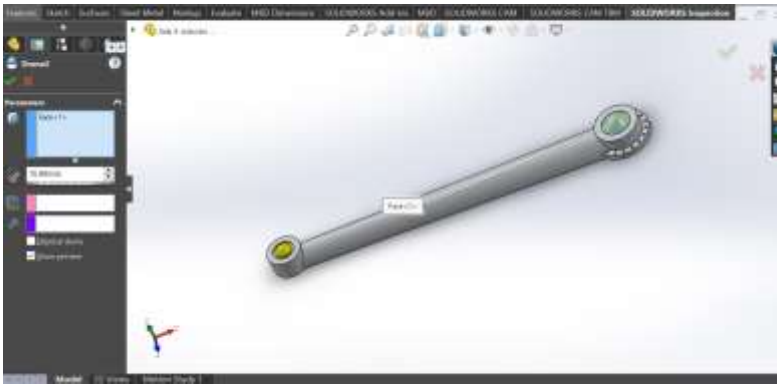


3.6.3.3 STEP 3

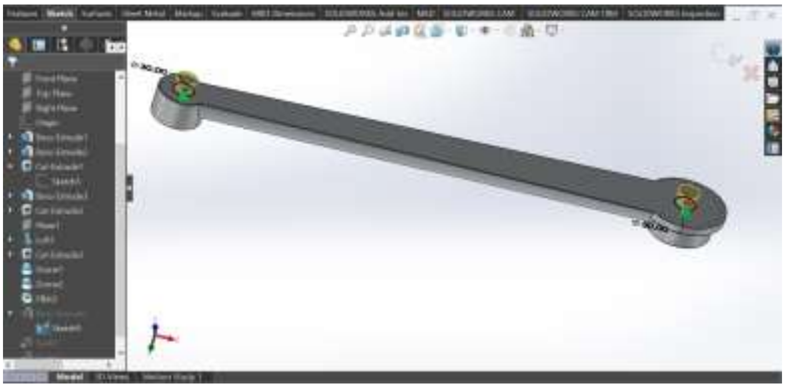
In the final step we look into creating a bolted surface on one of the circular sketch which is then cut extruded through.



As seen above the bolt shape is sketched and cut extruded through, the design was built in one part which is then later circular patterned around the shape, on the two surfaces a dome like shape is placed on it which give beauty to the design placement.



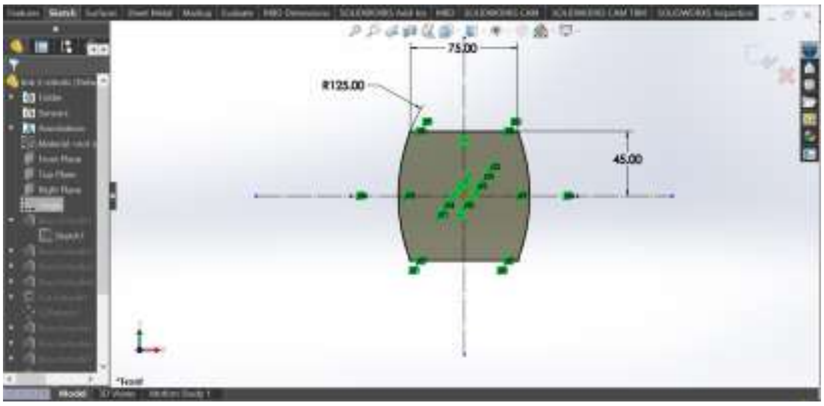
On this note the final sketch for link 3 is then designed where by the nut like shape is built on the surface of the circular pattern which will be used to link the shape to link 2 and link 4 as we go on in the deign process



3.6.4 Link 4:

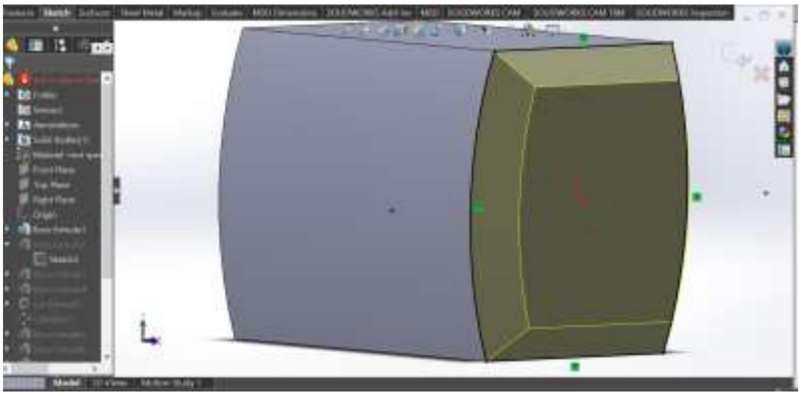
3.6.4.1 STEP 1.

The various processes below would bring the detailed sketch of how the link 4 was built for the robotic crane, the first sketch was built using the three point arc which was then linked using the line tool, after the top side has been sketched, the shape was then mirrored down to give the shape given now.



After the shape has been drawn we then boss extrude the given shape where by a certain thickness is then gotten from the sketch, as seen on the above picture the previous shape was boss extruded to give out a certain depth and size.

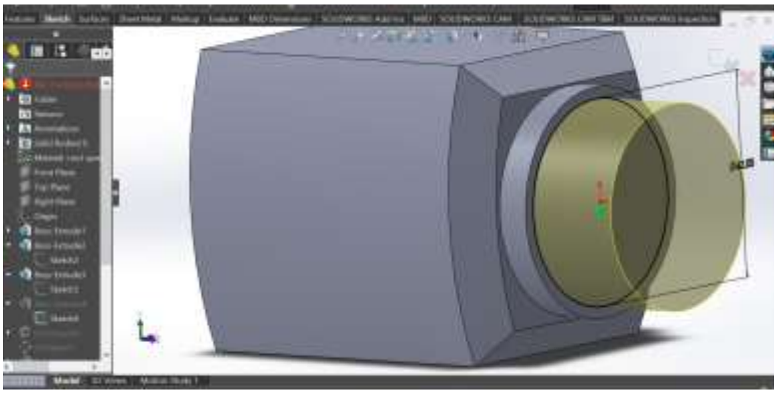
A secondary sketch is built on the current face which is then extruded to a certain angle as was detailed below.



After the process of the certain angle been extruded, a circular pattern is then boss extruded from the face of the sketch.

The sketch having its own diameter and extruded depth is the used as a base to sketch another surface extrude which is then with a different diameter and extruded size which defers for different roles.

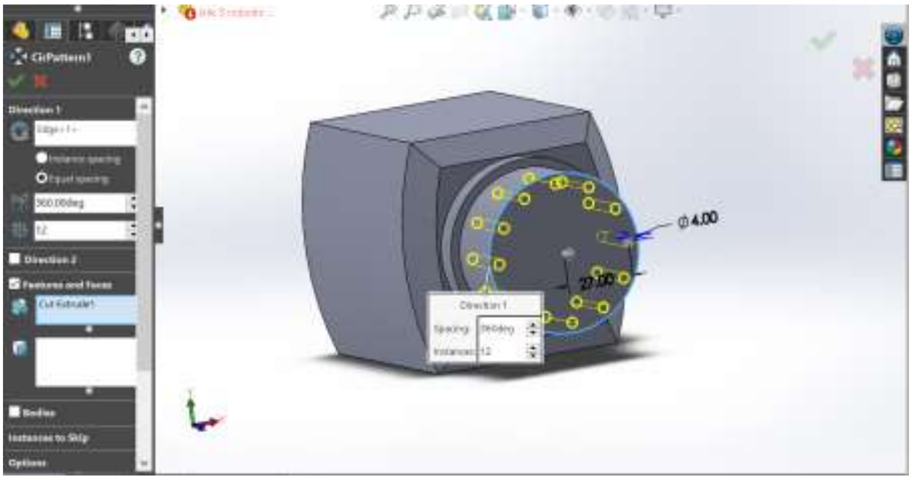
Below is the new circular sketch and the previous sketch, which is then boss extruded into place having the same reference point as the previous sketch.



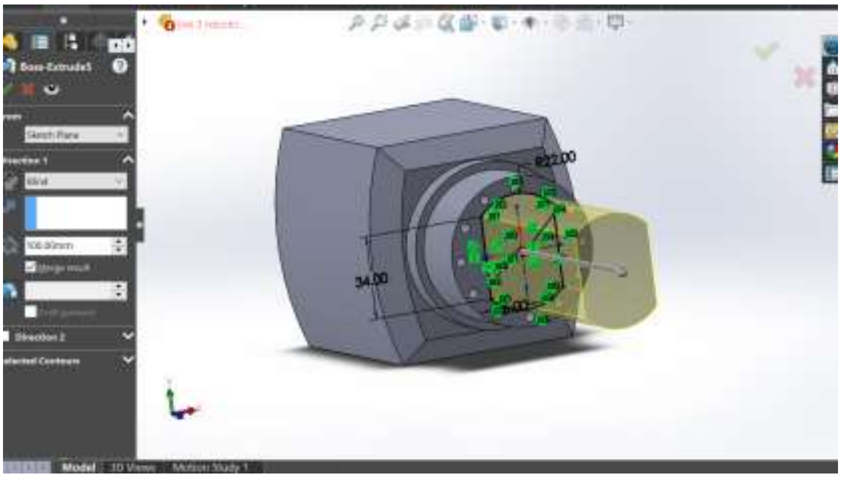
3.6.4.2 STEP 2

In the current phase of the arm design, we developed Link 4 To produce the geometry we intended, we utilized the circular pattern feature of SolidWorks. The first step was to perform an edge cut extrusion on the body of the link to create a dimensionally accurate opening on the surface. This cut was used as the base feature to pattern from.

To have a consistent, uniform and symmetrical component, the cut extrusion was then patterned around the central axis using the circular pattern feature. This allowed for spacing and alignment of each cut extrusion feature in systematic fashion, which increased the aesthetic balance and accuracy of the design. Additionally, the circular pattern feature reduces the amount of duplicate manual work, which also reduces the potential for design error while also providing an efficient modeling process.

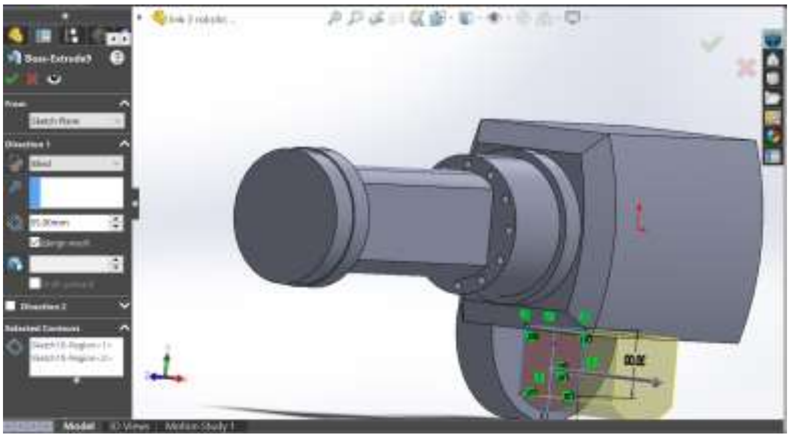


Using the boss extrusion tool to make an extrusion out of the surface in order to acquire the certain shape which is needed for completing the design.

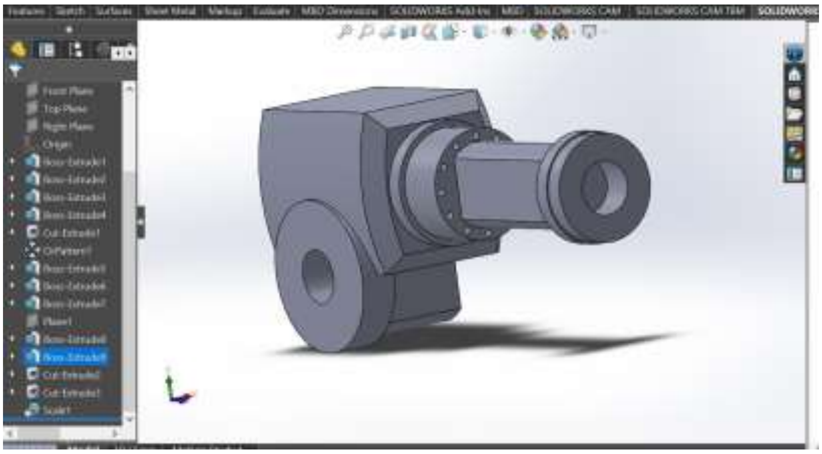


The next step was to utilize the boss-Extrusion Tool to create an added structural extension. Prior to the extrusion, a 2D sketch was created on the reference surface chosen. The sketch described the intended profile and dimensions of the section to be extruded.

Once the 2D profile was fully constrained and centered along the center axis, the Extruded Boss/Base feature was used to extrude the sketch outward from the reference surface. This extrude added thickness and volume to the link, converting the flat 2D sketch to a solid 3D feature. The extrusion added strength to the structure of the link, while also serving as a connection interface for the next pieces that make up the robotic arm.



The final view of the link 4 after the build has been completed.

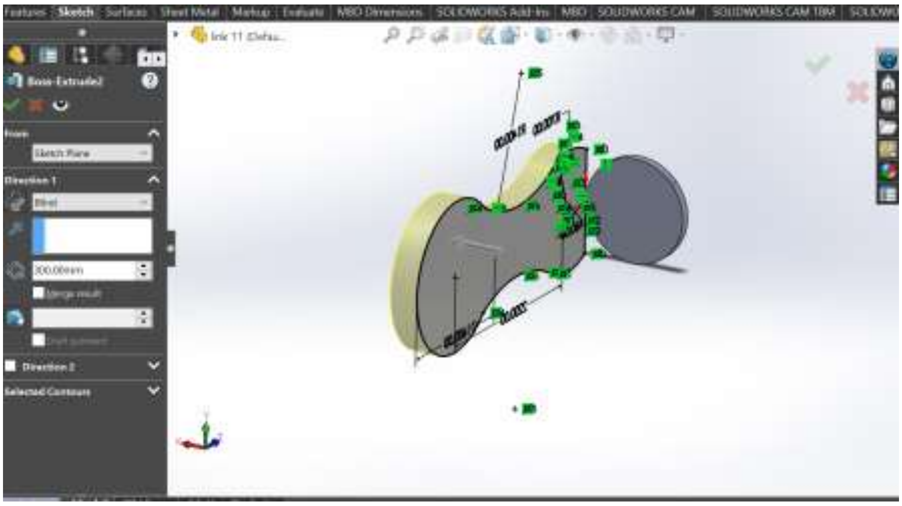


3.6.5 Link 5.

3.6.5.1 STEP 1

In the design of Link 5 of the robotic arm, the intention was to provide a more dynamic and functional design geometry. The Cellular Tool was employed to create a cellular pattern surface on the link, both aesthetically and structurally advantageous, as the distributed geometry also enhanced the strength-to-weight ratio of the link while keeping traditional geometries within the design.

After creating the cellular layout, a Boss extrude operation was performed to add an extruded surface to the patterned surface, which completed a tangible three-dimensional shape. The boss extrusion also ensured that the patterned cells were solidified to a designated height, yielding mechanical stiffness for consistent form.



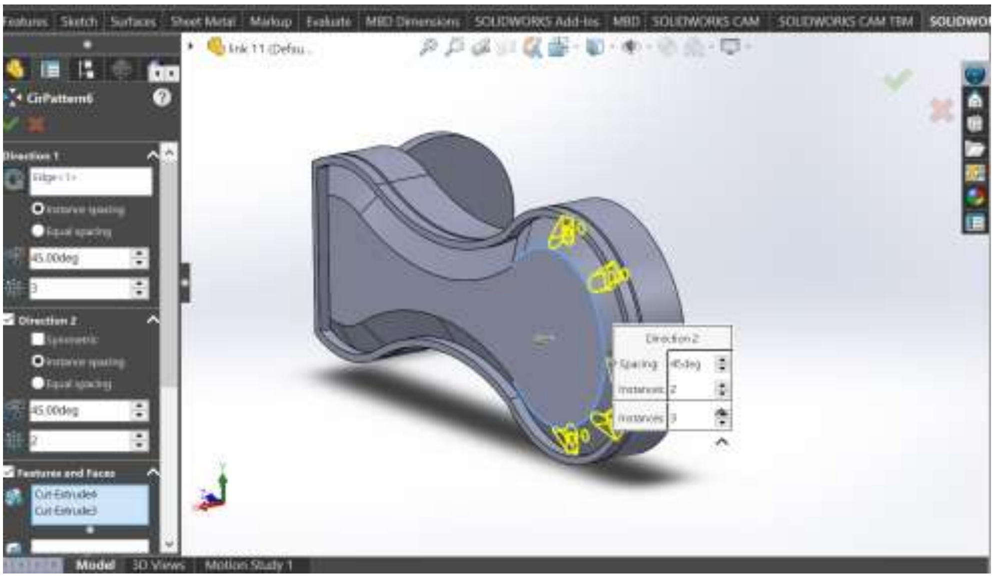
As an additional feature, along the lateral section of the link, a combination of the cellular tool and the Three-Point Arc were used to develop a custom curved geometry that transitions smoothly from the main link body geometry. This geometry was intended to be boss extruded, to reach the required thickness and curvature, creating an aesthetically pleasing extension to the link that compliments the overall kinematic design of the robotic arm.

The decision to employ a cellular geometry along with a custom curved geometry created additional mechanical stability and sophistication within the design.

3.6.5.2 STEP 2.

In the next stage of the Link 5 design, a unique geometric shape with given dimensions and parameters was introduced to serve a function in the component. To do this, a two-dimensional sketch was created first, where all constraints, angles, and reference lines were defined. Once the sketch was fully dimensioned, the Boss Extrusion Tool was then used to create a solid three-dimensional shape that projected outward from the reference surface to the desired thickness.

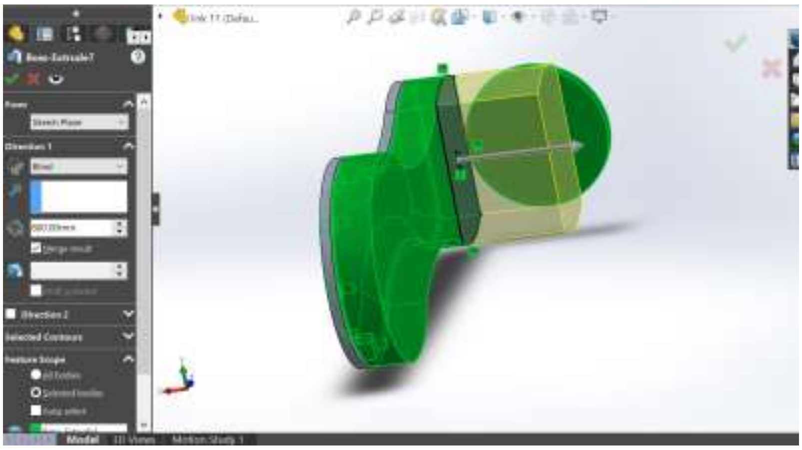
Next, a Cut Extrusion Pattern was created on the new surface. This cut, was intentionally implemented as notched or knurled spacings, which served as tightening or locking points for the bolt(s) or fastener to restrain it in place during assembly. The pattern was designed uniformly to allow consistent spacing at each point on the interface, optimizing the forces of grip both efficiently and reliably under motion or loads.



3.6.5.3 STEP 3.

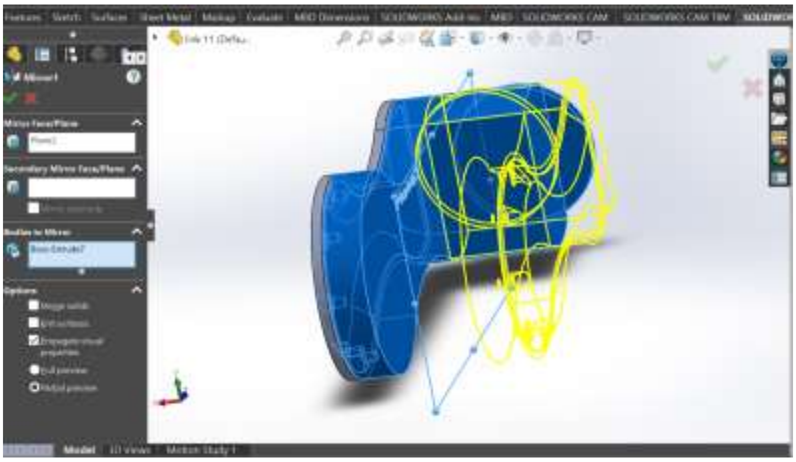
With the pattern cut section accomplished, the subsequent step was to create another surface feature on the upper portion of Link 5. To initiate the process, I developed a 2D sketch using a combination of the Three-Point Arc Tool and the Line Tool. I utilized the three-point arc to define the smooth curvature of the profile, while I closed the geometry with the line tool to define the shape boundaries, ensure the profile closed properly, and fully constrain the profile within the reference plane.

After properly dimensioning and orienting the sketch, I used the Boss Extrusion Tool to project the profile from the surface. This process converted the 2D sketch into a solid 3D feature that added thickness and a contour to the link. The extrusion depth was controlled to preserve proportionality with the established geometry and compatibility with the adjacent parts of the robotic arm.

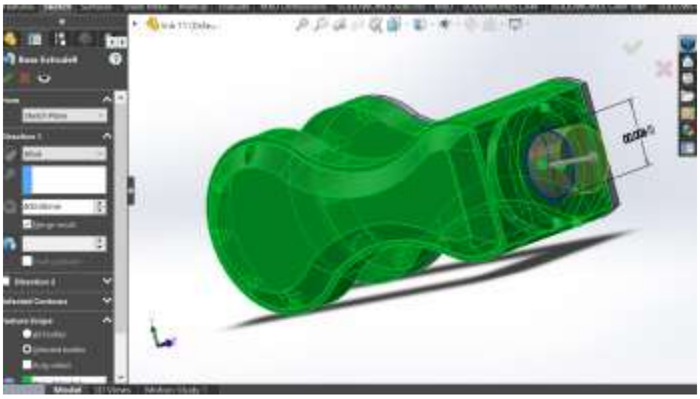


3.6.5.4 STEP 4.

The Mirror Tool was employed at this stage to guide the design procedure and produce geometrical symmetry. First, a midpoint reference plane was created to be the axis of symmetry for the object (the link). This reference plane was positioned accurately at the midpoint of the link's geometry so that all mirrored features would be created accurately on the opposite side of the model.



After the plane was defined, the previously modeled features like the extruded features, cut patterns, and curved profiles were mirrored onto the other side of the reference plane. The mirroring operation produced the entire feature set completely on the opposite side of the object. This created a symmetrical and uniform profile without the need to remodel each piece of the object individually.



