

DfX-based Design of a Multi-Robot Cell for Light Gauge Steel Panel Assembly and Manufacturing Operations

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Abstract –

As the construction industry undergoes a digital transformation, there is an increasing demand to transition from rigid manual fabrication to intelligent, flexible multi-robotic systems capable of managing complex design constraints. This research presents a generalized framework for a multi-robotic cell designed for Light Gauge Steel (LGS) assembly. The methodology utilizes a Design for Excellence (DfX) approach, incorporating Reconfigurability, Portability, Sustainability, Safety, Assemblability, and Stability, to optimize the physical and functional layout of a cell comprising a fixed industrial robot and an autonomous mobile robot. A resource-ontology-based framework defines the spatial and functional relationships between system components and the LGS assemblies. Structural validation via Finite Element Analysis (FEA) confirmed the design's integrity, with the gantry structure exhibiting a maximum von Mises stress of 6.449×10^7 N/m² and a minimum factor of safety (FOS) of 3.9. Stability analysis revealed robust tipping FOS values of 1.65 for the gantry and 139.1 for the rotary worktable, ensuring a reliable platform for automated construction applications.

Keywords –

Multi-Robotic System; DfX; Light Gauge Steel; Resource Ontology; Offsite Construction

1 Introduction

As the construction industry undergoes digital transformation, particularly in steel panel assembly processes, there is an increasing demand to transition from rigid, manual fabrication processes to the integration of highly flexible, intelligent multi-robotic systems capable of managing multiple tasks and addressing complex design constraints. The assembly of large-scale steel panels in construction applications such as shipbuilding, bridge construction, and architectural

frameworks or building components has traditionally relied on labor-intensive welding and positioning processes. Construction environments are known to be less favorable for the use of robotic technologies [1], owing to their messy, uncertain conditions and varying task requirements. Thus, construction work has mainly been handled manually despite the safety concerns and difficulty associated with such tasks [2] [3]. However, in the case of an off-site construction setting with precisely controlled manufacturing and assembly processes in a factory-based environment, the employment of robotics systems has proven to offer various benefits like enhancement of safety, quality, and productivity in the various stages of assembly and manufacturing procedures [4] [5] [6].

Japan, for instance, has adopted construction factory (CF) technology, a factory-like structure that surrounds a building and contains various robotic systems to automate construction tasks. Some examples include ABCS system (Obayashi Co.), T-UP method (Taisei Co.), AMURAD system (Kajima Co.), and ROOF PUSH-UP construction method (Takenaka Co.) [7] [8] [9] [10]. The RCA (Robot-based Construction Automation) project initiated in Korea is another example of implementing robot-assisted steel beam assembly tasks for a high-rise building [11]. Another major contribution of robotic systems for steel panel assembly is the reduction of overall construction project costs and time. One study presents an automated robotic assembly system comprising a robotic bolting device, a robotic mobile mechanism, and a bolting control system with a human-machine interface, which has been proven to save construction time and improve efficiency in the steel assembly process [12].

1.1 Research Motivation

The motivation for this research stems from the unique geometric and procedural complexities inherent in Light Gauge Steel (LGS) construction, which is used as a case study for this paper. Unlike heavy structural

steel, LGS panel assembly involves a high density of components and a multitude of discrete fastening points such as screws or rivets, which must be processed rapidly and precisely [13]. There is limited research on multi-robotic cell design for LGS assembly and manufacturing operations, which are commonly used in residential building structures such as walls, roof, and floor panels. Furthermore, there is a lack of research on multi-robot coordination for steel manufacturing and assembly in general, due to the complexity of the system. LGS assembly operations add an additional dimensional complexity to the already challenging multi-robotic cell design. Thus, it becomes crucial to design a generalized framework for the multi-robotic cell layout that can handle multifaceted manufacturing and assembly operations for LGS steel structures and, at the same time, be used repeatably for various panel configurations and sizes.

1.2 Design Objectives

The proposed multi-robotic cell design comprises one fixed Industrial Robot (IR) and an Autonomous Mobile Robot (AMR) with a manipulator arm, working in coordination to perform assembly and manufacturing operations on a Light Gauge Steel panel. Figure 1 maps the main objectives of multi-robotic cell design to the software and hardware design requirements and constraints.

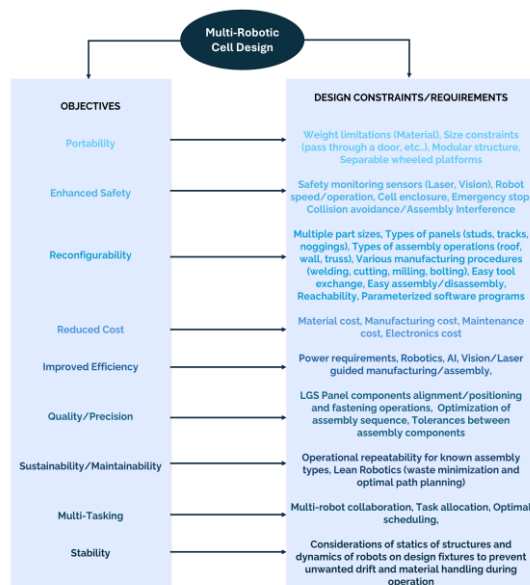


Figure 1. Multi-Robotic cell design objectives and the corresponding design requirements and constraints

1.3 Paper Contribution and Organization

The main contribution of this paper can be

summarized as follows:

- Formulation of the Design for Excellence (DfX) methodology/guidelines/algorithms to ensure that the design of the multi-robotic cell is optimized for structural integrity, repeatability for LGS assembly operations/sequences, multi-robot collaboration, and other objectives as defined in the previous section.
- The development of a resource ontology-based framework to define the spatial and functional relationships between the various components of the design and the IR and AMR. This will provide a blueprint for the cell layout based on the specific LGS panel dimensions and robot reachability constraints

Section 2 presents the DfX methodology with its various stages of design goals and their corresponding expected outcomes and step-by-step DfX guidelines to achieve those objectives for the multi-robotic cell design for LGS steel assembly operations. A DfX algorithmic flowchart applies the rules to multi-robotic cell design in a sequential manner based on the design stages to reach an optimized design. Section 3 presents the resource ontology of the multi-robotic cell design to outline the physical and functional relationships between the various components of the design. Section 4 discusses the finalized multi-robotic cell design optimized based on the DfX methodology. The static and stability analysis results on the design components such as the gantry structure and worktable as part of the final phases of the DfX process are also discussed. In Section 5, conclusions and future directions for the multi-robotic cell design for LGS panel assembly are outlined.

2 DfX-based Framework for Robotic Cell Architecture

Design for X (DfX) [14] is a systematic and proactive approach to designing a product that uses expert knowledge in various stages of the product development life cycle (design, manufacturing, testing, assembly) to ensure that the finalized artifact meets all the design requirements and, at the same time, retains quality, reliability, and durability. In this paper, the physical layout of the multi-robotic cell is optimized for LGS panel manufacturing and assembly operations using the DfX methodology.

2.1 DfX Methodology Flow Chart

The design process of the multi-robotic cell follows a sequential DfX methodology, ensuring that the physical structures and hardware/software systems are optimized for the complex assembly of light-gauge steel (LGS). The process initiates from a conceptual design and iterates through specific DfX foundational checkpoints to arrive at an optimal design concept, as shown in Figure 2.