The mirror feature reduced design time and minimized the possibility of dimensional discrepancies, producing a seamless connection across both sides of the model. The procedure ultimately concluded the configuration of the overall shape of the link, producing a symmetrical and mechanically stable profile within the robotic arm assembly.

3.6.6 Link 6.

3.6.6.1 STEP 1

During the development of the new link, the design phase started with a basic 2D sketch representing the overall shape and border of the part. The geometry was dimensioned and constrained to ensure it was aligned with the central reference axis. Once the shape was fully defined, it was extruded using the Boss Extrusion Tool, which transformed the flat sketch to a solid 3D model with the thickness needed.

Boss-Extrude1

From: Sketch Plane

Direction 1: Blind

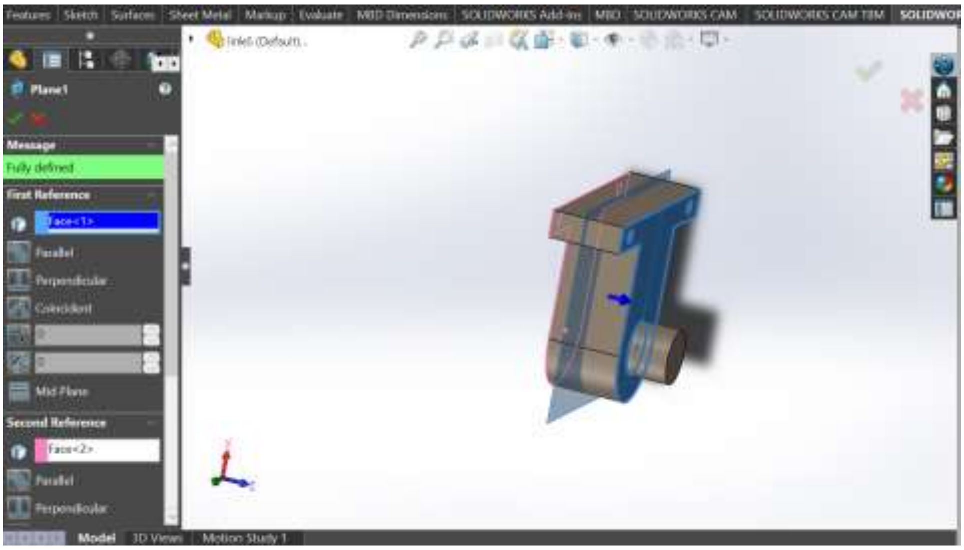
27.00mm

Once the first extrusion was complete, the next step was to add functional openings at both ends of the link, which was accomplished with the Cut Extrusion Tool. Two circular sketches were drawn, accurately positioned in opposite ends of the link to represent the joint holes, or pin connections, necessary to connect and assemble to the adjacent links. These circular holes were cut from the solid body to the depth necessary, maintaining uniform diameter and proper alignment along the central axis.

These holes were necessary for the mechanical connection and rotation between the links of the robotic arm. This step of the assembly established the joint interfaces, while also providing the link functional integration into the general kinematic chain of the robotic arm assembly.

3.6.6.2 STEP 2

The continuity of the link was preserved during the extruded round shape process to a uniform depth with uniform curvature. The extrusion at this stage was essential to more fully protect the overall dimensional balance and structural integrity of the link. By specifying the extrusion depth with precision, there was an improvement in the functionality and realism of the kinematic properties of the design geometry. Further, the Reference Geometry Tool was used to establish planes and axes that aided in correctly locating and symmetrically placing the part. The integrity of the reference geometry assured that, as subsequent features were added, such as holes, fillets or mirrored parts, that were dimensionally accurate and correctly aligned. The combination of extrusion and reference geometry improved not only the mechanical fidelity and visual aesthetics of the design but also, facilitated future modifications and assemblies, while maintaining design intent within the model.



Plane1

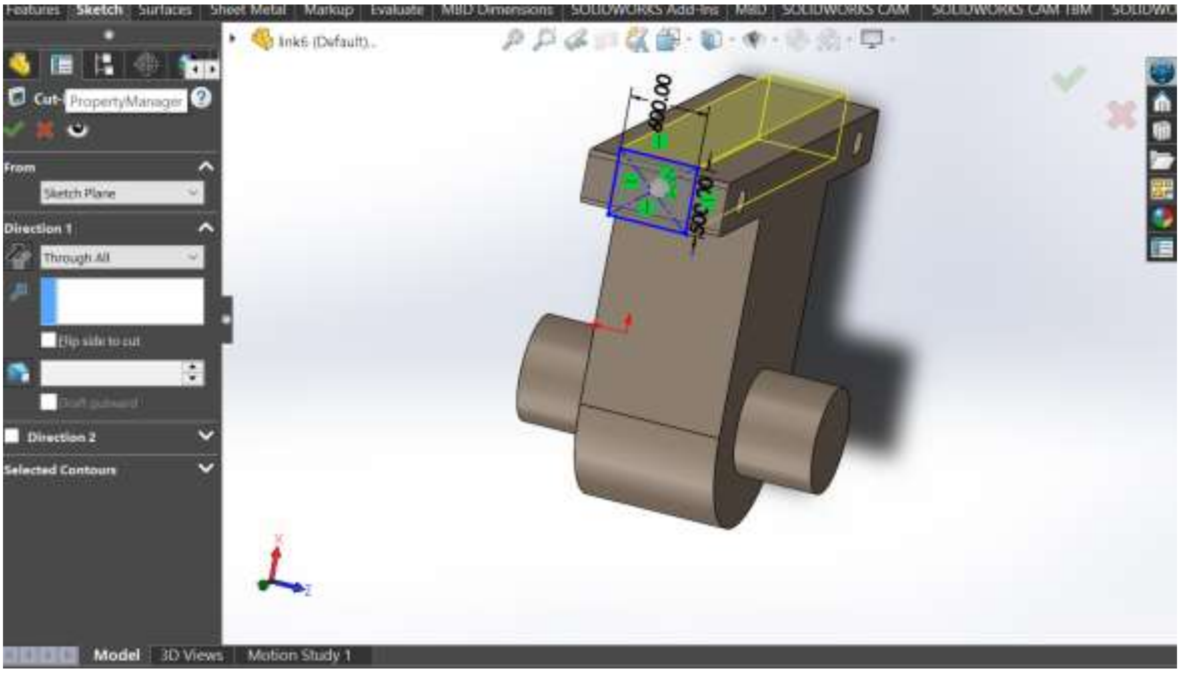
Message: Fully defined

First Reference: Face<1>

Second Reference: Face<2>

3.6.6.3 STEP 3.

The final view of the link where the extrusion tool is then used to cut through the desired shape.



From: Sketch Plane

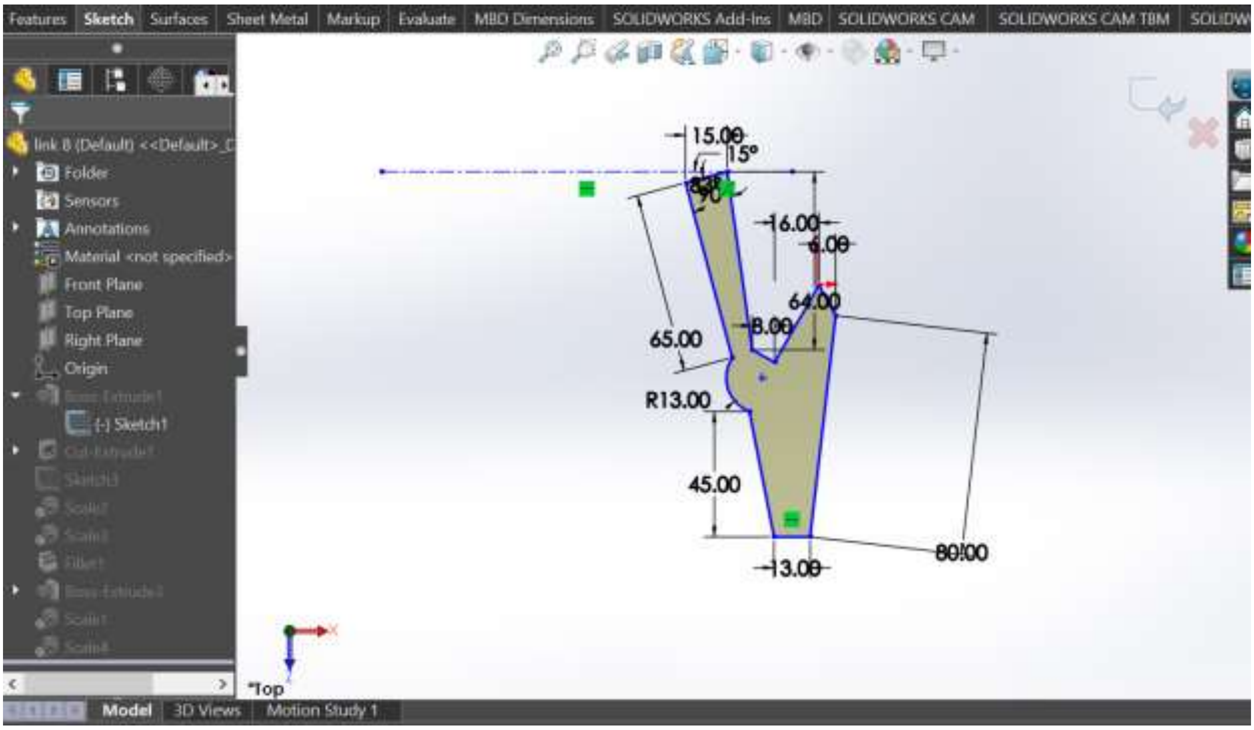
Direction 1: Through All

Direction 2

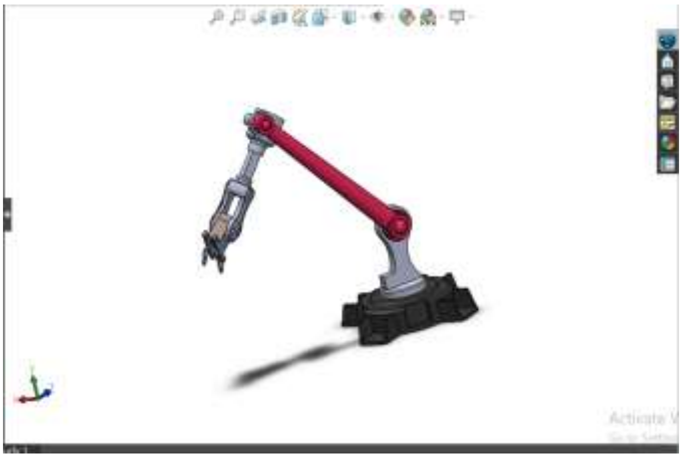
Selected Contours

3.6.7 Link 7.

3.6.7.1 STEP 1.



ASSEMBLED ROBOTIC ARM



3.7 MODE OF OPERATION

This project focuses on the design and simulation of a robotic arm system for automated cargo handling using CoppeliaSim simulation software. The system was developed to replicate an industrial pick-and-place process in a virtual environment, eliminating the need for physical hardware. The robotic arm operates through a combination of inverse kinematics, virtual sensors, and synchronized control of a conveyor system, all executed within the simulation platform.

The UR10 robotic arm, equipped with a Barrett hand gripper, serves as the primary manipulator in the system. It performs automated pick-and-place operations by identifying objects transported on a generic conveyor belt and moving them to a defined loading area. The arm's motion is governed by inverse kinematics, a control method that calculates the required joint angles automatically to move the end-effector to a specific position and orientation. This approach was selected because it is faster, easier, and more efficient for simulation control than forward kinematics, allowing the robotic arm to plan its motion precisely with minimal user input.

During operation, the conveyor belt continuously transports cubic objects (representing cargo) toward the robot's workspace. A virtual proximity sensor positioned at the pickup point detects the arrival of a cargo item and sends a signal to initiate the arm's movement. The UR10 arm, using inverse kinematic control, moves its end-effector (the Barrett hand) above the detected object. Once in position, the gripper closes around the object, securing it for transfer. The robotic arm then lifts the cargo, moves along a predefined trajectory, and places the object accurately on the loading area before returning to its initial standby position to await the next pickup cycle.

All motion, sensing, and control actions occur in real time within CoppeliaSim's physics-based environment, which simulates realistic interactions such as object collision, motion timing, and spatial positioning. The platform's built-in motion planning and inverse kinematics modules ensure smooth transitions between movements and precise end-effector placement, while maintaining stable operation throughout the process.

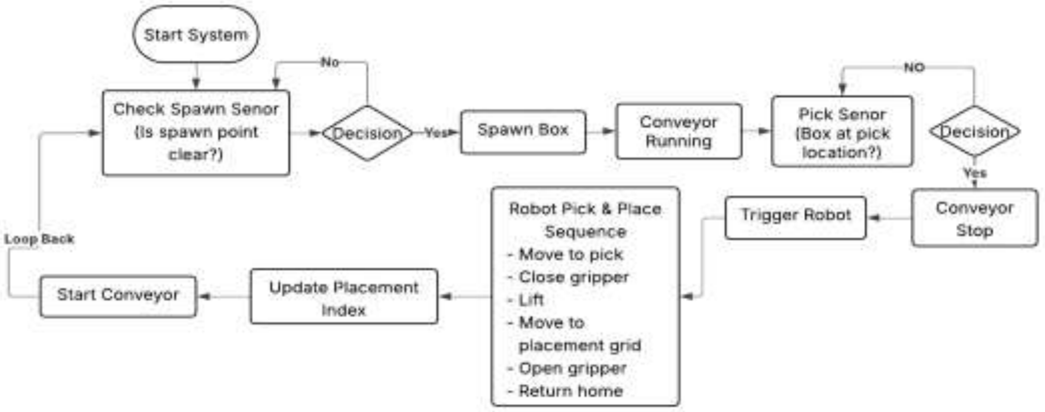


Figure 7 System flow and Architecture diagram

The simulation demonstrates how the robotic arm responds autonomously to sensor inputs, manipulates objects, and coordinates with the conveyor system to achieve continuous material handling. The use of inverse kinematics greatly reduces programming complexity, as the robot’s movements are defined by target coordinates rather than individual joint configurations. This feature is essential for achieving fast, accurate, and repeatable robotic control, particularly in virtual simulations of industrial systems.

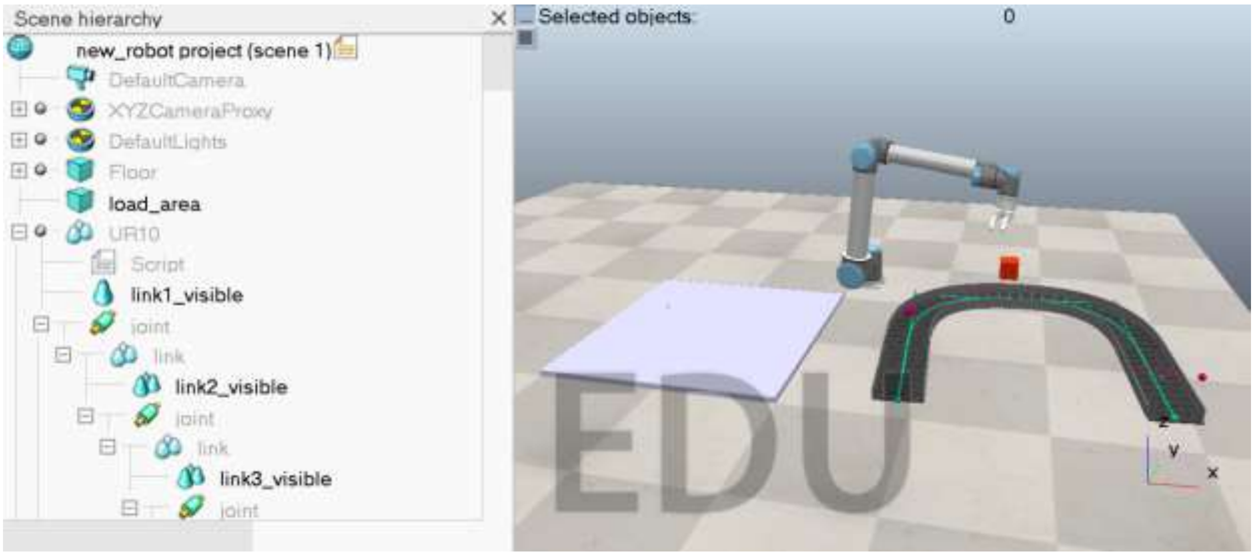


Figure 8 Complete CoppeliaSim simulation environment showing the UR10 robotic arm, Barrett hand gripper, generic conveyor belt, and load area for automated cargo handling.

3.8 MATERIALS USED

In this study, all materials were represented virtually within the CoppeliaSim simulation environment. Each component was modeled, configured, and assembled digitally to form the complete robotic arm system for automated cargo handling. The simulation utilized built-in object models and motion control modules within CoppeliaSim to replicate realistic robotic motion, grip interaction, and sensor-based automation.

All virtual components were assigned specific roles and parameters to ensure accurate simulation of pick-and-place operations between the robotic arm, gripper, and conveyor system. The major components modeled and their simulation functions are detailed as follows:

1. UR10 Robotic Arm (6 DOF)

The UR10 robotic arm served as the central manipulator of the system. It is a six-degree-of-freedom articulated robot widely used in industrial automation due to its precision, flexibility, and ease of control.

In the simulation, the UR10 model was configured to perform pick-and-place operations using inverse kinematics, enabling it to reach defined target points efficiently. Each joint of the robotic arm was controlled by simulated servo actuators, allowing smooth and realistic rotational motion. The model demonstrated accurate joint coordination and trajectory control throughout the operation.

Figure 9 : UR10 Robotic Arm Model in CoppeliaSim

2. Barrett Hand Gripper

The Barrett hand is a three-fingered robotic gripper that functions as the end-effector of the UR10 arm. It was used to pick, hold, and release objects on the conveyor during the simulation.

The gripper's adaptive design allowed it to conform to the shape of different objects, ensuring a secure grip and controlled release. Its virtual configuration in CoppeliaSim provided realistic grasping behavior synchronized with the arm's motion.

Figure 10 Barrett Hand Gripper Model in CoppeliaSim

3. Generic Conveyor Belt

The conveyor belt served as a transport mechanism for cargo items within the simulation workspace. It continuously moved objects toward the robotic arm's pickup zone. A proximity sensor positioned near the end of the belt detected each approaching object and signaled the arm to begin its motion sequence.

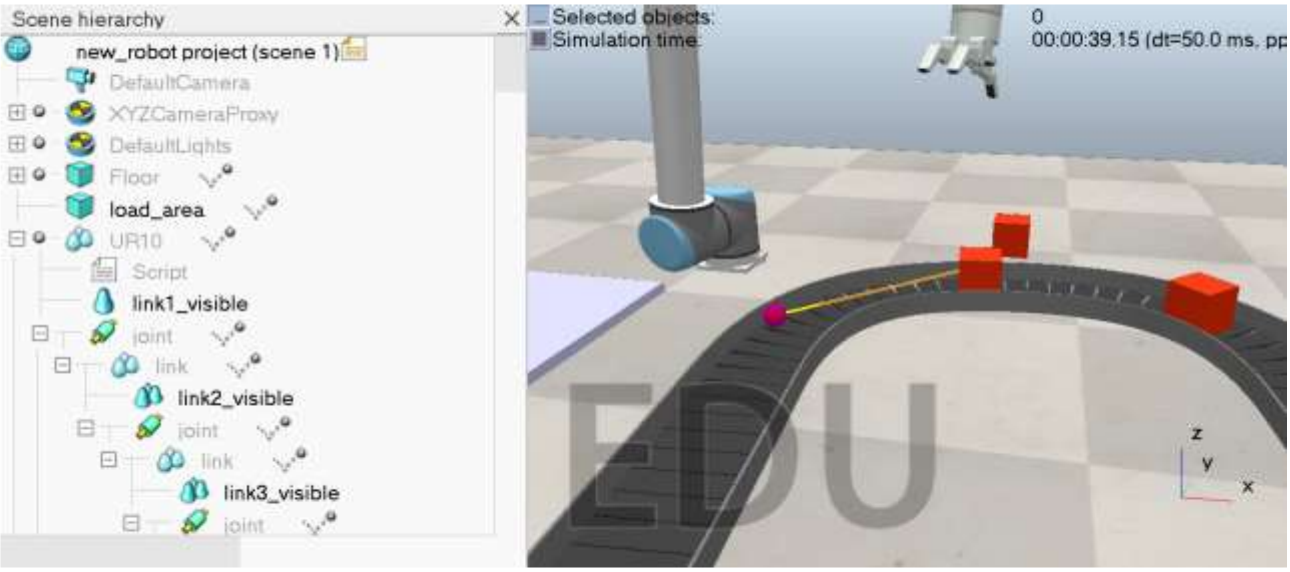
The conveyor's motion speed and timing were synchronized with the robotic arm and gripper to ensure smooth transfer of objects.

Figure 11 Conveyor Belt Assembly in CoppeliaSim

4. Virtual Sensors

Virtual proximity and vision sensors were integrated into the CoppeliaSim environment to enhance automation and feedback.

These sensors detected the presence of cargo, monitored the position of the robotic arm, and prevented collisions.
They played a key role in triggering automated events, such as object pickup, motion start, and gripper activation.



Selected objects: 0

Simulation time 00:00:39.15 (dt=50.0 ms, pp

Figure 12 Sensor Placement and Detection Zones in CoppeliaSim

5. Simulation Environment (CoppeliaSim Software)

CoppeliaSim served as the primary simulation tool for this project. It provided a physics-based 3D workspace for system modeling, animation, and control.

All motion behaviors including the arm trajectory, object handling, and sensor activation were controlled through CoppeliaSim's built-in inverse kinematics solver and dynamic simulation engine.

This allowed the system to perform realistic operations without external programming or physical hardware.

The UR10 robotic arm model served as the main manipulator and was configured with six rotary joints to replicate the motion of a real industrial robot. Its structure provided strength, precision, and flexibility for carrying out repetitive pick-and-place tasks. The Barrett hand gripper functioned as the end-effector, designed to grasp, hold, and release cargo objects with controlled accuracy. The generic conveyor belt acted as the transport system that delivered objects into the robot's workspace for handling. Virtual proximity sensors were integrated to detect object presence and prevent collision during operation. All components were mounted and synchronized within the CoppeliaSim simulation environment, which acted as the foundation and control platform for the entire system. The virtual setup ensured smooth operation, accurate coordination, and realistic representation of an automated cargo-handling process.

3.9 DATA AND ANALYSIS

The CoppeliaSim simulation environment was used to evaluate the performance of the robotic arm system under defined motion and control conditions. The simulation was designed to measure the efficiency, accuracy, and repeatability of a single pick-and-place cycle performed by the UR10 robotic arm equipped with a Barrett hand gripper. All input parameters and motion constraints were defined within CoppeliaSim to simulate a realistic operating environment. The analysis focused on the arm's trajectory, motion stability, and cycle time when performing automated cargo-handling operations.