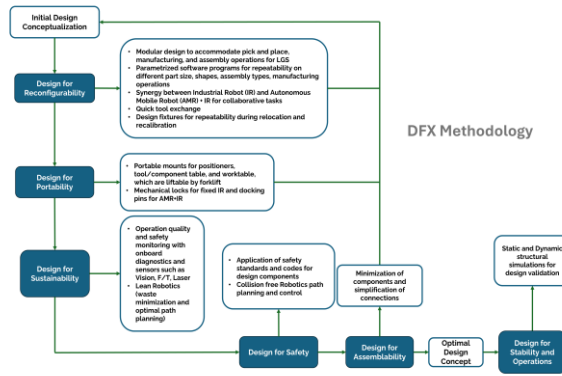


Figure 2. DfX methodology flowchart for the multi-robotic cell design

The various stages of the DfX process from the initial design stage to the optimal design concept and the corresponding outcomes of each stage are represented by a block beside it, connected by an arrow. The design stages, in order, are: Reconfigurability, Portability, Sustainability, Safety, Assemblability, and Stability. The reconfigurability phase targets the spatial and operational flexibility of the design, with the key outcome as effective IR-AMR synergy and a parametrized/modular software framework for assembly operations. The portability stage aims to make the design portable by installing fork-liftable, wheel-mounted mounts for the structures. The sustainability design phase ensures minimal waste during operation through optimal path planning and sensor-based monitoring. The safety stage ensures that the design is safety code-compliant and results in a collision-free operation. Assemblability aims to reduce design complexity by minimizing components and simplifying connections. Lastly, the Stability stage validates the structural integrity and reliability of the design through static and dynamic analysis.

2.2 DfX Guidelines and Algorithmic Flow Chart

To implement the DfX framework for the design of the multi-robotic cell, a step-by-step guideline has been developed for each DfX area, as shown in Table 1. DfX areas 1-6 correspond to the following in order: Reconfigurability, Portability, Sustainability, Safety, Assemblability, and Stability.

Based on Table 1, to ensure Reconfigurability and Portability, the system employs a gantry-mounted Industrial Robot (IR) decoupled from the ground, utilizing standard tool flanges and fiducial markers for autocalibration during relocation. Furthermore, effective task distribution among robots, such as heavy-duty work like assembly and manufacturing tasks for the fixed IR and light-duty tasks like tool carrying, panel holding, pick and place, and worktable rotation for the AMR, to

ensure operation in minimal time and energy. Multi-robot collaboration framework will be devised which implements a hybrid of centralized and decentralized techniques to plan and execute LGS panel assembly tasks. Physical mobility is facilitated by integrated forklift pockets and mechanical travel locks to maintain kinematic alignment during transportation.

Operational resilience is addressed through Sustainability and Safety guidelines and the integration of a high-performance sensor suite (F/T, laser, and vision) for real-time quality monitoring and SLAM-based obstacle avoidance. Safety guidelines are applied through the inclusion of on-board spare tool cabinets and collapsible safety enclosures. The multi-robotic cell's Assemblability and Stability are optimized through a minimalist approach to parts and connections and IP-rated electronics for environmental resilience. The structural integrity of the entire platform is verified under static loading and robotic dynamic forces using Finite Element Analysis (FEA) and a Digital Twin environment, ensuring the functional assembly of the Light Gauge Steel (LGS) panel with the design.

Figure 3 presents an algorithmic flowchart outlining a sequence of logical steps to execute the DfX rules/guidelines for the multi-robotic cell design to achieve an optimized configuration.

Table 1. DfX Guidelines for Multi-Robotic Cell Design

DfX Area	Guideline	Design Specifications (Software and Hardware)
1	- Modular fixtures and structural supports for Robots - Parameterized control programs to accommodate variation in LGS panel types - Easy tool exchange for the IR and AMR+IR - Autocalibration - Multi-robotic planning and task execution	- IR mounted on the gantry structure and rails - Standard tool flanges - Fiducial markers and pins for autocalibration during relocation and QR/Part ID-based path planning - Optimized spatial layout (localization and worktable rotation) - Combination of techniques such as Behaviour Tree/Finite State Machines, Leader-follower strategy, Event driven communication with shared ontology to plan and execute multi-robotic collaboration
2	Modular multi-robotic cell design, which can	- Bolted plates on skids - Forklift pockets integrated into the gantry system