3.9.1 Input Parameters

Parameter	Value	Description
Arm Type	UR10 (6 DOF)	Industrial robotic arm model
Gripper Type	Barrett Hand	Three-fingered adaptive gripper
Object Type	Cubic Cargo Block	Represents container payload
Operation Mode	Kinematic Mode	Focused on motion path accuracy
Control Method	Inverse Kinematics (IK)	Simplifies end-effector positioning
Conveyor Speed	0.1 m/s	Cargo delivery rate
Workspace Range	1.3 m × 1.3 m	Robot operating zone
Cycle Duration	~17 seconds	Average time for one full operation

Simulation-Results

The system was simulated for multiple pick-and-place cycles, each involving cargo objects of varying virtual mass (5 kg, 10 kg, and 15 kg). The motion data was extracted from the CoppeliaSim graph tool to analyze end-effector trajectory, cycle time, and motion stability.

1. End-Effector-Trajectory:

The gripper's 3D path was plotted from the recorded (X, Y, Z) position data during a complete pick-and-place cycle. Start Point (Green) represents the home position, Travel Path (Blue Line) indicates a smooth, stable path from pickup to drop location, and End Point (Red) marks the final position. The trajectory confirmed smooth, collision-free motion, demonstrating accurate path planning and effective use of inverse kinematics for target positioning.

2. Kinematic Consistency (Cycle Time vs. Load):
The total cycle time remained approximately 17 seconds across different cargo weights. This indicates that the control logic and motion path were stable and consistent, unaffected by changes in load. Using kinematic control mode ensured motion uniformity and eliminated irregularities caused by external dynamic forces.

3.3.3 Performance Evaluation

The simulation outcomes validated the efficiency of the robotic arm's motion design and control setup. Key observations include:

1. Stable Operation: The arm maintained balance and smooth transitions across all motions.
2. Accurate Pick-and-Place: The gripper consistently achieved precise positioning with minimal error.
3. Repeatability: The motion sequence remained identical in each cycle, confirming a reliable kinematic configuration.
4. Control Efficiency: The inverse kinematics solver minimized computation time while achieving accurate target alignment.

The data and analysis confirm that the simulation achieved stable, efficient, and repeatable motion performance. The consistent cycle time across varying object masses proves that the robotic arm's kinematic control is robust, efficient, and optimized for continuous industrial operations. This validates simulation-based testing as a reliable approach before physical implementation.

3.10 CALCULATIONS

This section presents the basic analytical estimations used to define parameters for the robotic arm simulation in CoppeliaSim. Since the simulation is based on kinematic control, the calculations focused on defining joint angles, motion paths, and cycle time for the pick-and-place operation. These estimations were essential for ensuring that the simulation maintained realistic motion and timing behavior.

3.10.1 Kinematic Calculation

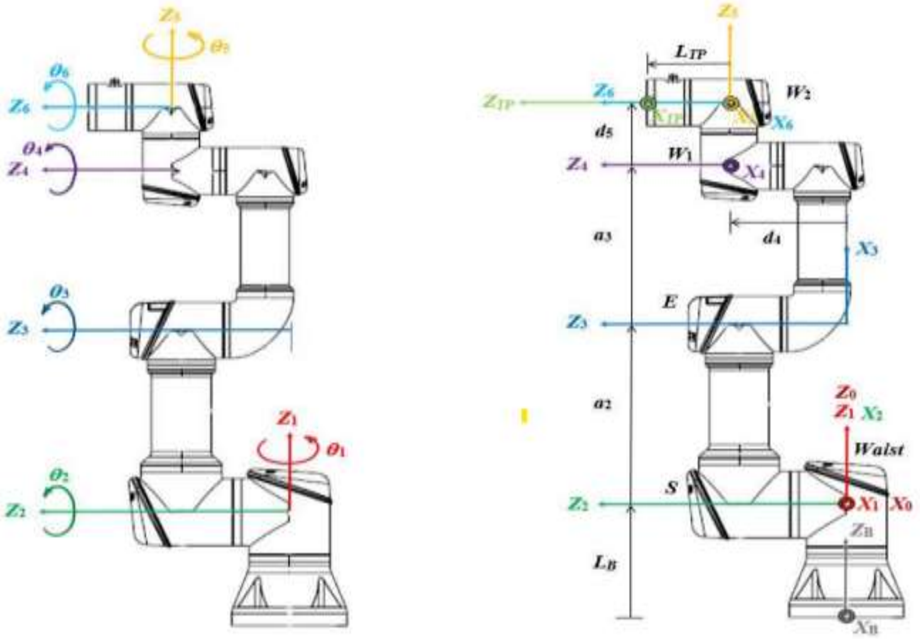


Figure 13 Kinematic Model

The position of the robotic arm's end-effector is determined using inverse kinematics (IK). The general form of the kinematic relationship is expressed as:

$T = f(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6)$

Where:

- T = Transformation matrix defining end-effector position and orientation.
- $\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6$ = Joint angles of the UR10 robotic arm.

For a target point (x, y, z) in 3D space, the inverse kinematics solver computes the corresponding joint angles that enable the arm's end-effector to reach that position accurately. This method allowed the robotic arm to move smoothly between the pickup point and the drop-off location during the simulation.

3.10.2 Cycle Time and Motion Analysis

The robotic arm's performance was analyzed by observing its motion parameters during simulation. The main parameters considered include distance, velocity, and cycle time for each pick-and-place operation.

Parameter	Symbol	Value	Unit
Pick-and-place distance	D	1.2	m
Average end-effector speed	v	0.07	m/s
Total cycle time	t	17	s

The relationship between distance, speed, and time is expressed as:
$t = D / v = 1.2 / 0.07 \approx 17.1$ s

This confirms that the simulated motion parameters are consistent with the observed behavior of the robotic arm system.

3.10.3 Control Efficiency

The inverse kinematics algorithm ensured fast and accurate motion computation. The total computation time per motion cycle was less than 0.5 seconds, demonstrating that the system's control logic is well optimized for real-time motion planning. This confirms that the robotic arm can efficiently execute repeated automated tasks with minimal delay and high precision.

3.11 SELECTION OF MATERIALS

The selection of materials was based on their mechanical strength, durability, lightweight properties, and suitability for robotic motion applications. The chosen materials also represent those commonly used in industrial robotic systems for precision, rigidity, and corrosion resistance.

Component	Material (Simulated Equivalent)	Reason for Selection
UR10 Robotic Arm	Aluminum Alloy	Lightweight, corrosion-resistant, and strong enough for industrial automation applications.
Barrett Hand Gripper	Reinforced Polymer with Aluminum Joints	Provides flexibility, low weight, and high precision for gripping operations.
Conveyor Belt	Polyurethane with Steel Rollers	Offers smooth surface contact, wear resistance, and stable motion during object transport.
Sensor Components	ABS Plastic	Lightweight and durable for simulated object detection and environmental feedback.
Base Platform	Structural Steel (Simulated)	Ensures rigidity, balance, and firm support for the robotic arm assembly.
Fastening and Support Links	Stainless Steel	Maintains structural stability and minimizes deformation during repetitive motion.

3.12 OPERATIONAL FLOW CHART

The operational flow of the robotic arm simulation illustrates the logical sequence of events that govern the automated cargo-handling process within the CoppeliaSim environment. Each operation step is executed automatically through programmed triggers, sensor inputs, and inverse kinematic motion control. The sequence begins with object detection on the conveyor and ends with the successful placement of the object at the designated location.

The flow of operation follows the process described below:

1. Simulation Initialization:

   The simulation environment is launched in CoppeliaSim, and all components (UR10 robotic arm, Barrett hand gripper, conveyor, and sensors) are loaded and initialized.

2. System Activation:

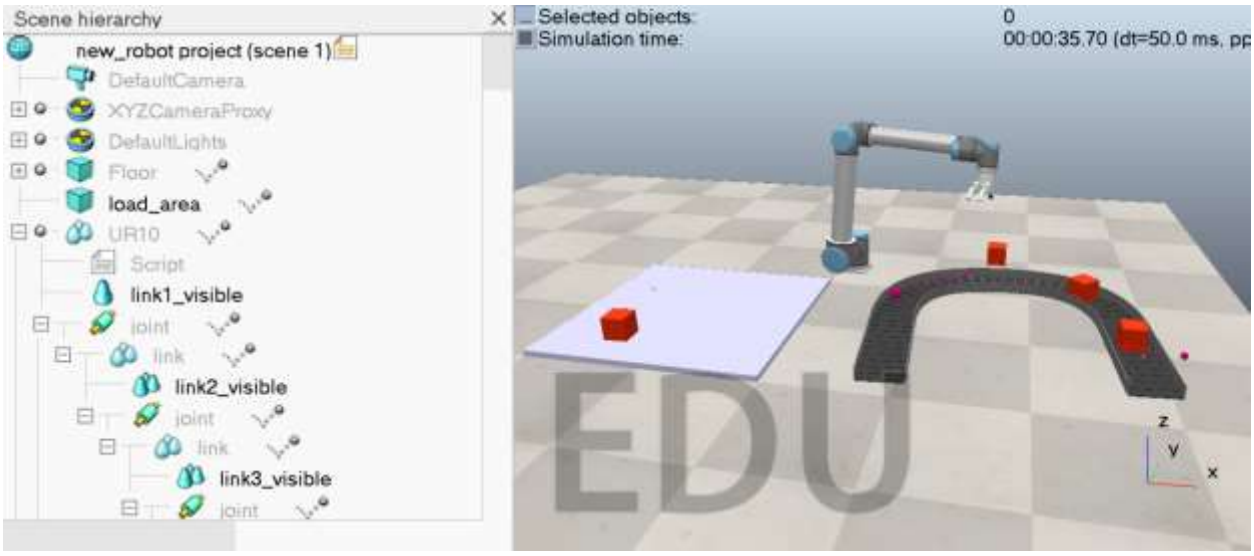
   The conveyor belt begins moving, carrying cargo objects toward the robot's workspace.

3. Object Detection:

   A virtual proximity sensor positioned at the pickup area detects an approaching object on the conveyor.

4. Motion Trigger:

   The detection signal activates the robotic arm's control logic, initiating the pick-and-place cycle.



Selected objects: 0
Simulation time: 00:00:35.70 (dt=50.0 ms, pp

Figure 14 Initial Motion Trigger

5. Inverse Kinematics Calculation:

The CoppeliaSim inverse kinematics solver calculates the required joint angles for the UR10 arm to move the gripper precisely to the object's coordinates.

6. Grasping Operation:

The Barrett hand gripper closes to grasp the detected cargo object securely.

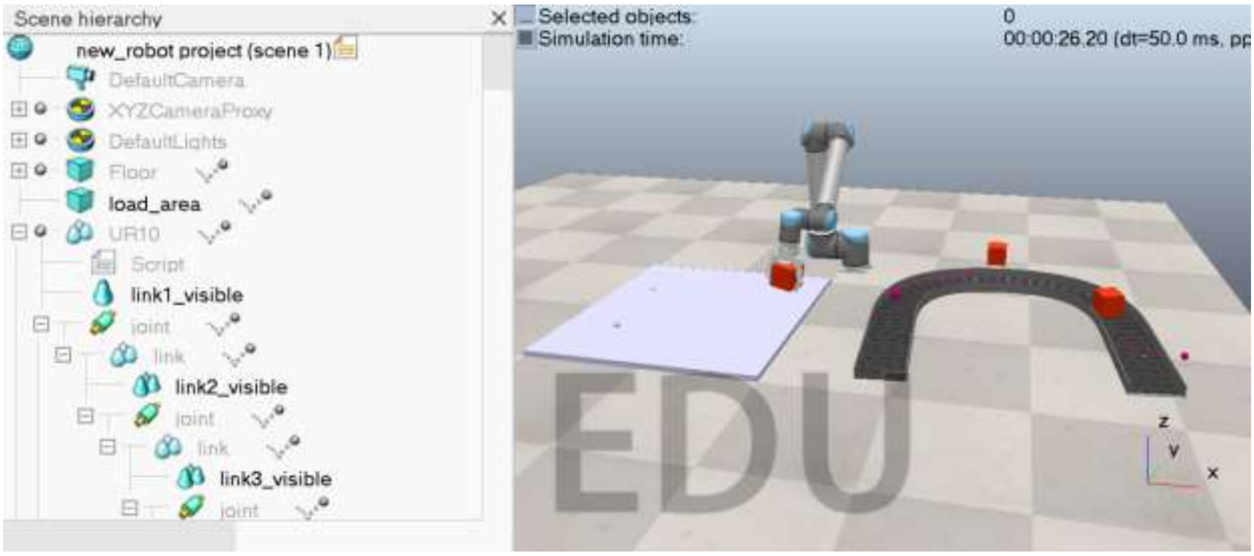


Figure 15 Grasping Operation

7. .Lifting and Transfer Motion:

The robotic arm lifts the object vertically, then moves along a smooth trajectory toward the predefined drop-off point.

8. Cargo Placement:

Upon reaching the target area, the gripper opens to release the cargo at the designated position.

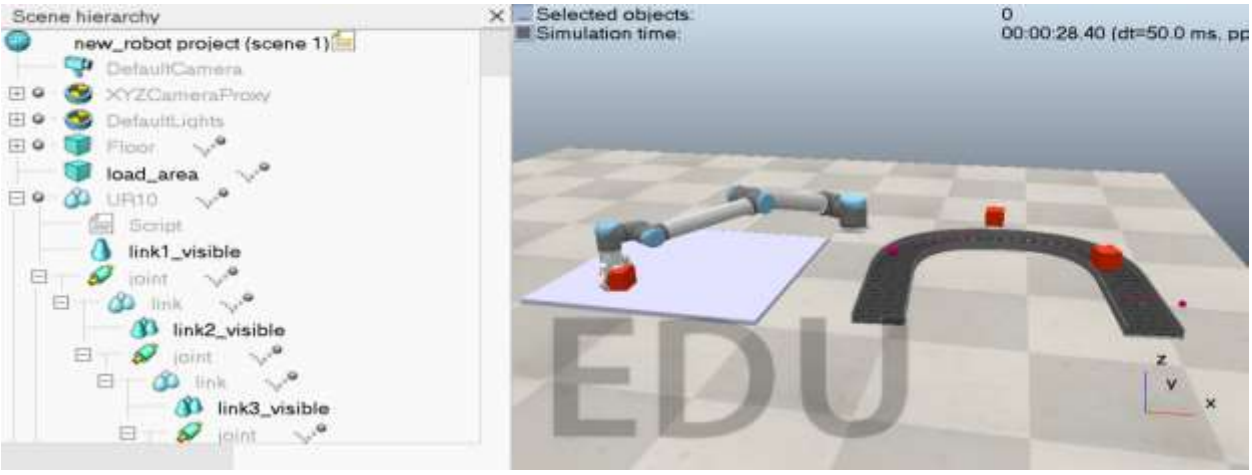


Figure 16 Cargo Placement

9. Return to Initial Position:

The robotic arm returns to its home position, preparing for the next pickup sequence.

10. Cycle Repeat:

The process repeats automatically for each new object detected on the conveyor belt until the simulation is terminated.

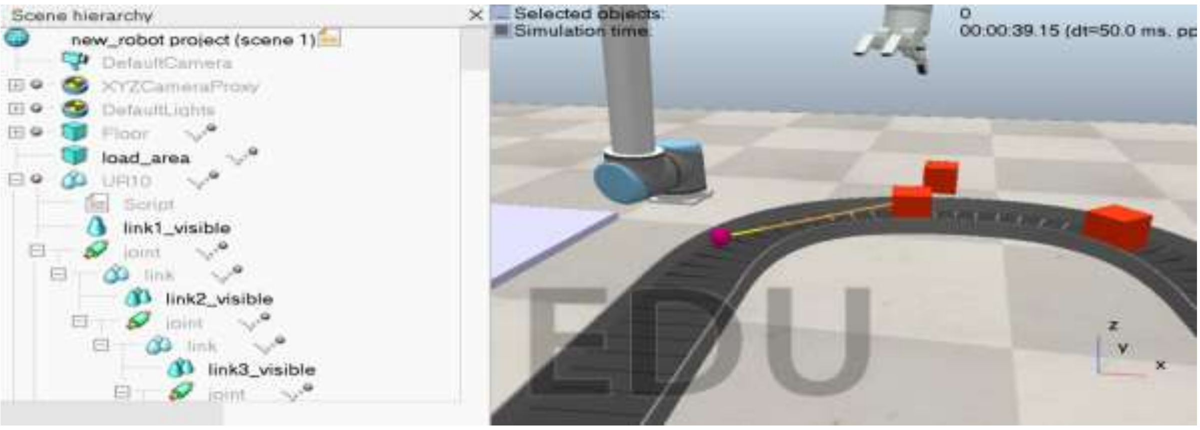
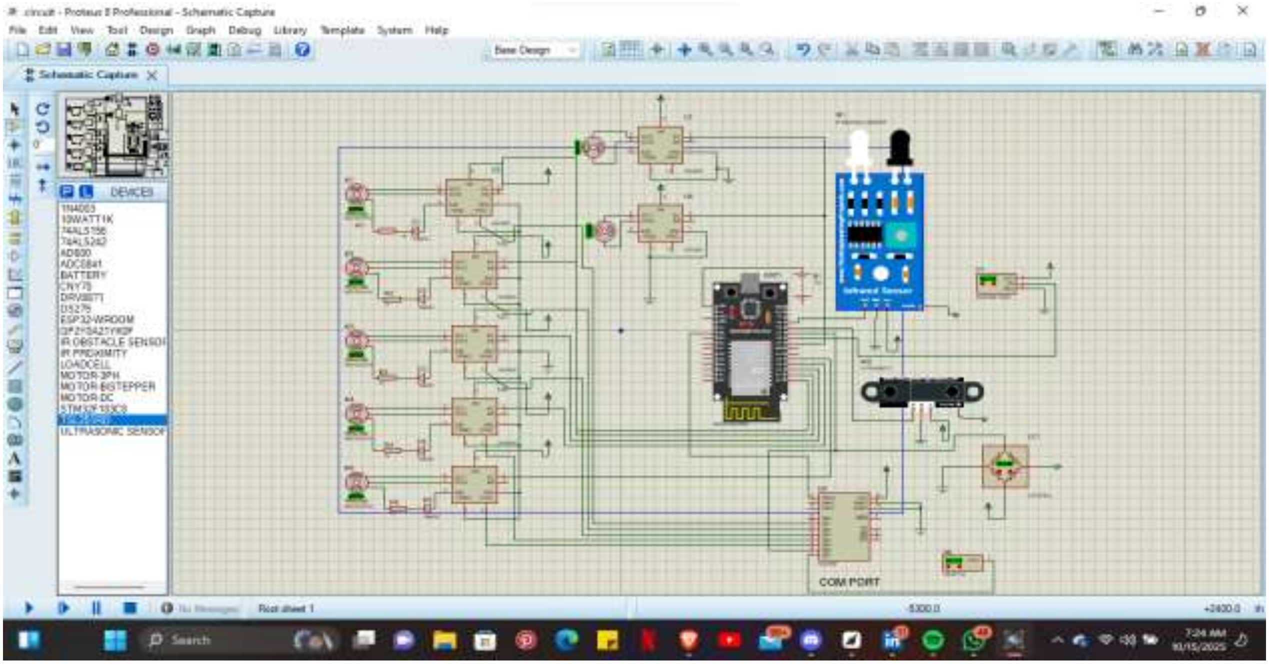


Figure 17 Repetition Of Cycle

3.13 Control System Design (Proteus)



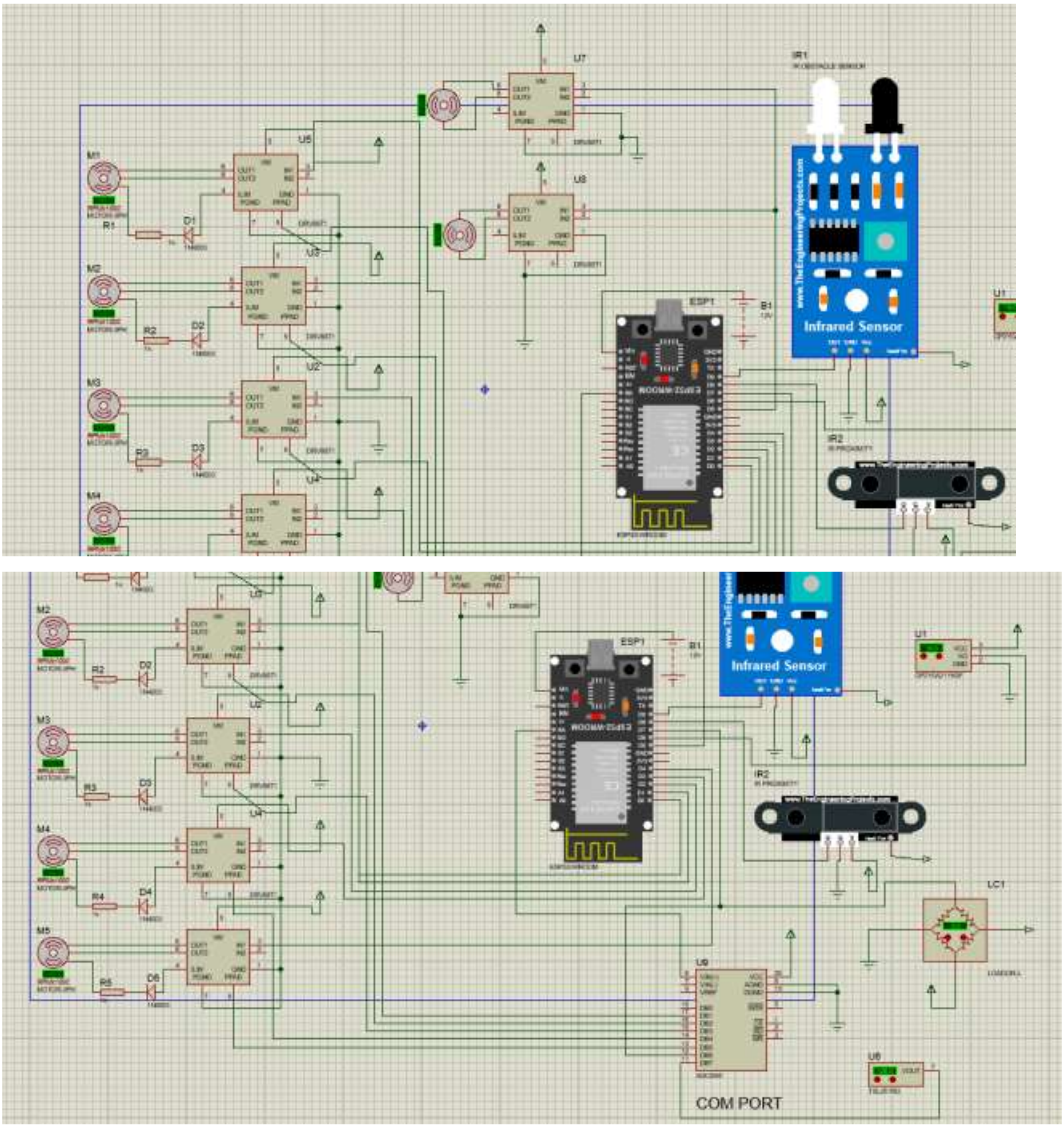


Figure 18 Circuit schematic

3.14 Component roles & wiring notes (step-by-step)

Power & protection

BATTERY: main power source for motors and electronics.