	be relocated with ease and stability	• Mechanical travel locks for Robots
3	• Operational longevity through on-board spare tool availability. • Real-time performance monitoring and quality checks.	• Tool cabinets for spare tools/parts • High-performance PC, PLC control systems, integrated sensor suite (F/T, cameras, lasers). • Real-time data collection for quality checks and optimized path planning for LGS assembly.
4	Maintainance of a secure workspace via physical barriers and intelligent, sensor-driven risk mitigation.	• Collapsible safety enclosures • Emergency stops on IR/AMR • Vibration-damping floor locks/pads for stability during operations. • SLAM-based obstacle avoidance • Robot motion control • ML/Computer Vision for part identification and interference-free joining.
5	Design minimalism and standardization in parts and connections to facilitate rapid setup and outdoor/indoor environmental resilience.	• Tool/worktables and gantry designed as Minimum Viable Products (MVPs) • IR on Gantry structure (decoupled from ground) • Standardized or self-adjusting fasteners • IP-rated electronics for on-site/off-site use
6	Structural integrity against static loading and dynamic robotic forces and verification of functional assembly sequences.	• Structural validation via FEA (e.g., ANSYS/Solidworks) • Digital Twin environment for full-scale simulation of multi-robot LGS assembly operations and functional verification

3 Multi-Robotic Cell Design Ontology Framework

In this section, the proposed system is defined by a semantically structured resource ontology to represent the complex interactions within the multi-robotic cell. This ontology serves as a digital knowledge base, categorizing the physical and functional entities required for the automated assembly of light LGS structures. The ontology is organized into three primary high-level classes: Machine, Physical Assets, and LGS.

The Machine class comprises the robots and their kinematic capabilities. This includes an ABB IRB-2600-20-1-65 IR, an ABB IRBT 2005 unit, which provides the necessary linear motion for the robot to traverse the work area, and an AMR + IR for secondary tasks such as tool transportation and worktable rotation. Each robot entity is equipped with a sensor suite (Laser, Vision, F/T) that enables, for example, high-precision IR tasks such as Pick and Place, Screwing, Nailing, and Welding.

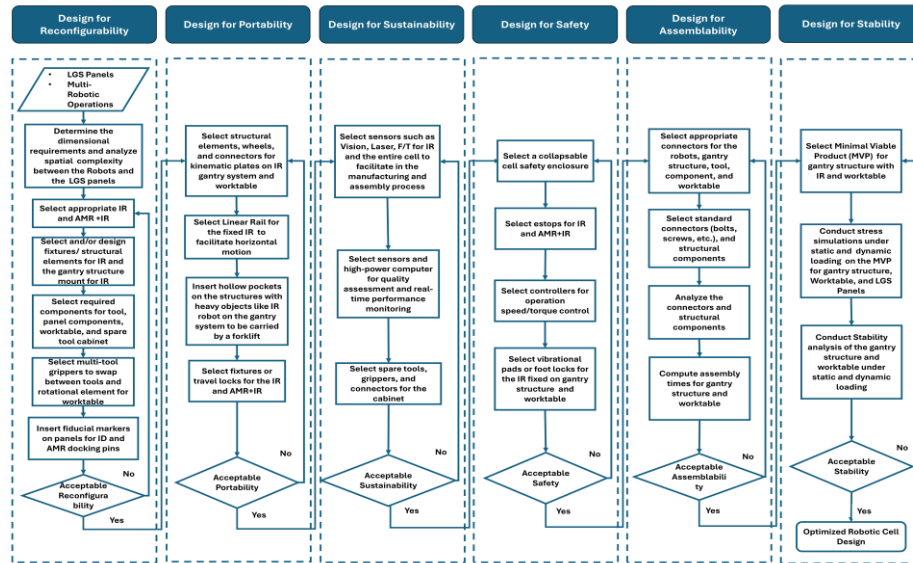
The Physical Assets class defines the stationary and modular components of the cell environment. This includes the gantry structure that supports the robotic rails for IR, the worktable for assembly operations, and tool/panel tables. These assets provide the spatial constraints and support surfaces required for the robots to interact with the LGS components.

The LGS class represents the structural elements of the product design, categorized into studs, tracks, and nogging. The ontology maps these individual components to specific assembly configurations (LGS Assembly 1 to 4). These assembly types correspond to different joint geometries, such as corner joints, T-junctions, and cruciform intersections, which are executed through the robotic fastening operations defined in the Machine layer.

4 Results and Discussion

In this section, the finalized optimal multi-robotic cell design is presented after being iterated through the step by step DfX algorithmic process shown in Figure 3. However, the design does not incorporate the hardware and software requirements at this stage, but only embodies the physical and spatial characteristics of the cell design.

Furthermore, static and stability analyses are performed on design components, such as the gantry structure and worktable. The structural integrity and



stability under loading conditions for these components is validated through stress and displacement simulation in SolidWorks. Moreover, structure-tipping calculations are performed to ensure that the gantry structure and worktable remain stable under static loading conditions.

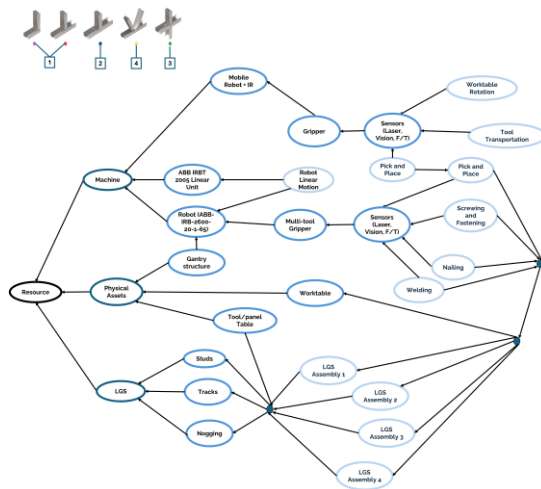


Figure 4. Resource Ontology modelling of the robotic cell design for four different LGS assembly types

4.1 Multi-Robotic Cell Design for Steel Panel Assembly

The optimized multi-robotic cell design can be visualized in Figure 5. Based on Figure 5, the cell has a 9 m x 5.050 m footprint and is fully enclosed within a collapsible safety perimeter. The layout is designed for

high-precision assembly and manufacturing, as well as ease of relocation.

The core of the cell features an ABB IRB-2600-20-1-65 industrial robot (IR) mounted on a 5 m ABB IRBT 2005 Linear Unit. This configuration allows the IR to traverse a gantry-mounted rail system, providing the necessary reach to handle large-scale LGS wall panels.

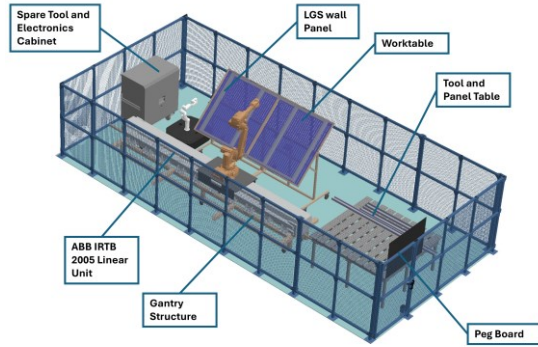
An AMR equipped with a smaller IR provides collaborative assistance as discussed previously. The AMR with IR combination has yet to be chosen, but the spatial/dimensional coverage will be the same as indicated in Figure 5.

The cell includes a dedicated tool and panel table for material staging and a specialized worktable for assembling LGS components. A Spare tool and electronics cabinet is located on board to ensure operational sustainability and rapid maintenance.

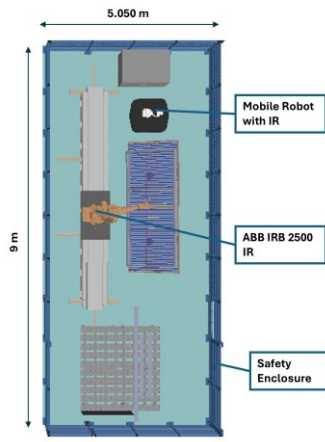
A pegboard is integrated with the tool table for organized tool storage and structural gantry supports that decouple the robots from the ground for portability.