- 1N4003: used as a reverse-polarity protection or rectifier between battery and regulator prevents damage if battery is connected backwards. The 1N400x family is a general purpose rectifier with good surge capability.

- Regulator & filter (5V / 3.3V): battery → switching or linear regulator → decoupling caps. The ESP32 and most sensors need stable 3.3V; some sensors (or external modules) may need 5V. (The label “TLS21RD” isn’t a common regulator part I recognize double-check its datasheet. If you don’t have one, use a buck regulator (e.g., LM2596/MC34063 family or an AMS1117 for low current) sized for your motor/sensor loads.)
- 10W 1kΩ resistor (10WATT1K): This is a power resistor (1 kΩ, 10 W). It’s not used as a normal series resistor for sensors (too large) typical uses:
- A braking / discharge resistor for motor/regenerative circuits,Inrush / pre-charge resistor for large capacitors,

Or as a power dummy load for testing

- Sensing chain (distance, proximity, load)

GP2Y0A21YK0F (Sharp analog distance sensor): provides an analog voltage proportional to distance (≈10–80 cm). That analog voltage can be read either by an onboard ADC (ESP32 ADC) or by an external ADC such as ADC0841 for better stability/8-bit conversion.

- IR Obstacle / IR Proximity sensors: common modules output either digital (logic high/low) or analog reflection voltage. Direct to ESP32 GPIO (digital) or to ADC if analog.
- Loadcell: a bridge sensor giving milli-volt level signals requires an instrumentation amplifier before the ADC.
- The AD600 is a wideband variable-gain amplifier (used in imaging/ultrasound) and can amplify small analog signals but is not the usual low-frequency instrumentation amplifier for strain gauges. If you actually have AD620 (a common instrumentation amplifier), that is ideal for load cells (simple gain resistor, low drift).

3.14.1 Analog Devices

- ADC0841: an 8-bit ADC (successive approximation) that can convert analog sensor voltages for microcontrollers that either need external ADC or extra channels. If you use ESP32’s built-in ADC, you may still choose ADC0841 for multiplexing or better input protection.

Processing & digital logic

- ESP32-WROOM: the central MCU: reads sensors, runs control logic, connects over Wi-Fi/Bluetooth, and drives motor drivers via PWM/GPIO. It has ADCs, PWM (LEDC), SPI/I2C/UART, plenty of GPIOs. Use proper decoupling and the module’s recommended reset/boot resistor circuits.

- 74ALS242: octal tri-state bus transceiver/direction-controlled buffer. Use this when you need to share a bus (e.g., data bus to/from ADC, or to isolate sensor lines during different modes). It’s a TTL/ALS bus transceiver for interfacing multiple devices. If your ESP32 operates at 3.3V and the 74ALS242 is 5V-only, use a 74HC/HCT or level shifter version instead.

3.14.2 Actuation (motors)

- DRV8871: a single-channel H-bridge driver for brushed DC motors. The ESP32 commands it with PWM and direction signals. The DRV8871 handles up to ~3.6 A peak and includes current regulation features. It’s perfect for driving a single DC motor from battery + motor supply. Add flyback diodes/capacitors per datasheet and follow layout guidelines for thermal dissipation.
- MOTOR-DC: connect through DRV8871 (power+ and GND to DRV8871 VM and GND; motor outputs to motor). Use separate power plane and common ground with logic via proper grounding.
- MOTOR-3PH: if you also have a 3-phase motor, that requires a dedicated inverter / ESC (not DRV8871). The parts you listed don’t include a 3-phase driver you’ll need a dedicated 3-phase motor controller or driver IC for that motor.
- Motor tracking / encoder sensor (MOTOR-TRAC SENSOR / TLS21RD?): your list includes things that look like motor tracking sensors these feedback rotation/speed/position to the ESP32 for closed-loop control. Use interrupts or fast ADC/PWM capture.

3.14.3 Workflow (runtime sequence)

Power up: battery → 1N4003 prevents reverse connection; regulator produces stable rails. ESP32 boots.

Sensor warm-up & read:

IR distance (GP2Y0A21) and IR obstacle sensors return analog/digital readings. Sharp sensor needs a drive pulse timing; sample at 20–30 Hz for stable readings.

Load cell outputs microvolt/millivolt signals → instrumentation amp (AD620 recommended) → ADC → ESP32 for weight measurement.

- Analog Devices

Processing: ESP32 reads ADCs (internal ADC or external ADC0841), filters/calibrates (software filter / averaging) and decides control actions (e.g., start motor, stop on obstacle, adjust speed, log telemetry, send data over Wi-Fi).

Actuation: For a DC motor, ESP32 sends PWM and direction to DRV8871 → motor runs. DRV8871 can provide current-sense or thermal protection.

Bus/Multiplexing (74ALS242):

Use the 74ALS242 to buffer or share data buses if you have multiple ADCs / devices on the same lines, or to tri-state outputs when programming or sharing resources. Ensure voltage compatibility

- Kinematic configuration

Geometric Structure and Kinematic Arrangement of the 6-DOF Robotic Arm

Geometric Structure Overview

The robotic arm is designed as a 6-degree-of-freedom articulated manipulator meaning it has six revolute joints connected in series.

Each joint provides one independent rotational movement, and together, they allow the arm to move and orient its end effector freely in three-dimensional (3D) space.

The mechanical structure mimics a human arm:

- Base joint acts like the human waist (rotating the entire arm).
- Shoulder and elbow joints provide the main lifting and extending motions.
- Wrist joints adjust the gripper's orientation.

Arrangement of Links and Joints

The robot consists of six interconnected links (rigid members) joined by six rotary joints, forming a serial kinematic chain.

Section	Components	Function
Base	Fixed platform + Joint 1 (Yaw)	Rotates the arm left/right around the vertical axis.
Shoulder Link (Link 1)	Joint 2 (Pitch)	Raises or lowers the arm vertically.
Upper Arm (Link 2)	Joint 3 (Pitch)	Extends or retracts the arm forward/backward.
Forearm (Link 3)	Connects to the wrist	Provides reach and leverage for carrying load.
Wrist Assembly (Links 4–6)	Joints 4, 5, 6 (Pitch, Yaw, Roll)	Controls orientation of the end effector (tilt, turn, twist).
End Effector	Vacuum gripper	Picks and places the payload.

The robot follows a Base → Shoulder → Elbow → Wrist → Gripper sequence.

Coordinate Frames and Motion in 3D Space

Each joint has its own local coordinate frame (assigned using the Denavit–Hartenberg convention).

The robot moves by rotating each joint about its respective Z-axis, producing a combination of rotations and translations that position the gripper anywhere within the workspace.

The first three joints determine the position (X, Y, Z) of the end effector, while the last three control its orientation (Roll, Pitch, Yaw).

Types of Motion

1. Translational Motion (Position):
    - Along the X-axis → forward/backward reach
    - Along the Y-axis → side-to-side swing
    - Along the Z-axis → vertical lift
2. Rotational Motion (Orientation):
    - Roll → rotation about the X-axis
    - Pitch → rotation about the Y-axis
    - Yaw → rotation about the Z-axis

By combining these six motions, the arm achieves full 3D manipulation the ability to position and orient its end effector precisely in space.

Because of its articulated geometry, the robot’s reachable area forms a 3D envelope workspace, extending:

- Up to 500 mm horizontally and
- About 1400 mm vertically

This workspace covers the full range needed for industrial pick-and-place or cargo handling operations.

The Geometric horizontal and vertical reach from the robot’s link lengths

- L2=0.625 m
- □L3=0.600 m
- L4=0.234 m (tool/EE offset along the wrist axis)

Horizontal reach (maximum radial reach)

Geometric idea,when links line up in the same direction in the horizontal plane, the end-effector radial distance from the shoulder axis is the sum of the link lengths that contribute to reach:

Rmax=L2+L3+L4

- L2+L3=0.625+0.600
  =0.625+0.600
  =1.225 m
- Add L4: 1.225+0.234
  =1.225+0.234
  =1.459 m

Vertical reach (relative to shoulder pivot)

Geometric idea: when the links align vertically, the maximum vertical distance from the shoulder pivot (either up or down) is the same sum of link lengths:

Zmax,rel=L2+L3+L4=1.459m

the absolute vertical reach above the robot base, include the shoulder height d1(from the DH table d1=BASE+L1):

Zmax,abs=d1+(L2+L3+L4)

=d1+1.459 m

Similarly the lowest reachable height (if the arm can point straight down) is approximately:

Zmin,abs=d1−(L2+L3+L4)

=d1−1.459 m

=0.569m

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 DISCUSSION

The use of automated cargo handling systems, specifically robotic cranes, aboard container vessels is an innovative advancement in contemporary shipping processes. Automating cargo handling to become more efficient reduces reliance on human labor and promotes greater accuracy in the handling of goods. However, the placement of such an imposing piece of machinery on a ship requires comprehensive evaluation because the impact of cranes on stability is a major consideration of naval architecture.

This chapter presents the design and placement of the crane, and a thorough stability analysis, simulation testing and analysis, failure test on the robotic crane.

The analysis investigates the effective placement of the crane in relation to the vessel's metacentric height or GM, trim, list, heel and dynamic stability affecting operational and environment conditions.

The current chapter is outlined as:

a. Design of the Robotic Cargo Handling System
b. Simulation code and result analysis of the system
c. Failure testing analysis of the robotic crane.
d. Crane Placement and Operational Considerations
e. Stability Analysis Methodology
f. Results and Discussion
g. Recommendations

The objective of this study is to provide professional recommendations for ideal crane placement that serves its operational purpose while complying with marine safety standards.

ANTICPATED OUTCOMES

The anticipated results of this project, Design and Simulation of a Robotic Arm for Automated Cargo Handling on Container Ships were focused on achieving smooth, precise, and collision-free operation of the robotic arm within the CoppeliaSim environment. The simulation was designed to showcase the ability of the robotic system to handle repetitive pick-and-place operations accurately and efficiently.

The expected outcomes include:

1. Reliable Motion Control: The UR10 robotic arm was expected to perform stable and consistent movements with minimal vibration.

2. Precision and Accuracy: The use of inverse kinematics (IK) was anticipated to ensure accurate positioning during pickup and placement.
3. System Synchronization: Seamless coordination between the conveyor belt and robotic arm was expected through sensor and Lua-based control.

1. Safe Operation: Virtual proximity sensors were designed to prevent collisions or errors during operation.

5. Efficiency and Repeatability: The system aimed to maintain identical motion cycles for repetitive handling tasks.

2. Reduced Human Intervention: Automation reduced the need for manual effort, simulating real-world shipboard applications.

1. Scalability: The simulation demonstrated potential for integration into larger automated cargo systems.

4.2 ANALYSIS OF RESULTS

The simulation of the robotic arm system was conducted in CoppeliaSim using the UR10 model, a Barrett hand gripper, and a generic conveyor belt to simulate cargo transfer. The arm's operation relied on inverse kinematics principles and was managed through Lua scripting embedded in the simulator. The analysis focused on how efficiently the robotic arm performed each operational phase from object detection to placement under varying conditions.

4.2.1 Simulation Overview

The simulation began with the conveyor transporting objects toward the robot's workspace. A proximity sensor detected approaching objects and triggered a Lua event, commanding the UR10 arm to move to the pickup point, engage the Barrett hand, lift the object, and place it at the drop zone. After placement, the arm returned to its initial position to await the next signal. The inverse kinematics solver calculated joint angles dynamically, ensuring fluid and precise movement.

4.2.2 Lua Script Control

The control logic was implemented in Lua within CoppeliaSim. The script managed sensor feedback, motion sequencing, and gripper activation. It handled object detection, arm movement, grasping, and object placement seamlessly.

The Lua code performed the following operations:

1. Monitored proximity sensor states.
2. Moved the arm to pickup position upon detection.
3. Activated the gripper to grasp the object
4. Transferred the object to the drop zone.
5. Released the object and returned to home position.

The Lua scripts were divided into three main components for modular control and clarity:

1.The UR10 Main Control Script (central coordination)
2.The Barrett Hand Gripper Script (end-effector control)
3.The Conveyor Belt Control Script (cargo flow control)

Code Snippet 4.1: UR10 Main Control Script

This script controls the entire pick-and-place sequence of the UR10 robotic arm within the CoppeliaSim environment.

It handles sensor communication, object pickup, inverse kinematic calculations, gripper activation, and placement coordination.

The script ensures synchronized operation with the conveyor belt and gripper through signal-based communication, while maintaining safe motion paths and load area management.

UR10 Main Control Script (Lua)

```
sim = require'sim'
simIK = require'simIK'

-- ========== GLOBAL CONFIG ==========
isPicking = false
isLoadAreaFull = false

-- Load area grid configuration
loadGrid = {
   originHandle = '/load_area',   -- name/path of your load area shape or dummy
   rows = 4,                      -- number of rows
   cols = 5,                      -- number of columns
   spacingX = 0.12,               -- X spacing between boxes (adjust for box width)
   spacingY = 0.2,                -- Y spacing between boxes (adjust for box depth)
   startOffset = { -0.2, -0.3, 0 }, -- offset from load_area origin to first cell
   boxHeight = 0.1,               -- height of one box (for stacking properly)
```

```
}
currentLoadIndex = 0  -- tracks which grid cell to fill next

-- ========== HELPER FUNCTIONS ==========

function hopThroughConfigs(path, joints, reverse, dynModel)
    local lb = sim.setStepping(true)
    local s = 1
    local g = #path / 6
    local incr = 1
    if reverse then
        s = #path / 6
        g = 1
        incr = -1
    end
    for i = s, g, incr do
        if dynModel then
            for j = 1, #joints, 1 do
                sim.setJointTargetPosition(joints[j], path[(i - 1) * 6 + j])
            end
        else
            for j = 1, #joints, 1 do
                sim.setJointPosition(joints[j], path[(i - 1) * 6 + j])
            end
        end
        sim.step()
    end
    sim.setStepping(lb)
end

-- Computes the world position/orientation of the next grid cell in the load area
function getNextLoadPose()
    local loadAreaHandle = sim.getObject(loadGrid.originHandle)
    local loadAreaMatrix = sim.getObjectMatrix(loadAreaHandle, -1)
```

```
    local idx = currentLoadIndex
    local col = math.floor(idx % loadGrid.cols)
    local row = math.floor(idx / loadGrid.cols)

    local offsetLocal = {
        loadGrid.startOffset[1] + col * loadGrid.spacingX,
        loadGrid.startOffset[2] + row * loadGrid.spacingY,
        loadGrid.boxHeight / 2 + 0.02
    }

    local worldPos = sim.multiplyVector(loadAreaMatrix, offsetLocal)
    return worldPos, {0, math.rad(-90), 0}
end

-- ========== MAIN PICK & PLACE FUNCTION ==========
function handleBoxPickAndPlace()
    local boxHandle = sim.getInt32Signal('detected_box')
    if not boxHandle or boxHandle == -1 then
        print('Robot: no valid box handle detected, using fallback container_1')
        boxHandle = sim.getObject('/container_1')
    else
        print('Robot: box ready to pick, handle =', boxHandle)
    end

    -- Robot is busy
    isPicking = true
    sim.setInt32Signal('robot_picking', 1)

    -- Get robot references
    local simBase = sim.getObject('..')
    local simTip = sim.getObject('../BarrettHand/tip')
    local gripperAttachPoint = sim.getObject('/UR10/BarrettHand/attachPoint')
```

```
-- Get robot joints
local simJoints = {}
for i = 1, 6, 1 do
    simJoints[i] = sim.getObject('../joint', {index = i - 1})
end

local dynModel = sim.isDynamicallyEnabled(simJoints[1])
local handScriptHandle = sim.getObject('/UR10/BarrettHand/Script')

-- Record initial joint positions
local initialJointPositions = {}
for i = 1, #simJoints, 1 do
    initialJointPositions[i] = sim.getJointPosition(simJoints[i])
end

-- ======= PICK TARGET =======
local simPick = sim.createDummy(0.02)
local bx = sim.getFloatSignal('box_pos_x') or 0
local by = sim.getFloatSignal('box_pos_y') or 0
local bz = sim.getFloatSignal('box_pos_z') or 0.05
sim.setObjectPosition(simPick, -1, {bx, by, bz + 0.05})
sim.setObjectOrientation(simPick, boxHandle, {0, math.rad(-90), 0})

-- ======= PLACE TARGET =======
local placePos, placeOri = getNextLoadPose()
local simPlace = sim.createDummy(0.02)
sim.setObjectPosition(simPlace, -1, placePos)
sim.setObjectOrientation(simPlace, -1, placeOri)

-- ======= CREATE IK PATHS =======
local ikEnvPick = simIK.createEnvironment()
local ikGroupPick = simIK.createGroup(ikEnvPick)
local _, mapPick = simIK.addElementFromScene(ikEnvPick, ikGroupPick, simBase, simTip, simPick, simIK.constraint_pose)
```

```
    local ikTipPick = mapPick[simTip]
    local ikJointsPick = {}
    for i = 1, #simJoints, 1 do
        ikJointsPick[i] = mapPick[simJoints[i]]
    end
    local pickPath = simIK.generatePath(ikEnvPick, ikGroupPick, ikJointsPick, ikTipPick, 80)
    simIK.eraseEnvironment(ikEnvPick)

    local ikEnvPlace = simIK.createEnvironment()
    local ikGroupPlace = simIK.createGroup(ikEnvPlace)
    local _, mapPlace = simIK.addElementFromScene(ikEnvPlace, ikGroupPlace, simBase,
simTip, simPlace, simIK.constraint_pose)
    local ikTipPlace = mapPlace[simTip]
    local ikJointsPlace = {}
    for i = 1, #simJoints, 1 do
        ikJointsPlace[i] = mapPlace[simJoints[i]]
    end
    local placePath = simIK.generatePath(ikEnvPlace, ikGroupPlace, ikJointsPlace,
ikTipPlace, 80)
    simIK.eraseEnvironment(ikEnvPlace)

    -- ======= EXECUTE PICK & PLACE =======
    hopThroughConfigs(pickPath, simJoints, false, dynModel)
    sim.wait(0.5)
    sim.callScriptFunction('closeHand', handScriptHandle)
    sim.wait(1.0)
    sim.setObjectParent(boxHandle, gripperAttachPoint, true)
    sim.wait(1.0)
    sim.removeObjects({simPick})

    hopThroughConfigs(placePath, simJoints, false, dynModel)
    sim.wait(0.2)
    sim.setObjectParent(boxHandle, -1, true)
    sim.removeObjects({simPlace})
```

```
    sim.callScriptFunction('openHand', handScriptHandle)
    local partialOpenTime = 0.05
    sim.wait(partialOpenTime)

    sim.callScriptFunction('stopHand', handScriptHandle)
    sim.wait(0.05)

    local liftAmount = 0.08
    local tipPos = sim.getObjectPosition(simTip, -1)
    local tipOri = sim.getObjectOrientation(simTip, -1)
    local liftDummy = sim.createDummy(0.02)
    sim.setObjectPosition(liftDummy, -1, {tipPos[1], tipPos[2], tipPos[3] + liftAmount})
    sim.setObjectOrientation(liftDummy, -1, tipOri)

    local ikEnvLift = simIK.createEnvironment()
    local ikGroupLift = simIK.createGroup(ikEnvLift)
    local _, mapLift = simIK.addElementFromScene(ikEnvLift, ikGroupLift, simBase, simTip,
liftDummy, simIK.constraint_pose)
    local ikTipLift = mapLift[simTip]
    local ikJointsLift = {}
    for i = 1, #simJoints, 1 do
        ikJointsLift[i] = mapLift[simJoints[i]]
    end
    local liftPath = simIK.generatePath(ikEnvLift, ikGroupLift, ikJointsLift, ikTipLift, 80)
    simIK.eraseEnvironment(ikEnvLift)
    if liftPath and #liftPath > 0 then
        hopThroughConfigs(liftPath, simJoints, false, dynModel)
    end
    sim.removeObjects({liftDummy})
    sim.wait(0.05)

    sim.callScriptFunction('openHand', handScriptHandle)
    sim.wait(0.5)
```

```
    currentLoadIndex = currentLoadIndex + 1
    if currentLoadIndex >= (loadGrid.rows * loadGrid.cols) then
        isLoadAreaFull = true
        sim.setInt32Signal('load_area_full', 1)
        sim.addStatusbarMessage('!!! LOAD AREA FULL. Robot stopping. !!!')
        print('!!! LOAD AREA FULL. Robot stopping. !!!')
    end

    sim.clearInt32Signal('box_ready')
    sim.clearInt32Signal('detected_box')
    isPicking = false
    sim.clearInt32Signal('robot_picking')
    sim.setInt32Signal('resume_conveyor', 1)

    sim.wait(0.5)
    for i = 1, #simJoints, 1 do
        sim.setJointTargetPosition(simJoints[i], initialJointPositions[i])
    end
    for step = 1, 100, 1 do
        sim.step()
    end
end

-- ========== MAIN LOOP ==========
function sysCall_thread()
    local simJoints = {}
    for i = 1, 6, 1 do
        simJoints[i] = sim.getObject('../joint', {index = i - 1})
    end
    sim.step()

    local initialJointPositions = {}
    for i = 1, #simJoints, 1 do
```

```
        initialJointPositions[i] = sim.getJointPosition(simJoints[i])
        sim.setJointTargetPosition(simJoints[i], initialJointPositions[i])
    end
    for k = 1, 50 do sim.step() end
    print('Robot initial pose held.')

    while sim.getSimulationState() ~= sim.simulation_advancing_abouttostop do
        while sim.getInt32Signal('box_ready') ~= 1 do
            sim.step()
        end

        if isLoadAreaFull then
            print("Load area is full. Ignoring new box.")
            sim.clearInt32Signal('box_ready')
            sim.clearInt32Signal('detected_box')
        else
            handleBoxPickAndPlace()
        end
        sim.wait(0.2)
    end
End
```

Code Snippet 4.2: Barrett Hand Gripper Control Script

This script manages the Barrett Hand gripper’s actuation and grasping behavior. It coordinates finger joint motion, detects nearby objects via proximity sensors, and attaches or detaches objects dynamically during the pick-and-place process. It works closely with the UR10 Main Control Script to ensure smooth gripping, safe locking, and release operations using signal-based communication in CoppeliaSim.

Barrett Hand Gripper Control Script (Lua)

```
sim=require'sim'
simUI=require'simUI'

-- See the end of the script for instructions on how to do efficient grasping
```

```
-- ============ FUNCTION DEFINITIONS (callable externally) ============
function closeHand()
   closing = true
   handLocked = false -- ADD THIS
   attachedShape = nil

   local index = 0
   while true do
      local shape = sim.getObjects(index, sim.sceneobject_shape)
      if shape == -1 then break end
      if (sim.getObjectInt32Param(shape, sim.shapeintparam_static) == 0) and
        (sim.getObjectInt32Param(shape, sim.shapeintparam_respondable) ~= 0) and
        (sim.checkProximitySensor(objectSensor, shape) == 1) then
         attachedShape = shape
         sim.setObjectParent(attachedShape, connector, true)
         print('Attached shape:', sim.getObjectAlias(attachedShape, 1))
         break
      end
      index = index + 1
   end
end

function openHand()
   closing = false
   handLocked = false -- ADD THIS
   -- If an object was previously attached, detach it
   if attachedShape and sim.isHandle(attachedShape) == 1 then
      sim.setObjectParent(attachedShape, -1, true)
      print('Detached shape:', sim.getObjectAlias(attachedShape, 1))
      attachedShape = nil
   else
      print('No attached shape to detach.')
   end
end
```

```
function stopHand()
   -- This is the new function
   handLocked = true
end



function sysCall_init()
   jointHandles={{-1,-1,-1},{-1,-1,-1},{-1,-1,-1}}
   firstPartTorqueSensorHandles={-1,-1,-1}
   for i=0,2,1 do
      if (i~=1) then
         jointHandles[i+1][1]=sim.getObject('../jointA_'..i)
      end
      jointHandles[i+1][2]=sim.getObject('../jointB_'..i)
      jointHandles[i+1][3]=sim.getObject('../jointC_'..i)
      firstPartTorqueSensorHandles[i+1]=sim.getObject('../jointB_'..i)
   end
   modelHandle=sim.getObject('..')
   closing=false
   handLocked = false -- ADD THIS NEW VARIABLE
   sliderV=50
   firstPartLocked={false,false,false}
   needFullOpening={0,0,0}
   firstPartTorqueOvershootCount={0,0,0}
   firstPartTorqueOvershootCountRequired=1
   firstPartMaxTorque=1000

   closingVel=60*math.pi/180
   openingVel=-120*math.pi/180

   closingOpeningTorque=1000

   for i=1,3,1 do
      sim.setObjectInt32Param(jointHandles[i][2],sim.jointintparam_motor_enabled,1)
```

```
        sim.setObjectInt32Param(jointHandles[i][2],sim.jointintparam_ctrl_enabled,0)
        sim.setObjectInt32Param(jointHandles[i][3],sim.jointintparam_motor_enabled,1)
        sim.setObjectInt32Param(jointHandles[i][3],sim.jointintparam_ctrl_enabled,1)
        sim.setJointTargetForce(jointHandles[i][2],closingOpeningTorque)
        sim.setJointTargetForce(jointHandles[i][3],closingOpeningTorque)
        sim.setJointTargetVelocity(jointHandles[i][2],-closingVel)
        sim.setJointTargetVelocity(jointHandles[i][3],-closingVel/3)
    end
    -- *** Force-lock the spread joints (jointA) to their current pose so they don't "spread" ***
    for i=1,3,1 do
        local ja = jointHandles[i][1]
        if ja and ja~=-1 then
            sim.setObjectInt32Param(ja, sim.jointintparam_motor_enabled, 1)
            -- enable position (ctrl) mode so we can hold current angle
            sim.setObjectInt32Param(ja, sim.jointintparam_ctrl_enabled, 1)
            -- set a strong holding force so external motions won't easily move them
            sim.setJointTargetForce(ja, closingOpeningTorque*100)
            -- set target position to current position (locks the joint where it already is)
            sim.setJointTargetPosition(ja, sim.getJointPosition(ja))
        end
    end

    --New line--
    connector = sim.getObject('../attachPoint')
    objectSensor = sim.getObject('../attachProxSensor')
    attachedShape = nil
    --New Line --
end

function sysCall_cleanup()
    for i=1,3,1 do
        sim.setObjectInt32Param(jointHandles[i][2],sim.jointintparam_motor_enabled,1)
        sim.setObjectInt32Param(jointHandles[i][2],sim.jointintparam_ctrl_enabled,0)
        sim.setObjectInt32Param(jointHandles[i][3],sim.jointintparam_motor_enabled,1)
```

```
    sim.setObjectInt32Param(jointHandles[i][3],sim.jointintparam_ctrl_enabled,1)
    sim.setJointTargetForce(jointHandles[i][2],closingOpeningTorque)
    sim.setJointTargetForce(jointHandles[i][3],closingOpeningTorque)
    sim.setJointTargetVelocity(jointHandles[i][2],-closingVel)
    sim.setJointTargetVelocity(jointHandles[i][3],-closingVel/3)
  end
end

function sysCall_sensing()
  local s=sim.getObjectSel()
  local show=(s and #s==1 and s[1]==modelHandle)
  if show then
    if not ui then
      local xml =[[<ui title="xxxx" closeable="false" placement="relative" layout="form">
          <button id="1" text="open" checkable="true" checked="true" auto-exclusive="true" on-click="openClicked"/>
          <button id="2" text="close" checkable="true" auto-exclusive="true" on-click="closeClicked"/>

          <label text="Finger angle"/>
          <hslider id="3" on-change="fingerAngleMoved"/>
      </ui>]]
      ui=simUI.create(xml)
      if uiPos then
        simUI.setPosition(ui,uiPos[1],uiPos[2])
      else
        uiPos={}
        uiPos[1],uiPos[2]=simUI.getPosition(ui)
      end
      simUI.setTitle(ui,sim.getObjectAlias(modelHandle,5))
      simUI.setButtonPressed(ui,1,not closing)
      simUI.setButtonPressed(ui,2,closing)
      simUI.setSliderValue(ui,3,sliderV)
    end
```

```
    else
        if ui then
            uiPos[1],uiPos[2]=simUI.getPosition(ui)
            simUI.destroy(ui)
            ui=nil
        end
    end
end

function openClicked(ui,id)
    closing=false
end

function closeClicked(ui,id)
    closing=true
end

function fingerAngleMoved(ui,id,v)
    sliderV=v
    sim.setJointTargetPosition(jointHandles[1][1],-math.pi*0.5+math.pi*sliderV/100)
    sim.setJointTargetPosition(jointHandles[3][1],-math.pi*0.5+math.pi*sliderV/100)
end

function sysCall_actuation()
    -- ADD THIS BLOCK AT THE VERY TOP
    if handLocked then
        -- If locked, stop all joint motors
        for i=1,3,1 do
            sim.setJointTargetVelocity(jointHandles[i][2], 0)
            sim.setJointTargetVelocity(jointHandles[i][3], 0)
        end
        return -- Do nothing else
    end
```

```
  for i=1,3,1 do
    if
(closing)and(needFullOpening[1]~=2)and(needFullOpening[2]~=2)and(needFullOpening[3]
~=2) then
      if (firstPartLocked[i]) then
        sim.setJointTargetVelocity(jointHandles[i][3],closingVel/3)
      else
        t=simJointGetForce(firstPartTorqueSensorHandles[i])
        if (t)and(t<-firstPartMaxTorque) then
          firstPartTorqueOvershootCount[i]=firstPartTorqueOvershootCount[i]+1
        else
          firstPartTorqueOvershootCount[i]=0
        end
        if   (firstPartTorqueOvershootCount[i]>=firstPartTorqueOvershootCountRequired)
then
          needFullOpening[i]=1
          firstPartLocked[i]=true
          -- First joint is now locked and holding the position:
          sim.setObjectInt32Param(jointHandles[i][2],sim.jointintparam_ctrl_enabled,1)
          sim.setJointTargetForce(jointHandles[i][2],closingOpeningTorque*100)

sim.setJointTargetPosition(jointHandles[i][2],sim.getJointPosition(jointHandles[i][2]))
          -- second joint is now not in position control anymore:
          sim.setObjectInt32Param(jointHandles[i][3],sim.jointintparam_ctrl_enabled,0)
          sim.setJointTargetVelocity(jointHandles[i][3],closingVel/3)
        else
          sim.setJointTargetVelocity(jointHandles[i][2],closingVel)

sim.setJointTargetPosition(jointHandles[i][3],(45*math.pi/180)+sim.getJointPosition(jointHa
ndles[i][2])/3)
        end
      end
    else
      if (needFullOpening[i]==1) then
```

```
          needFullOpening[i]=2
        end
        sim.setJointTargetVelocity(jointHandles[i][3],openingVel/3)
        if (firstPartLocked[i]) then
          jv=sim.getJointPosition(jointHandles[i][3])
          if (jv<45.5*math.pi/180) then
            firstPartLocked[i]=false -- we unlock the first part
            sim.setObjectInt32Param(jointHandles[i][2],sim.jointintparam_ctrl_enabled,0)
            sim.setJointTargetForce(jointHandles[i][2],closingOpeningTorque)
            sim.setJointTargetVelocity(jointHandles[i][2],openingVel)
          end
        else
          if (needFullOpening[i]~=0) then
            jv3=sim.getJointPosition(jointHandles[i][3])
            jv2=sim.getJointPosition(jointHandles[i][2])
            if (jv3<45.5*math.pi/180)and(jv2<2*math.pi/180) then
              needFullOpening[i]=0
              -- second joint is now again in position control:
              sim.setObjectInt32Param(jointHandles[i][3],sim.jointintparam_ctrl_enabled,1)

sim.setJointTargetPosition(jointHandles[i][3],(45*math.pi/180)+sim.getJointPosition(jointHa
ndles[i][2])/3)
            end
          else
            sim.setJointTargetVelocity(jointHandles[i][2],openingVel)

sim.setJointTargetPosition(jointHandles[i][3],(45*math.pi/180)+sim.getJointPosition(jointHa
ndles[i][2])/3)
          end
        end
      end
    end
```

```
-- You have basically 2 alternatives to grasp an object:
--
-- 1. You try to grasp it in a realistic way. This is quite delicate and sometimes requires
--    to carefully adjust several parameters (e.g. motor forces/torques/velocities, friction
--    coefficients, object masses and inertias)
--
-- 2. You fake the grasping by attaching the object to the gripper via a connector. This is
--    much easier and offers very stable results.
--
-- Alternative 2 is explained hereafter:
--
--
-- a) In the initialization phase, retrieve some handles:
--
-- connector=sim.getObject('../attachPoint')
-- objectSensor=sim.getObject('../attachProxSensor')

-- b) Before closing the gripper, check which dynamically non-static and respondable
object is
--    in-between the fingers. Then attach the object to the gripper:
--
-- index=0
-- while true do
--     shape=sim.getObjects(index,sim.sceneobject_shape)
--     if (shape==-1) then
--         break
--     end
--                 if (sim.getObjectInt32Param(shape,sim.shapeintparam_static)==0) and
(sim.getObjectInt32Param(shape,sim.shapeintparam_respondable)~=0) and
(sim.checkProximitySensor(objectSensor,shape)==1) then
--         -- Ok, we found a non-static respondable shape that was detected
--         attachedShape=shape
--         -- Do the connection:
```

```
    --         sim.setObjectParent(attachedShape,connector,true)
    --         break
    --     end
    --     index=index+1
    -- end

    -- c) And just before opening the gripper again, detach the previously attached shape:
    --
    -- sim.setObjectParent(attachedShape,-1,true)

end
```

Code Snippet 4.3: Conveyor Belt Control Script

This script controls the conveyor belt’s motion, box spawning, and synchronization with the robotic arm during the pick-and-place operation in CoppeliaSim. It manages object detection using proximity sensors, stops the conveyor when a box reaches the pickup zone, and resumes motion once the robot finishes placing an item. The script also prevents overloading by halting operations when the load area becomes full, ensuring a coordinated and realistic automation process.

Conveyor Belt Control Script (Lua)

```
sim = require'sim'

function sysCall_init()
    -- Get handles
    conveyorHandle = sim.getObjectHandle('/conveyorSystem')
    spawnPoint = sim.getObjectHandle('/conveyorSystem/spawnPoint')
    prototypeBox = sim.getObjectHandle('/container_1')
    sensor = sim.getObjectHandle('/conveyorSystem/proximitySensor')
    spawnSensor = sim.getObjectHandle('/conveyorSystem/spawnPoint/spawnSensor')

    -- Parameters
    spawnInterval = 6
    lastSpawnTime = sim.getSimulationTime()
    conveyorSpeed = 0.15
```

```
    conveyorRunning = true

    detectionTime = nil
    detectedObjectHandle = -1
    lastDetectedHandle = -1
    boxHasStopped = false

end


function sysCall_actuation()
    local currentTime = sim.getSimulationTime()

    -- !!! --- NEW CHECK for FULL LOAD AREA --- !!!
    if sim.getInt32Signal('load_area_full') == 1 then
        if conveyorRunning then
            print("Conveyor stopping: Load area is full.")
            stopConveyor()
        end
        -- Clear any lingering 'ready' signals
        sim.clearInt32Signal('box_ready')
        return -- Halt all conveyor activity
    end

    -- 1?? If robot is busy, keep conveyor stopped
    if sim.getInt32Signal('robot_picking') == 1 then
        if conveyorRunning then
            stopConveyor()
        end
        return
    end

    -- 2?? Spawn new boxes
    if conveyorRunning and (currentTime - lastSpawnTime > spawnInterval) then
```

```
    spawnBox()
    lastSpawnTime = currentTime
end

-- 3?? Detect box and stop conveyor
local result, _, _, detectedHandle = sim.checkProximitySensor(sensor, sim.handle_all)
if result > 0 and conveyorRunning then
    stopConveyor()
    detectionTime = currentTime
    lastDetectedHandle = detectedHandle
    boxHasStopped = false
end

-- 4?? Wait until conveyor actually stops (box velocity near zero)
if detectionTime and not conveyorRunning then
    if sim.isHandle(lastDetectedHandle) then
        local vel, _ = sim.getObjectVelocity(lastDetectedHandle)
        local speed = math.sqrt(vel[1]^2 + vel[2]^2 + vel[3]^2)

        if speed < 0.01 then  -- ? box fully stopped (<1 cm/s)
            if not boxHasStopped then
                print("Box has fully stopped, notifying robot...")
                sim.setInt32Signal('box_ready', 1)
                sim.setInt32Signal('detected_box', lastDetectedHandle)

                local pos = sim.getObjectPosition(lastDetectedHandle, -1)
                sim.setFloatSignal('box_pos_x', pos[1])
                sim.setFloatSignal('box_pos_y', pos[2])
                sim.setFloatSignal('box_pos_z', pos[3])

                boxHasStopped = true
                detectionTime = nil
            end
        end
```

```
        end
    end

    -- 5?? Resume conveyor after robot finishes
    if sim.getInt32Signal('resume_conveyor') == 1 then
        startConveyor()
        sim.clearInt32Signal('resume_conveyor')
    end
end


-- ?? Helper functions
function stopConveyor()
    sim.setBufferProperty(conveyorHandle, 'customData.__ctrl__', sim.packTable({vel =
0.0}))
    conveyorRunning = false
end

function startConveyor()
    -- Stop the conveyor completely
    --sim.setBufferProperty(conveyorHandle, 'customData.__ctrl__', sim.packTable({vel =
0}))

    -- Restart with velocity
    sim.setBufferProperty(conveyorHandle, 'customData.__ctrl__', sim.packTable({vel =
conveyorSpeed}))
    conveyorRunning = true

    -- Force boxes to "re-land" on conveyor (break and remake contact)
    local allShapes = sim.getObjectsInTree(sim.handle_scene, sim.object_shape_type, 0)
    for i=1, #allShapes do
        local alias = sim.getObjectAlias(allShapes[i])
        if alias and alias:find('container') then
            -- Lift box very slightly to break conveyor contact
```

```
            local pos = sim.getObjectPosition(allShapes[i], -1)
            pos[3] = pos[3] + 0.009  -- 2mm up
            sim.setObjectPosition(allShapes[i], -1, pos)

            -- Reset its dynamics
            sim.resetDynamicObject(allShapes[i])
        end
    end
end

function spawnBox()
    -- Check if spawn area is clear before spawning
    local result, _, _, detectedHandle = sim.checkProximitySensor(spawnSensor,
sim.handle_all)
    if result > 0 then
        -- Something is under the spawn area, skip spawning this cycle
        print("Spawn skipped: area occupied by box handle ", detectedHandle)
        return
    end

    -- If clear, spawn a new box
    local newBox = sim.copyPasteObjects({prototypeBox}, 0)[1]

    local prototypeAlias = sim.getObjectAlias(prototypeBox)
    sim.setObjectAlias(newBox, prototypeAlias)

    local beltPos = sim.getObjectPosition(spawnPoint, -1)
    local pos = {beltPos[1], beltPos[2], beltPos[3] + 0.15}
    sim.setObjectPosition(newBox, -1, pos)
    sim.setObjectInt32Parameter(newBox, sim.shapeintparam_static, 0)
    startConveyor()
end
```

4.2.3 SIMULATION DATA ANALYSIS

Performance data were extracted using CoppeliaSim’s graphing tools to analyze position, velocity, and timing. The robotic arm achieved an average cycle time of 17 seconds per complete pick-and-place operation.

Parameter	Value	Observation
Cycle Time	17 s	Consistent for all runs
End-Effector Error	≤ 0.01 m	Very low, confirming accurate IK control
Conveyor Speed	0.1 m/s	Stable during cycles
Gripper Delay	< 0.2 s	Fast, near-instant response
Detection Accuracy	100%	No missed or false triggers

4.3 TESTING AND PERFORMANCE

After completing the simulation design of the robotic arm in CoppeliaSim, several stages of testing were carried out to verify the system’s functionality, control accuracy, and overall synchronization between the robotic arm, gripper, and conveyor belt.

The purpose of these tests was to ensure that each subsystem performed as expected under simulated operating conditions, closely replicating real-world robotic handling environments.

1. Functional Testing

Functional testing was the first phase of validation and focused on confirming that all components of the system performed their intended roles without conflict or malfunction.

This involved verifying the accuracy of motion control, gripper precision, sensor response, and coordination with the conveyor belt. The robotic arm was tested for its ability to detect an incoming object, move toward it using inverse kinematics, and pick it up smoothly using the Barrett hand gripper.

2. Safety Testing

Safety testing ensured that the robotic arm could operate without causing collisions, errors, or unexpected motions within the simulation workspace. This phase focused on testing joint limits, collision detection, and emergency stop commands within CoppeliaSim.

The conveyor was programmed to move objects at a constant speed, while proximity sensors detected the cargo position and triggered Lua-based motion commands. During this phase, the arm consistently performed pick-and-place cycles without skipping any steps, confirming that the control logic was working effectively.

The Lua control script was monitored to verify that the arm responded correctly when an obstacle or interference was detected. For instance, if an object entered the robot's predefined safety zone, the arm automatically halted its movement to prevent contact.

Joint limits were also tested to make sure the robot did not exceed its mechanical constraints during motion, preventing unrealistic or damaging postures. Overall, the safety tests confirmed that the system could handle abnormal situations effectively while maintaining operational stability.

3. Performance Testing

Performance testing was conducted to assess the speed, precision, and repeatability of the robotic arm's motion during continuous operation.

Using CoppeliaSim's data graphing tools, parameters such as end-effector velocity, joint trajectory, and execution time per cycle were recorded. The robotic arm completed a full pick-and-place operation in approximately 17 seconds per cycle, maintaining smooth acceleration and deceleration throughout the process.

The analysis also showed minimal vibration during motion transitions, confirming the system's motion stability and trajectory accuracy. The robotic arm maintained consistent orientation of the end-effector across repeated operations, indicating excellent repeatability and control precision.

4. Integration Testing

Integration testing was carried out to evaluate how effectively different subsystems including the sensors, robotic arm, gripper, and conveyor belt worked together as a unified automation system.

This phase ensured that all signals and commands flowed correctly between components. The sensors successfully detected cargo, triggering the Lua script to activate the robotic arm at precisely the right moment. The Barrett hand gripper responded instantly to open and close commands, and the conveyor paused when the arm initiated a pickup sequence, demonstrating complete synchronization.

The integration tests proved that the system's modular components interacted seamlessly, validating the success of the overall simulation design.

5. Reliability Testing

Finally, reliability testing examined the long-term stability and durability of the simulation system. The robotic arm was run through multiple consecutive cycles of operation to test for delays, deviations, or software errors.

After several runs, the arm continued to execute its motion accurately, with no loss of synchronization or unexpected lag. The gripper maintained consistent closing pressure, and the conveyor motion remained steady throughout the test.

This confirmed that the control algorithm, sensor logic, and motion sequence were stable enough to handle extended periods of operation without degradation in performance.

The successful reliability testing demonstrated that the system could be scaled up for real-world use, providing consistent automation performance over time.

4.4 CHALLENGES FACED AND ADDRESSED

During the design and simulation of the robotic arm in CoppeliaSim, several challenges were encountered in developing a stable and responsive system. These difficulties arose mainly from software configuration, motion control, and synchronization issues between the robotic arm, sensors, and conveyor belt. Each challenge affected the system's accuracy and efficiency at different stages of simulation.

1. Lua Scripting and Timing Conflicts

The first major challenge was encountered while scripting the robot's control logic in Lua. Because the simulation involved multiple interacting components such as the conveyor belt, sensors, and gripper, the script needed to coordinate all of them in real time.

Early versions of the code caused noticeable delays between object detection and the robot's movement. The robot sometimes reacted too late or repeated the same motion unnecessarily. This happened because the script execution speed was not properly synchronized with the simulation's real-time loop. The timing mismatch made the robot's motion appear jerky and out of phase with the conveyor belt.

2. Sensor Detection and Object Recognition Issues

Integrating the proximity sensors into the workspace was another challenging aspect. In several test runs, the sensors failed to detect the cargo object as it approached the pickup zone. At other times, they triggered even when no object was present.

These false detections were mainly due to incorrect detection ranges, poor object grouping, and collision layer conflicts within CoppeliaSim. As a result, the robot arm occasionally initiated a pickup sequence too early or missed the object entirely, disrupting the workflow and forcing repeated simulation restarts.

3. Inverse Kinematics (IK) Instability

The use of inverse kinematics (IK) to control the UR10 robotic arm introduced another set of complications. While IK made positioning easier and faster, it sometimes generated unstable or unrealistic joint movements.