4.1.1 Gantry Structure Design

Figure 6 shows the gantry structure design constructed from aluminium extrusions. The design incorporates wheels for movement and pockets for forklift access, enabling the entire IR and Linear unit mount to be relocated as a single modular unit. Additional features, such as sidebars for counterweights and cable-routing bars, ensure the structure remains stable and organized during dynamic movement. Foot locks need to be added to design to prevent movement during operations.



(a)



(b)

Figure 5. Multi-Robotic cell design for LGS panel assembly; (a) isometric view; (b) top view

4.1.2 Rotatory Worktable Design

The assembly worktable design features a rotatory component that allows for 360 ° tabletop rotation and locked in four different orientations using a pin. This capability, managed via a handle for manual or robotic adjustment, ensures that the robot can access all sides of an LGS panel from a single position. Like the gantry, the table is built with aluminum extrusions and wheels, maintaining the system-wide requirement for modularity and easy repositioning. The worktable top is designed to accommodate the largest LGS wall panel size of 1.2 m x 2.7 m.

4.2 Static Analysis on the Gantry Structure

The final “Design for Stability and Operations” stage is validated through static simulations using SolidWorks. Loading due to the IR robot, linear unit, and counterweights was considered for the gantry structure. The load due to IR was assumed to be on the left-most side to test for an extreme case of highly unbalanced forces, shown as blue arrows in Figure 10.

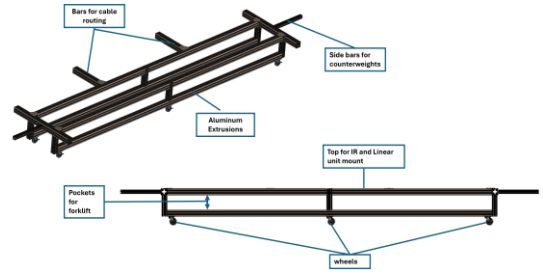


Figure 6. Gantry structure design

Counterweights are indicated by red arrows on the side bars with a mass of 900 kg, roughly the same as the robot, on each side bars in case the robot translates to left or right edge.

The structure is fixed, where the six wheels are located for simulation purposes. Furthermore, for the aluminum extrusions, the material properties of Aluminum 6560 are applied to the structure. The simulation results for stress distribution, displacement, and the Factor of Safety (FOS) are shown in Figures 7, 8, and 9, respectively.

Structural analysis of the gantry mount identifies critical Von Mises stress areas, with a reported maximum stress of approximately $6.449 \times 10^7 \text{ N/m}^2$, well within the yield strength limits. Displacement simulations show a maximum deformation of roughly 4.565 mm under static loads, located only on the tips of the side bars, while Factor of Safety (FOS) distribution plots confirm a minimum safety factor of 3.9. These results verify that the modular gantry design maintains sufficient structural integrity to withstand the static forces imposed.

4.3 Stability Analysis on the Gantry Structure and Worktable

4.3.1 Gantry Structure

The stability analysis involved calculating the overturning and restraining moments to determine the system’s FOS against instability. Based on the load distribution profile, as can be seen in Figure 10, the robot mass, rail weight, and gantry self-weight, the overturning moment was calculated at 34209.67 Nm. To counteract these static forces, the design incorporates side bars for counterweights of 9000 N, resulting in a significant restraining moment of 56700 Nm. This relationship yields a high overturning FOS of 1.65 using equation (1). This suggests a robust design can maintain equilibrium under extreme loading conditions

$$\text{FOS} = \frac{M_{\text{restrain}}}{M_{\text{overturn}}} \quad (1)$$

$$I = \frac{1}{12} m w^2 \quad (2) \quad F_{\text{ext}} = \frac{I \alpha}{r} \quad (3)$$