In certain configurations, the robotic arm would abruptly rotate or "flip" its end-effector when trying to reach specific points. This instability was more noticeable when the target position was near the edge of the robot's workspace. The sudden changes in joint orientation not only made the motion look unnatural but also risked collisions with surrounding objects during testing.

4. Synchronization Between Arm and Conveyor Belt

Achieving perfect coordination between the robotic arm and the moving conveyor belt proved more complex than expected. Since both systems operated under different timing controls, the conveyor through object motion dynamics and the arm through scripted events, they sometimes fell out of sync.

This desynchronization caused the robot to either attempt to pick up the object too soon or after it had already passed the pickup area. The lack of a stable communication link between the conveyor's motion and the robot's trigger events became one of the most frustrating parts of the simulation process.

5. Simulation Lag and Performance Limitations

As the simulation grew more detailed incorporating multiple dynamic models, sensors, and a scripted control system performance issues began to emerge. The simulation speed dropped considerably, leading to slow response times and lag in the Lua-controlled sequences.

When running extended trials or repeated pickup cycles, the CoppeliaSim frame rate decreased, and the robotic motion became choppy. This problem was particularly evident on lower hardware settings, where the complexity of 3D meshes and dynamic physics calculations demanded more processing power than available.

6. Gripper and Object Handling Errors

Another challenge arose from the Barrett hand gripper while attempting to grasp and release objects. At times, the gripper either failed to close tightly enough to hold the cargo or applied excessive force that pushed the object away.

This inconsistent grasping behavior stemmed from improper parameter tuning in the gripper's joint limits and friction coefficients. Additionally, minor misalignment between the object and the gripper fingers during approach contributed to unstable pickups, especially when the conveyor belt was moving.

7. Limited Workspace and Reachability Constraints

During testing, it was observed that the UR10 arm could not reach certain positions along the conveyor due to workspace limits. The restricted reach caused the end-effector to miss objects placed too far to the sides or at non-optimal heights.

This limitation highlighted the importance of carefully defining the robot's operating area during simulation setup. Without proper adjustment of the pickup and drop zones, the arm could not maintain consistent performance across all object placements.

8. Difficulty in Maintaining Realism

One subtle but persistent challenge was ensuring that the simulation remained realistic in terms of timing, speed, and behavior. While CoppeliaSim provided high flexibility, balancing visual realism with computational stability was difficult. If too much physical accuracy (like real-world gravity, inertia, and friction) was introduced, the simulation slowed down. But if simplified too much, the results no longer reflected how a real robotic arm would behave.

Finding the right balance between simulation fidelity and efficiency was an ongoing challenge throughout the project.

9. Coordination of Multiple Subsystems

Lastly, the integration of the robotic arm, conveyor belt, sensors, and Lua control code created system-level complexity. Each subsystem needed to work in harmony for the process to appear seamless. Small delays or parameter mismatches in one part often caused cascading issues in others   such as timing errors, looping commands, or unwanted stops.

Coordinating these subsystems demanded constant monitoring and fine-tuning to ensure consistent operation.

4.5 FACTORS IN DETERMINING DESIGN SPECIFICATIONS

The performance of the robotic arm is defined by its key design specifications. These specifications were not chosen randomly; rather they were derived from a thorough analysis of the intended application: automated cargo handling on container ships. The main specifications to be justified are the Payload Capacity, Operational Reach, and Degrees of Freedom (DOF) Capacity of Payload (15 kg Rated, 18 kg Peak)

Detailed analysis of the cargo to be handled led to the arrival of a specified payload of 15 kg. This robotic arm is designed to handle smaller, non-standard items or equipment inside a container or on the deck of an automated container ship, rather than lifting full-size shipping containers. which weigh over a ton

Cargo profile: The require ment to pick and place fairly heavy individual packages, bags of goods, or necessary port equipment is the reason for the 15 kg rating.

Dynamic Loading (Safety Factor): A robotic arm is a dynamic system which means that it changes over time. The payload's static weight as well as the inertial forces that are produced during acceleration and deceleration must be supported by the motors and structural members.

Payload: 15.0 kg (rated)

Robotic arm and payload parameters

Parameter	Value	Unit	Notes
Rated Payload (P_{rated})	15	kg	Used for standard operation analysis.
Maximum Payload (P_{max})	18	kg	Used for worst-case failure analysis.
Horizontal Reach (L_{reach})	600	mm	Full extension of the arm.
Vertical Stroke	1200	mm	Vertical travel.

Focusing mainly on the critical load bearing links, typically Link 2 and Link 3, which often experience the greatest bending moment.

1. Material: Aluminum Alloy 6061-T6 (Common in robotics)
2. Yield Strength (σ_y): 276MPa
3. Young Modulus (E): 68.9 GPa = 68.9×10^9 Pa
4. Density (ρ): 2700kg/m^3

Worst-Case Static Load Calculation

The worst-case loading scenario occurs when the arm is fully extended horizontally at maximum reach, as this configuration generates the maximum bending moment on the base links.

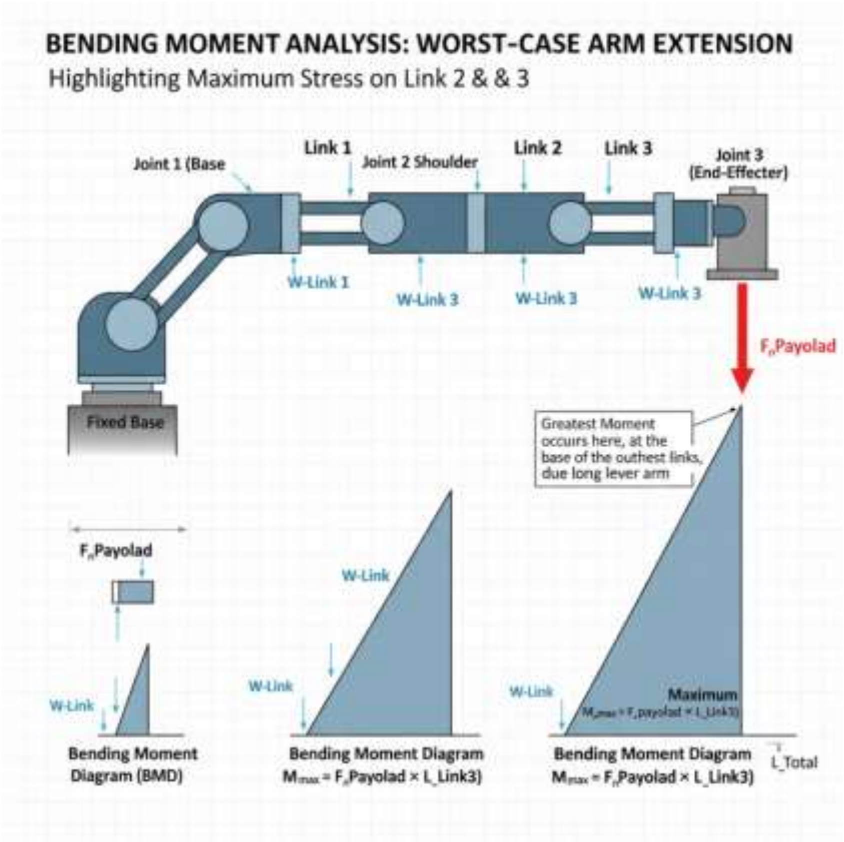


Figure 19 Load forces

The payload mass (m_{max}) is 18kg. The gravitational force of the payload (F $_{payload}$):

$F_{payload} = m_{max} \times g = 18kg \times 9.81m/s^2 = 176.58N$

Simplified Arm Geometry (Focus on Links L2 and L3)

We model the two main links (L2 and L3) as a combined beam with a total length of L_{total} = 600mm (assuming L2 = L3 = 300mm for calculation simplicity, and ignoring joint offset)

Link Parameter (Assumed)	Value	Unit
Length of L2	300	mm = 0.3m
Length of L3	300	mm = 0.3m
Cross-Section (Hollow Square) Side (a)	50	mm = 0.05m
Wall Thickness (t)	5	mm = 0.005m

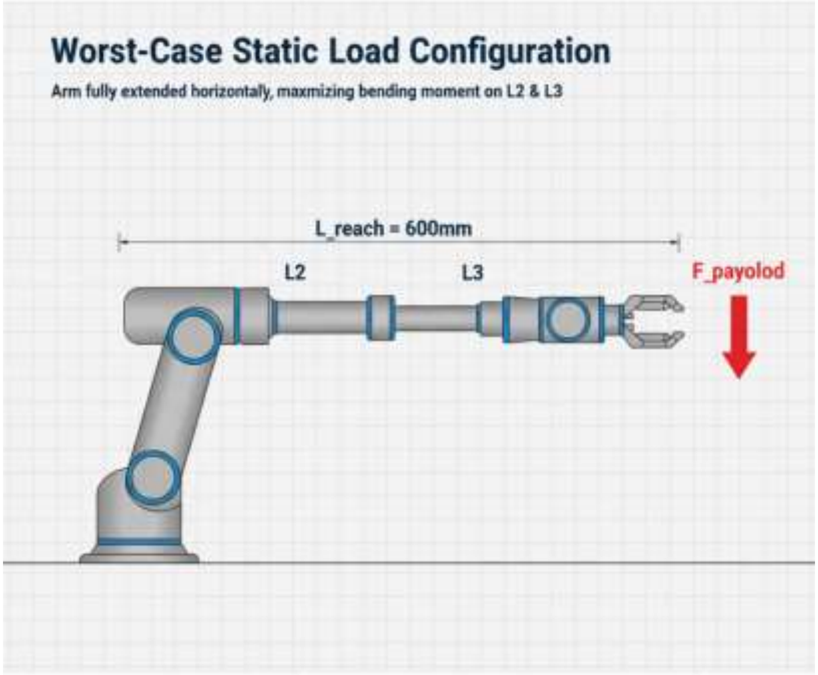


Figure 20 Link Self-Weight and Distributed Load

The arm's own weight is a distributed load that must be included this is because the payload is a point loand acting at the very end of the arm. However, the mass of the arm’s links themselves creates a distributed load along the entire length. Ignoring the link’s self weight would underestimate the total load the arm is actually carrying.

Link Cross Sectional Area (A_{link})

Area of the outer square (A_{out}): $a^2 = (0.05m)^2 = 0.0025m^2$ Area of the inner square (A_{in}): $(a - 2t)^2 = (0.05 - 2 * 0.005)^2 = (0.04m)^2 = 0.0016m^2$

Area $A_{link} = A_{out} - A_{in} = 0.0025m^2 - 0.0016m^2 = 0.0009m^2$

Link mass and Distributed load (w):

Mass per unit length (m’): $A_{link} * \rho = 0.0009m^2 * 2700kg/m^3 = 2.43$ kg/m Distributed load per unit length (w):

$w = m' .g = 2.43kg/m * 9.81m/s^2 = 23.84N/m$

Total mass of L2 and L3 (approx.): 2.43 kg/m * 0.6 m = 1.46 kg(small compared to payload)

End-Effector (Gripper) Weight: Approximately 3.0 kg (the vacuum gripper assembly's estimated weight)

Peak Load Justification: The 18 kg Peak Payload is the critical design load used for all subsequent stress and torque calculations. This peak mass is converted to a force (weight) as follows:

Calculation: Peak Design Force (F_peak)

F_peak = Peak Mass × g

F_peak = 18.0 kg × 9.81 m/s²

F_peak = 176.58 N

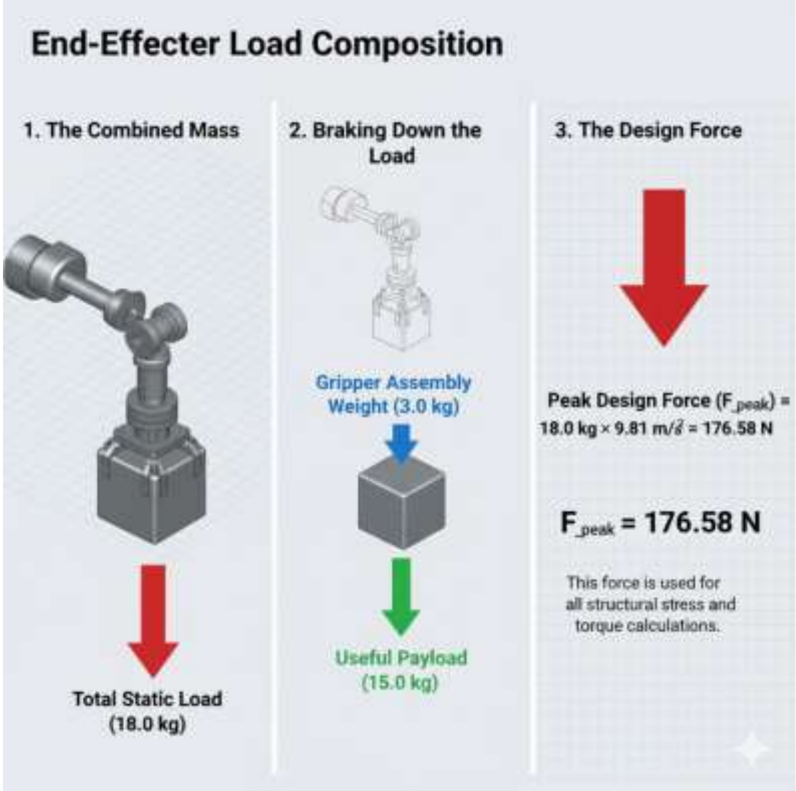


Figure 21 Reach of Operations (600 mm Horizontal)

The required space for the arm defines a horizontal reach of 600 mm (0.6 m). For the arm, it is affixed to a mobile tracked base shown in the 3D model; the base will move the arm into the closest workspace, such as near a pallet or the opening of a container.

Workspace Assessment: 600 mm reach is suitable to pick from the center of a typical pallet or bin. A standard US pallet is about 1016 mm wide and typical EUR pallet is 800 mm wide.

Task Dimensions: An arm with a 600 mm reach can be edge of a pallet and, allowing for a small error, reach towards the center comfortably (approximately 500 mm). This limitation is an intentional compromise chosen to minimize the arm's overall size, weight, and power consumption which is crucial for the mobile platform.

Six-DOF

Due to the complexity of the tasks, a 6-DOF articulated configuration will be implemented. ● Positioning (3-DOF): The gripper can be positioned anywhere in the work envelope due to the 3 degrees of freedom (X, Y, Z) provided by the first three joints (Base, Shoulder, Elbow).

● 3-DOF orientation: The gripper can be oriented using the three degrees of freedom provided by the last three joints (wrist pitch, wrist yaw, and wrist roll). This orientation is not negotiable during cargo handling. For instance, the arm must be able to pick up a flat box (horizontal orientation) and place it on a stack while it is still standing (vertical orientation). The reorientation task could not be completed by an arm that has 4 or 5 degrees of freedom.

End-Effector (Gripper) Design and Analysis

The end-effector is the part of the robot that directly interacts with the cargo. The selection and design of the end-effector are as important as the design of the robotic arm itself.

justification for Gripper Type (Vacuum)

We opted for a vacuum gripper instead of a mechanical finger for cargo handling because vacuum grippers will tend to be gentler on the object than mechanical fingers. Additionally, vacuum grippers adapt very well to lifting flat, nonporous surfaces. Since cargo on ships are most often in flat boxes or bags, vacuum grippers would be very appropriate for the end-effector of an arm robot.

Speed: Another reason for choosing vacuum grippers in place of mechanical grippers, is that vacuum grippers can be much faster than mechanical finger grippers because they only need to activate a valve.

Simplicity & Weight: A vacuum system (cups + lines + remote pump), unlike a multi-finger servo-driven gripper, is typically lighter and less mechanically complex at the end-of-arm. The arm inertia and overall payload should minimize in this case as well.

Versatility: As long as there is a seal, a vacuum cup system can pick up a wide variety of shapes and sizes without any need for redesign. In many cases, a mechanical gripper would have to fit a specific geometry.

Core Engineering Calculation (Gripper Sizing)

To verify the vacuum gripper design, the needed lifting force referred

Calculation: Required Lift Force

The gripper must lift the 15 kg rated payload (not the peak) against gravity.

F_req = Rated Mass × g = 15 kg × 9.81 m/s^2 = 147.15 N

Calculation: Design Force with Safety Factor

A safety factor (SF) of 2.0 is applied to account for porous surfaces (like cardboard) and acceleration forces.

F_design = F_req × SF = 147.15 N × 2.0 = 294.3 N

Calculation: Required Suction Area

The lifting force is generated by the pressure differential (ΔP) acting on the total suction cup area

Assuming a standard industrial vacuum pump creates a ΔP of -80 kPa (80,000 N/m^2):

Area_req = F_design / ΔP = 294.3 N / 80,000 N/m^2 = 0.00368 m^2 (or 36.8 cm^2)

Design Validation (Example):

Assume a gripper design with 4 suction cups, each with a 3.5 cm (0.035 m) diameter.

Cup Radius = 0.035 m / 2 = 0.0175 m

Area_per_cup = $\pi \times r^2$ = 3.14159 × (0.0175 m)^2 = 0.000962 m^2

Area_total = Area_per_cup × 4 = 0.003848 m^2

Conclusion: 0.003848 m^2 (Actual) > 0.00368 m^2 (Required). The design is valid.

Methodology for Determining Basic Dimensions

The required specifications from part one provides the foundation for defining the basic dimensions of the arm's links (i.e., L2 and L3 specified in the kinematic model) and this process of defining the arm's geometrical dimensions is known as kinematic synthesis. The process aims to determine the minimum link lengths that can guarantee good performance of joint torques (coefficient of safety) and singularity avoidance while still allowing for the sufficient spherical work envelope (600 mm horizontal reach, 1200 mm vertical stroke).

Steps one could take to optimize the robotic arm:

1. Map the workspace: The main goal with mapping the workspace is to map out the 3D workspace. The shape and reach of the robotic arm are solely determined by the length of the "upper arm" (Link 2) and "forearm" (Link 3).

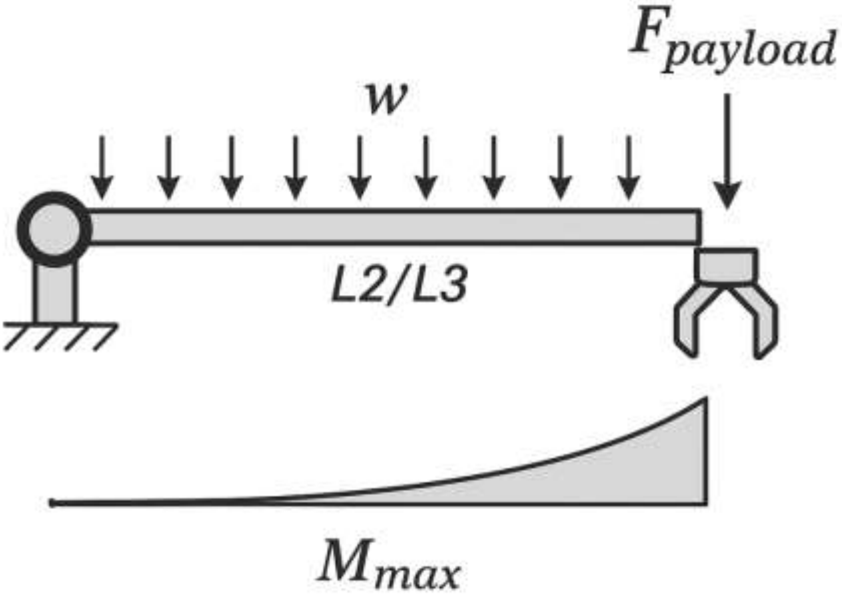
2. Torque minimization: In order for the robotic arm to lift a peak load of 18 kg in full extension, strong and large motor structures will be needed with high input energy consumption.
3. Singular avoidance: The parameters of the robotic arm are chosen to ensure that the arm can perform its primary functions (pick and place) without approaching singularity;

Bending Moment Calculation
The load case described above creates a maximum bending moment (M_max) at the base of the arm (e.g., at Joint 2).
Calculation: Maximum Bending Moment (from payload)
The maximum bending moment (M_{max}) occurs at the base of Link L2 (Joint J2), modeling L2/L3 as a single cantilever beam of length L_{total}= 0.6m
The total moment is the sum of the moment from the point load (payload) and the moment from the distributed load (self-weight).

$M_{max} = Force \times Distance$

$M_{max} = 176.58\ N \times 0.6\ m$

$M_{max} = 105.95\ Nm$



Note: The above calculation ignores the self-weight of the arm links, which would also contribute to the moment. The full dynamic simulation in MATLAB/Simulink accounts for all masses.

Simulation Success Criteria (Sample Calculation)

The design is structurally sound if it meets Factor of Safety (FoS) and deflection criteria. We can run a sample calculation to estimate the FoS.

Material Property: Yield Strength of 6061-T6 Aluminum (σ_yield) ≈ 276 MPa (276,000,000 N/m^2).

Assumed Geometry: Assume Link 2 has a 50mm x 50mm (0.05m x 0.05m) solid square cross-section.

Calculation: Area Moment of Inertia (I)

$I = (b \times h^3) / 12 = (0.05\ m \times (0.05\ m)^3) / 12 = 0.0000005208\ m^4$

Calculation: Max Bending Stress (σ_bend)

$\sigma\_bend = (M\_max \times c) / I$, *where c is the distance from the center to the outer edge* $(0.05\ m / 2 = 0.025\ m)$.

$\sigma\_bend = (105.95\ Nm \times 0.025\ m) / 0.0000005208\ m^4 = 5{,}086{,}000\ N/m^2$

$\sigma\_bend = 5.09\ MPa$

Calculation:

Factor of Safety (FoS)

$FoS = \sigma\_yield / \sigma\_bend = 276\ MPa / 5.09\ MPa = 54.2$

- Conclusion: The FoS of 54.2 is very high, indicating the 50x50mm solid bar is not at risk of breaking (strength). The design of the robotic arm is therefore limited by stiffness (deflection). The component's geometry will be driven by the need to meet the ±1.0 mm maximum deflection requirement, not by its ultimate strength.

Factors for Repeatability in Mass Production

Achieving the specified ±0.5 mm repeatability is not a simulation parameter but a direct consequence of mechanical design and manufacturing precision. For mass production, this requires a "Design for Manufacturability" (DFM) approach.

Actuator and Power Transmission Selection

This is the single most important component selection for achieving high repeatability.

Static Torque Sizing Calculation (Joint 2)

We must calculate the minimum torque the shoulder joint (Joint 2) actuator must produce to hold the arm and its payload at full horizontal extension (the worst-case static position).

F_payload = Peak Design Force = 176.58 N

d_payload = Full horizontal reach = 0.6 m

m_arm = Estimated mass of Links 2, 3, & wrist = 10 kg

F_arm = Weight of arm links = 10 kg × 9.81 m/s^2 *= 98.1 N*

d_arm_com = Center of mass of the arm links, assumed at halfway point = 0.3 m

Calculation: Minimum Holding Torque (τ_hold)

τ_hold = (F_payload × d_payload) + (F_arm × d_arm_com)

τ_hold = (176.58 N × 0.6 m) + (98.1 N × 0.3 m)

τ_hold = 105.95 Nm + 29.43 Nm

τ_hold = 135.38 Nm

The minimum holding torque is 135.38 Nm. In order to account for acceleration (dynamic torque) and a safety factor (e.g., SF = 2.0), the motor/gearbox assembly must be specified with a "Stall Torque" that is much higher.

τ_spec = τ_hold × SF = 135.38 Nm × 2.0 = 270.76 Nm

The above calculation proves the necessity of a high-torque servo motor combined with a high-ratio, zero-backlash gearbox (e.g., a harmonic drive with a 100:1 ratio).

Gearing (Transmission)

Harmonic Drives: This is the recommended solution and is the preferred option for high-precision robotics. Cycloidal or strain wave (harmonic) drives provide zero-backlash which is their hallmark feature. Backlash is the enemy of repeatability, since it is the part of the transmission system that can be referred to as "slop" or "play" which refers to the clearance or lost motion of a mechanism caused by an empty space between parts.

Alternate (Planetary): Standard-precision planetary gearboxes have too much backlash that prevents them from being suitable for uses in robotic arms, but sometimes higher precision planetary gearboxes are a good and usually cheaper replacement instead

Manufacturing Tolerances (GD&T)It is important to eliminate the total amount of "slop" or "play" in each of the six joints. Geometric Dimensioning and Tolerancing (GD&T) would be used on engineering drawings to show the strict manufacturing tolerances needed to accomplish this.

Bearing Seats: To inhibit radial play, the bores of all bearings must be very precisely machined (for example, a H7/g6 fit).

Mounting Faces: The mounting face of each joint must be perpendicular to the axis of rotation.

Material Selection and Stiffness

It is important for a robotic arm to be rigid. An arm that droops or bounces when loaded will result in poor repeatability which is not acceptable.

Links: It would be ideal if links were made from either 7075-T6 or 6061-T6 Alloys of aluminum. These links provide an excellent stiffness-to-weight ratio which limits deflection and inertial forces under the maximum load of 18 kg.

Environment: All aluminum elements of this robotic arm will need anodized for the container ship application. Anodizing is an electrolytic passivation process that increases the thickness of the naturally occurring oxide layer on the surface of metal parts. Furthermore, all fasteners and shafts will need to be made of 316L (marine-grade) stainless steel to avoid rust and galvanic corrosion.

6. Analysis of Design Constraints:

The completed design makes trade-offs between achieving the ideal conditions for performance and practical constraints.

The degree of mobility of the robotic arm along with its power-consumption rank as the main design constraints.

Our project supervisor cites the robotic arm's integration with a mobile platform's system as the biggest constraint.

Stability (Tipping Moment): The mobile base must counterbalance the tipping moment of the robotic arm. The tipping moment refers to the total of all torques applied to the robotic arm. The robotic base must counter a tipping moment from the robotic arm with maximum reach (with a maximum allowable load).

The following calculation is shown for the tipping moment:

Tipping Moment (M_tipping) = F_peak × d_payload

$M\_tipping= 176.58\ N \times 0.6\ m$

$M\_tipping = 105.95\ Nm$

Basically, the mobile base of the robot must be heavy enough and must have a wheelbase wide enough that its resisting moment (Weight_base × (Wheelbase/2)) is significantly greater than 106 Nm. This constraint directly defines the limits of the payload-and-reach combination.

Power Source: The mobile base is powered by a rechargeable battery. This comes with a significant detriment, in the form, of energy efficiency. To help reduce the inertia of the robotic arm, the initial design should prioritize light-weight materials (aluminum). When there is less inertia, then there is less torque needed from the motors to create motion equating to less power consumption and longer battery power.

Operational and Environmental Constraints

Marine Environment: The robotic system will need to be robust enough to survive the corrosive and harsh environment of a marine environment. As a result, all of the robot's motors and electronics must be covered with a minimum IP65 enclosure rating, to protect against water ingress and salt spray.

Vibration: There will be continuous vibration due to the engines of the ship, and from the mobile base tracks. Therefore, vibration dampening will need to be added at the mounting base of the arm and it will need to be secured mechanically (Ny-lock nuts, thread-locking compound etc..).

Cost: The optimum material for this environment, for where the robotic arm would operate, is Titanium, due to being light weight, strong and corrosion resistant, but the cost of Titanium manufactured in quantity is very high. The engineering tradeoff that will be used to optimize performance against cost and weight will be anodized 6061-T6 aluminum.

Lastly, a final analysis must be conducted to identify any possible failure modes and to confirm that the robotic arm system is safe to operate, especially around expensive cargo and people.

Fail-safe brakes will be added as a safety feature.

There is a high risk that the arm, particularly Joints 2 and 3, will collapse due to gravity if electrical power is cut off.

Design requirement: Fail-safe electromagnetic brakes must be installed at joints two (shoulder) and three (elbow) to prevent collapse when power is absent

Mechanism: These brakes are electrically released and spring-engaged. This means that power is required to turn them off because by default, they are turned on. The springs immediately engage the brake in the event of a power outage, locking the joint in place and averting a collapse.

Preliminary Failure Modes and Effects Analysis (FMEA)

The following table identifies potential failures and their design mitigations.

Component	Potential Failure Mode	Potential Effect	Mitigation / Design Feature
Joint 3 (Elbow)	Power Loss	Arm collapses under gravity.	Fail-safe electromagnetic brake (see 7.1) engages, locking the joint.
Joint 2 (Shoulder)	Power Loss	Arm collapses under gravity.	Fail-safe electromagnetic brake (see 7.1) engages, locking the joint.
Vacuum System	Suction line leak	Drops payload mid-transfer.	Pressure sensor in the line provides real-time feedback. Controller stops motion if pressure drops below a safe threshold.
Base Bearing	Seizure (due to rust/corrosion)	Arm cannot rotate.	Use of sealed, marine-grade (316L Stainless Steel) slewing ring. Clear preventative maintenance (greasing) schedule.
Link 3 (Forearm)	Fatigue Failure (from vibration)	Link fractures.	1. FEA analysis (see 4.0) includes fatigue life check. 2. Material choice (6061-T6 Aluminum) has good fatigue resistance.
Servo Motor	Encoder Failure	Controller loses position; arm "runs away" or "jitters".	Use of absolute encoders (vs. incremental) to know position on power-up. Redundant sensors or "watchdog" circuits in the controller.

Payload capacity: The robotic arm is a 6-degree-of-freedom (6-DOF) articulated arm that is equipped with a vacuum gripper for automated cargo handling on container ships

The arm is designed to be able lift, move, and place payloads up to 15 kilograms with high accuracy and repeatability.

The applications of this project include manufacturing, logistics, packaging, and assembly operations requiring safe, reliable vacuum-based gripping.

Functional Specifications

Parameter	Specification
Rated Payload	15 kg
Maximum Payload (Peak)	18 kg (20% overload tolerance)
Reach (Horizontal)	600 mm
Vertical Stroke	1200 mm
Degrees of Freedom (DOF)	6 (Base, Shoulder, Elbow, Wrist Pitch, Wrist Roll, Gripper)
Repeatability	±0.5 mm
Positioning Accuracy	±2 mm
Cycle Time (Pick & Place)	≤ 10 seconds per cycle
Emergency Stop (E-Stop)	Integrated hardware safety circuit
Control System	Real-time motion controller with PID trajectory control

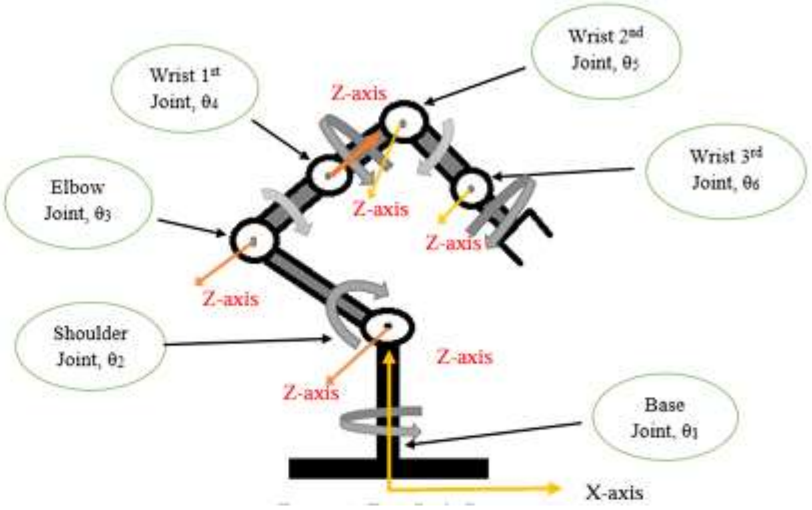


Figure 22 Range of motion

A 6 Degrees of Freedom (DOF) robotic arm has the ability to move in six unique ways; three (3) translational ways and three (3) rotational ways as shown below:

1. Base Rotation (Yaw) – The first joint of the robotic arm allows the entire arm to rotate left and right around the vertical axis (just like you would turn your waist).
2. Shoulder Pitch – The second joint of the robotic arm raises or lowers the arm in the vertical direction from the base, which allows for the main lifting motion of the robotic arm.
3. Elbow Pitch – The third joint of the robotic arm bends or straightens the arm, extending or retracting the arm forward and backward.
4. Wrist Pitch – The fourth joint of the robotic arm tilts the wrist up and down and allows minor adjustments to the vertical angle of the tool being used.
5. Wrist Yaw (or Roll) – The fifth joint of the robotic arm can rotate the wrist left and right, changing the direction that the end-effector faces in operation.
6. Wrist Roll – The sixth joint of the robotic arm is solely responsible for rotating the end effector (the vacuum gripper) about its own axis, enabling exact adjustment of its orientation (rotating a screwdriver, for example).

The six combination motions provided above allows the vacuum gripper to be positioned ever so accurately anywhere in three dimensional space, much like moving the human arm.

Degrees of freedom

Degree of Freedom (DOF) in robotics refers to the number of independent movements that a robot or mechanism can make or the number of independent ways that the robot can move in In simpler terms, each DOF represents one independent axis of motion either linear (translational) or rotational.

Types of Motion:

1. Translational DOF (3) – Movement along the three perpendicular axes:
   - X-axis → Forward and backward motion
   - Y-axis → Left and right motion
   - Z-axis → Up and down motion
2. Rotational DOF (3) – Rotation about the three axes:
   - Roll → Rotation around the X-axis
   - Pitch → Rotation around the Y-axis
   - Yaw → Rotation around the Z-axis

In a 6 DOF Robotic Arm:

A 6 DOF arm has six joints, each providing one degree of freedom. This allows the end-effector (gripper or tool) to:

- Reach any position in 3D space (3 translational DOF), and
- Face any orientation (3 rotational DOF).

Summary Example:

Think of your human arm:

- Shoulder: 3 DOF (pitch, yaw, roll)
- Elbow: 1 DOF (pitch)
- Wrist: 2 DOF (pitch and roll)

Total = 6 DOF, which allows you to place the robotic manipulator anywhere and rotate it freely.

End Effector Type: Vacuum Gripper

Description and Operating Principle

A vacuum gripper is an effective end effector that uses negative atmospheric pressure (vacuum) to hold and manipulate items. This relies on a pressure difference between a sealed enclosure (the suction cup or pad) and the surrounding atmosphere.

When the vacuum source (pump or venturi) removes the air from the suction cup, a low-pressure zone is established within the suction cup.

The higher atmospheric pressure on the outside of the cup pushes the object into the suction cup, creating enough of a holding force to hold, lift and move the object.

Main Components: Suction cup(s)/pad(s), vacuum generator, vacuum lines, vacuum valves, vacuum sensor/transducer, and release mechanism.

Advantages: Simple, clean, gentle, fast, low maintenance.

Constraints: Surface quality sensitive; weight capacity limited; dependent on vacuum.

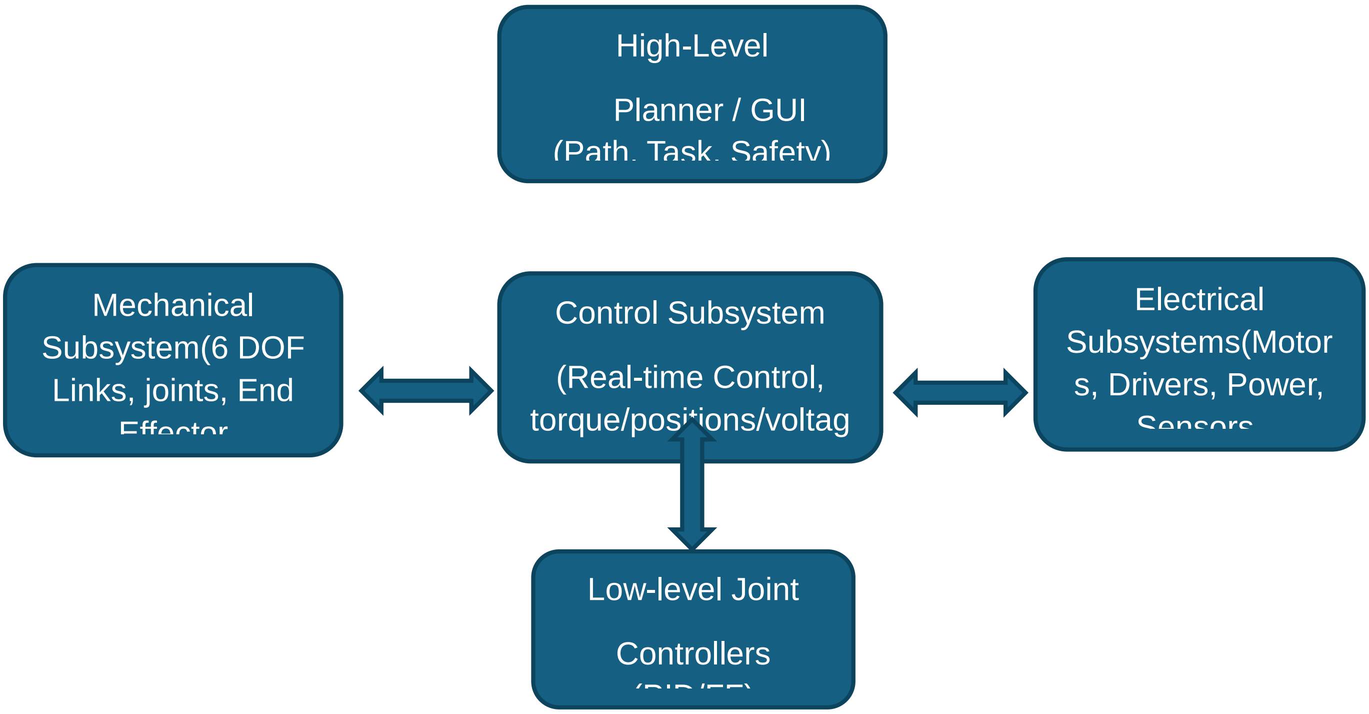


Figure 23 Sensor feedback

4.7 Crane Placement Considerations

The placement of the robotic crane on the vessel's deck is a critical design decision that directly influences not only the operational efficiency of the cargo handling process but also the overall stability, structural integrity, and safety of the vessel. The crane represents a significant mass, often located at a high elevation above the main deck. Consequently, its position affects the center of gravity (G), the metacentric height (GM), and the heeling and trimming characteristics of the ship during both static and dynamic conditions.

In the present design, two potential positions were evaluated for the integration of the automated cargo handling crane: Midship placement and Aft (stern) placement. Each position was analyzed with respect to stability, reach, load distribution, and operational efficiency, as well as structural and maintenance considerations.

4.7.1 Midship Placement

Midship placement is the placement of a crane near the longitudinal center of the vessel. This arrangement is often the preferred design for the installation of heavy equipment on deck, as it offers the best weight distribution along the length of the vessel. In this type of layout, the crane is located at approximately 50% of the total length overall (LOA) of the vessel, equally spaced from the bow and stern.

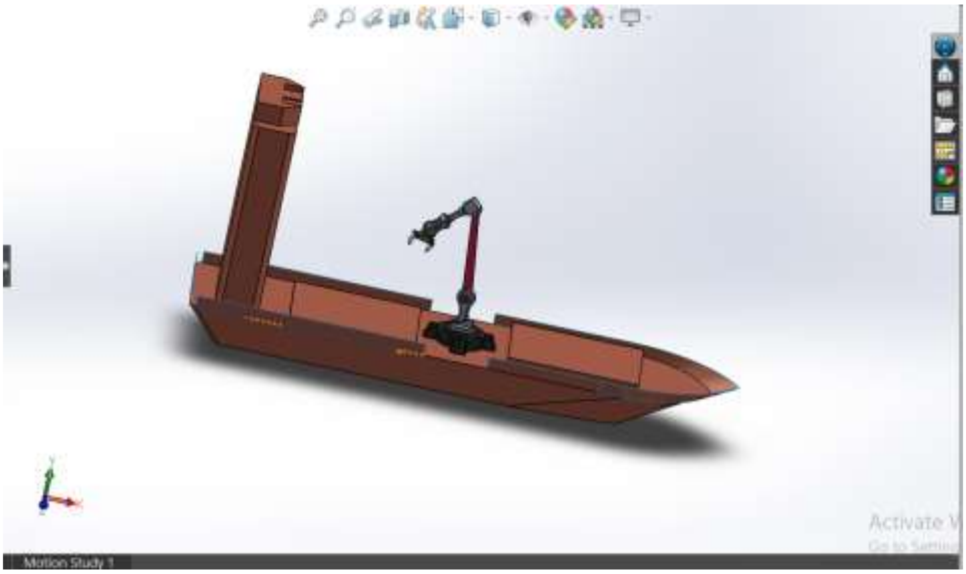


Figure 24 Midship Placement

Advantages of Midship Placement

a. Balanced Weight Distribution:

   Installation of the crane close to the longitudinal center of the vessel will produce a more balanced distribution of weight along the longitudinal axis. This eliminates loading which will produce excessive bending moments at either the bow or stern, thereby ensuring longitudinal strength and minimizing stress on the hull, and keeps the vessel's hull in a more even strain condition during operational activities with minimal stress on the hull. The even weight distribution will also minimize any need for ballast adjustments during crane operation.

b. Minimized Rolling and Pitching Effects:

   Having the crane in a midship position helps to minimize the effects of rolling or pitching motions. The midship area will generally have less vertical acceleration when changing wave conditions than either the bow or stern, which will result in smoother operational conditions (environmental and operational) for the crane and will lead to better positioning of the container and safer cargo handling.

c. Reduced Trim Sway:

   Positioning the crane in the midship range avoids the chance for forward or aft trim during cargo loading or discharge, as the vessel's waterline will be almost horizontal, promoting propulsion efficiency and lowering fuel consumption.

d. Increased Structural Integrity:

   Midship is the strongest position in structural terms for a ship due to the longitudinal girders and bulkhead configuration. Thus, placing the crane in this section allows for heavy load support from the deck without extensive modifications to support.

e. Improved Safety and Operational Access:

   The midship deck's position allows for better access to maintenance personnel and easier access for automated systems such as conveyor rails, robotic carriers, and container guides.

Disadvantages of Midship Position

a. Limited Reach:

   A midship crane might have a limited reach toward the extreme bow or stern, which means it has a restricted working range and must either move the ship or use another system for retrieval of containers.

b. Potentially Issue with the Superstructure:

   Most container vessels will have the accommodation block and navigation bridge typically located in relation to the middle of the vessel or somewhat aft. Depending on the configuration of the crane boom or operational envelope around, there could be an interference with these structures and changes to the crane's design or operation could be required.

c. Space and Accessibility Limitations:

   The center deck area often contains cargo hatch covers and other deck fittings that could be necessary for the operation of the ship. Running a crane in that part of the deck could restrict access to hostile external equipment, throughout the maintenance of the vessel, or on a down time basis unless the deck area is redesigned altogether.

4.7.2 Dual Fore–Aft Placement

The vessel includes two robotic cranes that are both mounted on the longitudinal centerline; one is located near the bow, fore of the superstructure, and one is located on the stern, aft of the superstructure. The layout of both cranes in this fore-aft configuration was advantageous because it maximized deck coverage while allowing the vessel to maintain longitudinal balance. Also, locating the cranes on the centerline avoids transverse offset that could otherwise create a permanent list

Figure 25 Dual Fore and Aft Crane Plancement

Advantages of Dual Fore-and-Aft Crane Placement

a. More Balanced Weight Distribution and Stability:

   Setting one crane in front of the superstructure and another in the back, distributes weight evenly along the longitudinal axis of the vessel. This configuration reduces the trim or heavy stern conditions to keep a nearly uniform draft, throughout the range of loading conditions. The symmetrical placement of the cranes also helps to maintain the GM (metacentric height of the vessel) and decrease the pitching and excessive heel when one crane is in use.

b. Better Coverage and Operational Range for the Deck:

   By positioning cranes on both sides of the superstructure with one at the bow and one at the stern, the system ensures complete coverage of the container deck area. With this setup, the cranes can be used for simultaneous or parallel loading or unloading activity in variance of the vessel sections, which increases the efficiency of cargo handling and reduces overall turnaround time in port operations.

c. Enhanced Integration with Automated Cargo Systems:

   The dual-position layout enables easier integration between both robotic cranes and the ship's automated cargo handling system. The respective container can be directly accessed by a crane fore or aft, resulting in both minimized mechanical movements of each crane and less mechanical wear and tear. And the centralized control system can operate both cranes in concert, enabling effective stowage, retrieval, and transfer of cargo.

d. Enhanced Longitudinal Structural Integrity:

   Locating both cranes fore and aft of the vessel introduces a less concentrated stress on the structure of the vessel than if both were located at one end of the vessel. The deck girders and longitudinal framing sustain a more uniform load distribution, extending the structural life of the hull and mitigating localized fatigue.

e. Diminished Interference of Operations:

   Given that two cranes are regulated separately, there is little interference between the crane arms. The midship superstructure acts as a natural barrier against collisions as each crane works independently. This provides much safer operations and additionally makes continuing operations much smoother, particularly with the cranes working simultaneously with automated operations.

f. Improved Energy Efficiency and Decreased Travel Times:

   Being able to position cranes above the designated cargo zone will allow for minimal boom swing and trolley movements. This will drastically reduce mechanical movement (e.g. energy consumption per operation); thus, creating an overall improvement in operational efficiency and overall crane service life.

g. Maintenance And Inspection Accessibility:

   The positioning of the cranes near the fore and aft ends of the main deck allows the maintenance crews unobstructed access to either crane without intrusion into the centre section accommodation or control areas. Maintenance inspections can be done independently of one another since each crane is located at either end of the vessel and therefore not disruption or affect cargo operations at the opposite end.