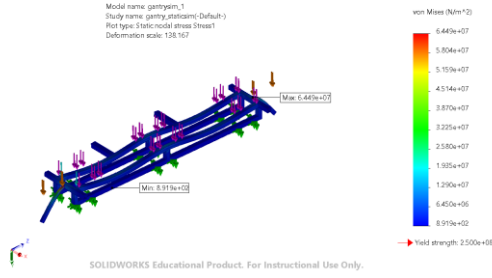


Figure 7. Stress profile under loading

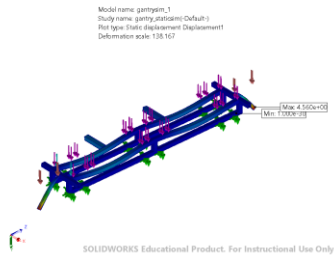


Figure 8. Displacement profile under loading

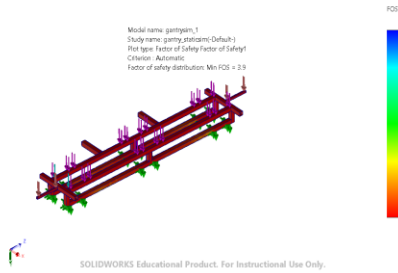


Figure 9. Factor of Safety profile under loading

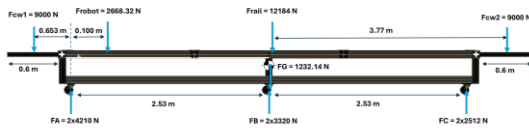


Figure 10. Gantry structure FBD

4.3.2 Rotatory Worktable

The stability of the rotatory worktable is evaluated by comparing the overturning moment generated by the x component of the applied external force, F_{ext} with the restraining moment provided by the weight of the worktable and the y-component of F_{ext} . The external force is caused by the manual rotation of the tabletop with the panel, which was calculated using equations (2) and (3). The maximum angular acceleration was 1.5 rad/s^2 . The side configuration was considered for tipping due to the greater likelihood of tipping during operation. The

loading profile of the worktable can be viewed in Figure 11.

For the current loading condition, an external force of 2.762 N with horizontal and vertical components of 1.465 N produces an overturning moment of only 2.3 Nm. In contrast, the stabilizing reactions at the wheels acting over the 0.914 m base width generate a much larger restraining moment of 320 Nm. The resulting tipping FOS computed using equation (1) is 139.1, indicating an extremely stable configuration. This very high factor of safety means that the applied force required to initiate tipping is over two orders of magnitude greater than the current loading, confirming that the worktable remains well within a safe, non-critical stability regime under the given loading conditions.

For both the static and stability analyses of the gantry structure and worktable, the dynamic forces imposed by the IR robot during assembly and manufacturing operations were not considered in this paper and need to be analyzed as future work.

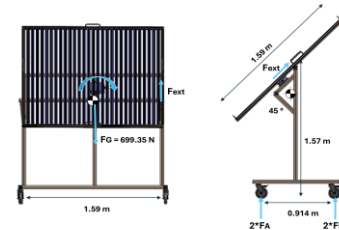


Figure 11. Worktable FBD

5 Conclusions and Future Directions

This research presented a comprehensive framework for the design and validation of a multi-robotic cell tailored for Light Gauge Steel (LGS) assembly. By integrating a Design for Excellence (DfX) methodology with a resource ontology, the study successfully moved from conceptual modularity to a structurally verified system.

The finalized design utilizes an ABB IRB-2600 IR on a 5-meter linear unit and a collaborative AMR with IR, providing a balanced task distribution between heavy-duty fastening and secondary logistics.

Structural analysis confirmed the gantry's integrity, with a peak von Mises stress of $6.449 \times 10^7 \text{ N/m}^2$, well below the yield limit of $2.5 \times 10^8 \text{ N/m}^2$ and a minimal displacement of 4.565 mm. Stability assessments yielded high Factors of Safety (FOS), with the gantry at 1.65 and the rotatory worktable at 139.1, ensuring a robust platform for high-precision off-site construction tasks.

Future research will transition from static modeling to dynamic force analysis to evaluate the impact of robot dynamics during high-speed operations on the gantry structure and worktable designs. Additionally, efforts will focus on selecting and integrating the AMR-IR pair

and implementing AI-driven computer vision for autonomous part identification and interference-free joining. Moreover, a multi-robotic collaboration framework incorporating the ontology, task planning and control, and communication protocols will be developed to facilitate the assembly process in minimal time and energy.

Acknowledgments

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