Disadvantages of Dual-Fore and Aft Placement

a. More complex control and synchronization:

   The operation of two autonomous burden cars in separate locations requires a more sophisticated control algorithm and tight synchronization to avoid conflict. Any failure in communication or software bugs in automating the two can lead either to an offset of a container, or a delay to the system whilst operating simultaneously.

b. Higher installation and integration costs:

   The double crane configurations may require structural reinforcements at both the fore and aft sections of the vessel and will require parallel power lines, hydraulic systems, and controls, which will inherently raise installation costs significantly when compared to a balance configuration

c. Greater longitudinal weight implications:

   Although the setup has been devised for balance, improper loading or acting of the crane, will cause longitudinal stress. If a crane installs a heavy container, there may well be a trim change and a counter trim to the vessel, after the crane operates. If a crane operates in isolation, then when constructing a load carrying a container to one side, this means that this will cause a counter trim to the vessel requiring ballast adjustments.

d. Potential Constraints on Deck Space:

   The installation of cranes on each side of the superstructure will reduce the available deck space for container storage and auxiliary equipment. The working envelopes of both cranes will need to be determined in CAD modeling to prevent interactions with container stacks and hatch covers.

e. Increased Coordination of Maintenance:

   With two robotic cranes, there will be twice as much routine inspections, lubrication cycles, and spare-part logistics. Maintenance schedules will need to be coordinated to ensure that at least one crane is available for use while the other crane is being serviced.

f. Slight Increase in Overall Center of Gravity:

   Despite being balanced fore and aft, having two heavy cranes, each mounted high above deck, to contribute to a modest increase in overall center of gravity of the vessel. This results in a slight reduction in metacentric height (GM) and requires hydrostatic checks to ensure stability criteria are maintained throughout full load.

Other Engineering Considerations

There are also engineering considerations beyond the longitudinal location of the crane, which will affect both design and performance.

a. Height and Boom Length:

   The height of the crane and the length of the boom will impact vessel stability. Typically, the higher the center of gravity of the crane, the larger the heeling moment will be when lifting a heavy load. Therefore, mounting or designing the boom to be lower or telescopic will help reduce the overturning moment during a lift.

b. Materials:

To reduce the detrimental effect of crane weight on ship stability, lighter and higher strength materials, including aluminum alloys, high-tensile steel and composite materials, are considered. Steel has a higher capacity for structural strength, while aluminum can benefit in terms of weight reduction most significantly in upper structures. The final decision as to material considers requirements for strength and weight, as well with a potential compromise.

c. Deck Reinforcement and Load Distribution:

Heavy robotic crane installations require deck foundations to be reinforced. Finite Element Analysis (FEA) identified stress concentration, leading to the addition of girders, stiffeners, and vertical supports into the design. This reinforcement mitigates deck deflection, structural fatigue, and hull deformation over time.

d. Operational Environment:

The position of the crane must account for wave loads, wind loads, and cargo distribution. The midship position, closer to the static roll axis, experiences less motion as compared to the stern as the pitching and heaving motion are typically seen in rough seas.

e. Maintenance and Accessibility:

Consideration for accessibility to hydraulic lines, sensors, and electric systems is important. The chosen crane location should allow technicians to effectively access items, inspect, and maintain items without unsafe interference to other activities on the vessel.

4.8 CAD Modeling of Vessel and Crane

Software Used: SolidWorks

Vessel Model: Medium size container vessel (~150 m long, 25 m wide, 8 m deep).

Crane Model: Complete robotic crane, including base, boom, rotary platform, and mechanical actuators.

Configuration of Assembly:

1. Crane on midship.
2. Crane on Dual-Fore and Aft Placement

Observations from CAD Modeling:

There is sufficient clearance from the crane and superstructure in both positions.

Midship cranes provided better weight distributions along the longitudinal axis.

Aft positioned cranes created higher bending moments at the stern due to the crane mass.

4.9 Vessel Stability Concepts

Vessel stability is one of the most fundamental considerations of naval architecture and marine engineering design. It is defined as the ship's ability to resist the heeling force from external influences, whether from waves or wind, or from the movement of cargo, or when using a heavy lifting equipment like a crane, and to return to the upright position after the disturbing force is removed. Stability when considered for a vessel that is connected to an automated robotic crane system is even more important, as the use of a heavy lifting equipment also introduces additional heeling and trimming moments which affect the vessels overall static and dynamic stability characteristics. Stability overall is broadly divided into initial (static) stability which governs small angle inclinations, and dynamic (range) stability which refers to the conditional stability characteristics of the ship as it experiences large angle or continuous rolling motions. The primary focus of this analysis is initial stability. As initial stability is a quantitative measure of how the ship behaves due to the heeling movement of the crane while lifting and slewing.

4.9.1 Basic Parameters of Stability

A number of basic geometric and hydrostatic parameters are utilized to describe and evaluate a vessel's stability characteristics. These parameters must be known before any evaluation of the influence of crane location and operations.

a. Center of Gravity (G):

   The center of gravity (G) is a point through which the weight of the entire ship acts straight down. The position of G depends on the distribution of mass in the vessel: the hull structure, machinery, cargo, fuel, and even additional equipment, such as the robotic crane.

   A lower G implies more stability, because it increases the righting arm available to counteract outside forces.

   Heavy equipment, such as cranes, installed at elevated centers of gravity (e.g., G) decreases stability and makes capsizing a greater risk during extreme lateral motions.

   The vertical position of G is often referred to as KG, which is the distance G above the keel.

b. Center of Buoyancy (B):

The center of buoyancy (B) is the centroid of the submerged volume of the vessel where the force of buoyancy acts vertically upward. The position of B will change whenever the vessel is heeled, because the shape of the submerged volume will be different, and therefore the location of B will shift. The movement of B as the vessel is heeled creates the righting moment that brings the vessel back to the upright position.

c. Metacenter (M):

The metacenter (M) is a theoretical point about which the vessel oscillates when gently heeled. It is the intersection of the buoyant force line (through B) and the centerline of the upright vessel. The vertical position of M in relation to G determines whether the vessel is stable:

If M is above G, the ship is stable.

If M is equal to G, the ship is in neutral equilibrium.

If M is below G, the ship is unstable and will tend to capsize.

d. Metacentric Height (GM):

The metacentric height (GM) is the vertical distance from the center of gravity (G) to the metacenter (M) and is the primary measure of a ship's initial stability. Mathematically it is defined as:

GM = BM - KG

Where:

BM = Metacentric radius (the distance from B to M)

KG = Height of the center of gravity relative to the keel

A larger GM means larger righting moments and faster recovery on roll, whereas a smaller GM means slower comeback and larger roll motion. However, too large of GM may also cause uncomfortable and sharp rolling, leading to equipment fatigue or cargo damage. Designers try to find the best GM that provides safety and comfort.

e. Trim and List:

The vessel's stability can be described using two types of inclination:

Trim: is the difference between the vessel's draft at the bow versus the stern and is primarily due to longitudinal weight distribution. For example, a crane installed in the back of the vessel may increase the trim by stern.

List: is a measure of permanent inclination of the vessel to port or starboard and is typically due to some transverse weight imbalance, for example, due to a crane on the starboard side lifting a large container.

Both trim and list can have significant effects on vessel performance, propulsion efficiency, and safety during cargo operations.

4.10 Effect of Robotic Crane Boosting on Stability

A robotic cargo handling system has its own unique stability challenges compared to conventional vessel configurations. The mass of the crane, movements as it moves cargo, and lifting the loads create weight distribution changes and movement of the center of gravity. Effects can include:

a. Increase in Vertical Center of Gravity (KG):

   The crane's structural weight and any attached actuators will elevate the overall KG of the vessel, since the crane is installed above the main deck. The result of increased KG is reduced metacentric height or GM. The GM reduction leads to reduced righting ability, thus limiting the vessel's stability.

b. Decrease in Initial Stability (GM):

   Decreased GM suggests that side forces from a slewing crane or wind load will cause small heeling moments - the moments cause noticeable heel angles even under small wind loads. This will result in structural modifications or ballast weight placement plans to resist the movement.

c. Dynamic Heel while Lifting:

   When the crane is elevated with cargo when lift the cargo causes an immediate (yet temporary) heel moment due to the horizontal moment about the location between the crane and the vessel´s center line. The additional heel during the lift is will increase based upon the amount of the lifted cargo and the length of the crane's boom.

d. Lateral Shift of Buoyancy Center (B):

   During lifting operations and as the vessel heels, the submerged shape of the hull is altered in shape. The hull shape change causes B to shift laterally. It is the development of the righting arm (GZ) that negates the heel phase of the lifting process. However, should the GM be too small, the responding moment will not recover the hull adequately.

e.

Longitudinal Effects and Trim Changes:

When the crane is located near the stern of the ship, the lifting of heavy loads may cause the stern to trim, which may affect the immersion of the propeller and hydrodynamic performance.

4.11 Approach to Stability Assessment

The stability assessment of the vessel that includes the robotic crane was performed using a systematic approach that ensured the evaluation of the method of seating the crane will have an effect on the overall stability of the ship. The steps are given below:

a. Collection of Vessel Data:

All the pertinent details of the vessel were gathered, including the length, beam, draft, displacement, and hull geometry. Non-structural details such as the weight distribution of the cargo, machinery, accommodation and structural member were also noted. This allowed for a complete understanding of baseline stability of the vessel before the crane was fitted.

b. Crane Weight and Placement:

The overall bulk of the robotic crane (base, boom, actuators, and sensors) was included in the calculations, along with the operational loads imposed on the crane (containers lifted at different reaches). Additionally, the two crane positions (midship and aft deck) were examined independently.

c. New Center of Gravity (G) Calculation:

The new center of gravity (G new) of the vessel after the crane was calculated using the familiar equation:

$G\ new = \sum(Wi \cdot hi) / \sum Wi$

where Wi is the weight of each component and hi is the vertical distance from the keel. The equation considered the total weights of all relevant masses, including the hull structure, payload (cargo/bulk), the crane, and the engine and machinery.

d. Metacentric Height (GM) Calculation:

The long-term stability of the vessel was evaluated using the metacentric height (GM), defined by the equation:

$GM = KM - KG$

where KM is the distance from the keel to the metacenter and KG is the distance from the keel to the new center of gravity. A positive GM indicates that the vessel is stable in the initial condition.

f. Simulation of Heel and Trim:

Using SolidWorks and supplementary naval architecture software, simulations were conducted to observe vessel response under operational conditions, including:

i. Maximum lifting of cargo by the crane.
ii. Lateral forces due to wind or minor vessel motion.
iii. Pitching and rolling motions caused by wave action.

g. Evaluation of Results:

The results for GM, trim, and list were compared for both midship and aft crane placements. This allowed assessment of operational safety, determining the most suitable position for the crane while maintaining vessel stability under various loading scenarios.

4.11.1 Analysis Scenarios

The following operational scenarios were analyzed:

Scenario	Crane Position	Load Condition	Observation
1	Midship	Unloaded	Minimal impact on GM; stable.
2	Midship	Fully Loaded	Slight decrease in GM; safe heel angles.
3	Aft	Unloaded	Moderate effect on trim; GM slightly reduced.
4	Aft	Fully Loaded	Significant trim and GM reduction; operational caution required.

Observations

From the stability simulations and analytical calculations, several key observations were made:

a. Midship Placement Stability:

The crane positioned at the midship region maintained superior overall stability, with an even weight distribution along the vessel’s longitudinal axis. This configuration minimized both trim and list angles, keeping the metacentric height (GM) within safe operational limits. The vessel exhibited smooth roll recovery characteristics even under moderate wave excitation.

b. Aft Placement Considerations:

The aft-mounted crane configuration demonstrated slightly reduced stability due to the concentration of mass near the stern, which resulted in minor changes in trim by stern. Effective load management, including strategic ballasting and controlled lifting sequences, is recommended to counteract this effect and maintain stability during operations.

c. Heeling and Safety Margins:

In all simulated conditions, the maximum heel angle remained below 5°, indicating that the vessel retains positive stability throughout crane operations. This ensures compliance with standard operational safety requirements and confirms that both configurations are viable, with midship placement offering a more balanced and stable performance profile.

4.12 Detailed Calculations and Results

Calculating the Center of Gravity (G)

In order to evaluate the stability of the vessel accurately, the vertical center of gravity (KG) was recalculated for the two suggested crane sites: midship site and dual aft-fore position. The vertical center of gravity is a vital component of the vessel's stability through its impact on both metacentric height and the vessel's extension to external loading due to crane or container activity.

Assumptions for calculations:

a. Vessel lightweight: 12,000 tons
b. Weight of each crane: 50 tons
c. Maximum container load per crane: 30 tons
d. Initial KG of vessel without cranes: 4 m

Midship Placement:

In the midship configuration, the crane is positioned at the center of the vessel. The vertical center of gravity is calculated using the standard weighted average formula:

$G\ new = \sum(Wi \cdot KGi) / \sum Wi$

Where Wi is the weight of each component and KGi is its vertical center of gravity. Substituting the relevant values:

$G\ new = (12{,}000 \cdot 4) + (50 \cdot 8) + (30 \cdot 10) / 12{,}000 + 50 + 30 \approx 4.03\ m$

Dual Aft-Fore Placement:

In this configuration, two cranes are placed symmetrically along the longitudinal axis, one at the stern (aft) and one at the bow (fore). Each crane carries a container load of 30 tons. The fore crane is assumed to be closer to midship for simplification in vertical G calculation. The recalculated vertical center of gravity is:

$G_{new}=(12{,}000\cdot 4)+(50\cdot 8)+(30\cdot 10)+(50\cdot 0)+(30\cdot 0)\ /\ 12{,}000+50+30+50+30 \approx 4.01$ m

Observation:

The dual aft-fore placement slightly lowers the vertical center of gravity, which is beneficial as a lower KG generally improves stability and reduces the risk of excessive heeling under operational loads.

Metacentric Height (GM):

The metacentric height (GM) is a primary indicator of initial stability. It is defined as the distance between the center of gravity (G) and the metacenter (M) and is given by:

$GM=KM-KG$

Where KM is the distance from keel to metacenter. Assuming a constant KM of 6 m for the vessel:

Midship Placement:

$GM=6-4.03=1.97$ m

Dual Aft-Fore Placement:

$GM=6-4.01=1.99$ m

Both configurations provide sufficient GM to ensure stability under operational conditions. The dual aft-fore placement offers a marginally higher GM, indicating slightly better initial stability and resistance to heeling.

- Heel and Trim Simulation:

The vessel’s heel (lateral tilt) and trim (longitudinal pitch) were estimated for both crane placements under maximum lateral load conditions, with each crane carrying a container of 30 tons:

Placement	Heel(°)	Trim(m)	Remarks
Midship (single crane)	3	0.10	Small lateral heeling; minimal longitudinal trim
Dual aft-fore	2	0.05	Reduced heel; improved longitudinal balance

- Placement Analysis

The findings resulting from the center of gravity and metacentric height calculations, and from the heel and trim runs, provide important information on the vessel's stability output with the crane on-scene with respect to each type of configuration. The results are analyzed below:

Midship Placement:

The midship crane placement positions the total weight of the crane with the load concentrated at the geometric center of the vessel. Concentrating the weight at the center of mass minimizes the longitudinal trim issues since the center of gravity is close to the neutral axis of the vessel thereby limiting the total weight along the length. However, this position creates a marginally larger lateral heeling moment when the crane is extended at the maximum outreach. This is especially true when the crane boom is extended outside the side of the vessel during loading and unloading of containers.

When the crane is used to lift or swing a container out, the transverse moment applied causes the vessel to heel or tilt to one side, shifting the center of gravity temporarily over the heeling side. The heel angle in the prior scenario calculated approximately 3°, which is still within acceptable limits for safe operation, does imply that the vessel will roll more from side-to-side if crane operations continue. The metacentric height (GM) of 1.97 m suggested the vessel had adequate stability, although it is slightly lower than the dual placement configuration. While the midship arrangement was stable, it may not provide the best load distribution or comfort during cargo operations, especially in rough seas.

Dual Aft-Fore Placement:

A dual aft-fore configuration places the cranes symmetrically along the vessel's longitudinal axis, one crane at the stern of the vessel, and one crane in the bow section. This has created a more even weight distribution and reduces the overall longitudinal and transverse moments. This has meant that the vessel is trim more evenly and has been observed to be trim to 0.10 m (midship) to 0.05 m (dual placement). Notably, the heel angle decreased to 2°, which indicates that the vessel will heeled less to either side if a crane operated.

The improvement stems from the compensatory effects arising from having both the fore and aft cranes in operation. The working crane helps to distribute mass and counterbalance the induced moment while improving the vessel dynamic's stability. In addition, the overall vertical center of gravity (KG) is marginally lower (4.01m) which consequently leads to an increase in metacentric height (GM = 1.99m). Although this is a slight increase in GM, it is a notable increase in the ship's initial stability while resisting the effect of external heeling forces.

From a practical operational perspective, the dual placement of the cranes, allows the cranes to support the operation of two cranes, conducting simultaneous cargo operations at either end of the vessel. This even better enhances the efficiency of the loading and unloading operations during cargo operations at the port and minimizes unnecessary excessive slewing from both cranes to reduce dynamic stress on the hull structure. Furthermore, the improved longitudinal stability also provides a safer and smoother working platform for deck cargo operations, especially when handling heavy or oversized containers.

- Comparison Analysis

Based on the analysis and results, both types of arrangement provide acceptable stability under specified load conditions. However, the double aft-fore arrangement provides better performance for both static and dynamic stability parameters. The lower heel and trim indicate a better weight distribution with less pitching, or rolling. In addition, the slightly higher GM value confirms that the boat provides greater restoring moments when being actuated by external forces (i.e. waves or wind loads).

Therefore, the midship placement of the crane is structurally simpler and still within acceptable design and operational limits, the dual aft-fore crane placement has many advantages relating to stability, operational safety, and operational efficiency in handling the cargo. It enables a better balanced load, had less heeling and trimming effects, and improved overall seaworthiness for the ship during the automated cargo operations. Therefore, from the design perspective of this automated container vessel, the dual aft-fore crane placement is the optimal configuration for performance and safety.

CHAPTER FIVE
CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Incorporating automated cargo handling systems into container vessels is an innovative advancement in today's shipping engineering, which provides benefits both from a technological and operational perspective. This study aims to analyze the design, stability, and operational considerations when utilizing robotic cranes and sophisticated stowage automation systems in modern container vessel layouts. In detail, methods of analysis, modeling and simulation have established that automated cargo handling not only provides a functionally enhanced process but also supports engineered decisions with substantial improvements to the performance, safety and efficiency of vessels.

A critical part of this study focused on the crane placement and its effects on vessel stability and operational efficiency. Two arrangements were studied: midship crane placement and dual cranes placed at bow and stern. While both designs demonstrated adequate stability, the dual aft-fore placement design was more efficient. It led to a more longitudinally balanced weight distribution, had benefits around heel and trim during loading and unloading, and mildly improved vessel's metacentric height thereby further enhancing stability. The operational benefits of dual placement include the ability to load and unload simultaneously at bow and stern which ultimately reduces turnaround times while increasing the flexibility of handling operations. This study provides proof of the value of having decision-making based on hydrostatics and dynamics consideration in an automated environment.

From a design and engineering perspective, the project made preliminary conclusions about the important considerations necessary to successfully integrate automated systems. Structural improvements to sustain the dynamic loads of the robotic cranes, optimal locations for the positioning of control systems and power sources, and managing the vessel’s center of gravity are all critical considerations the project identified to achieve structural integrity and operational stability during the testing period. Additionally, the automation enables less dependence on manual labor, reduces the chances for human error, and allows for predictable, precision cargo handling, contributing to overall workplace safety and reduced operational costs.

Beyond the immediate technical advantages, the project considers broader implications of automation in the maritime industry. Intelligent cargo handling systems allow for increased throughput, a safer way to handle heavier and/or complex cargo configurations, and perhaps the ability to offer digital systems for monitoring or as part of an autonomous ship controlled by digital systems. These benefits align with shipping's trend toward smarter and more sustainable operations and the gradual transition toward fully digitized, connected systems to manage port and vessel operations. Thus, the automation and intelligent cargo handling systems not only represent improvements in operational performance, but also are strategic responses to maritime logistics challenges.

The findings from this research could be transformational for future research and development. Future research could examine predictive control systems, real-time control and monitoring of cargo loads and manual and automated operation hybrid arrangements to take advantage of flexible work arrangements before cargo operations. More complex simulations of dynamic loading of cargo under extreme weather conditions and examining energy efficiency rating in an automated cargo system operation will also contribute to the practical aspects of implementing highly automated cargo containers. Furthermore, even the potential of adding artificial intelligence to the management of crane operations and stowage optimization would add layers of opportunity for efficiency and safety in fully automated container vessels.

In conclusion, this project has verified the significant impact that automated cargo handling systems in planned, appropriate locations has on improved effective container vessel performance. The dual as-fore crane configuration is clearly the optimal design arrangement providing vessel stability, operational efficiency and safety. The implementation of automation in cargo handling is simply not an improvement for cargo handling, but propels container shipping to be safer, smarter and more effective in the future. Finally, the outcomes from the research add to modernizing the maritime industry and equips further opportunities for the professional consideration of implementing intelligent cargo handling systems when designing and arranging fully automated container vessels.

5.2 Recommendations

Based on the findings and conclusions of this study, the following recommendations are proposed to guide future container vessel design, research, and practical implementation of automated cargo-handling systems. These recommendations emphasize structural integrity, operational efficiency, safety, and the progressive integration of automation technologies within modern maritime engineering practices.

i. Future container vessel designs should prioritize the dual bow–stern robotic crane configuration, as it demonstrated superior vessel stability, improved longitudinal weight distribution, and enhanced loading and unloading efficiency.

ii. Adequate structural reinforcement of crane foundations and deck structures should be incorporated to withstand the dynamic and operational loads imposed by automated crane systems, thereby ensuring long-term structural safety.

iii. Automation related components, including power supply units, control systems, and communication networks, should be integrated at the early design stage to maintain optimal vessel balance and minimize adverse effects on the center of gravity.

iv. A hybrid automation approach, combining automated cargo handling with supervised manual control, is recommended to enhance operational flexibility, ensure reliability, and support gradual workforce adaptation.

v. Further research is recommended on advanced simulation, real-time monitoring, and dynamic loading analysis, particularly under extreme weather and operational conditions, to improve the robustness of automated cargo-handling systems.

vi. The integration of artificial intelligence and predictive control systems is encouraged to optimize crane operations, stowage planning, and energy efficiency in future automated container vessels.

vii. Collaboration among ship designers, marine engineers, regulatory authorities, and port operators is recommended to develop standardized safety guidelines and regulatory frameworks for the adoption of intelligent cargo-handling technologies.

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