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SCUOLA DI ARCHITETTURA URBANISTICA INGEGNERIA DELLE COSTRUZIONI

MetaBend

Augmented construction for sheet metal applications through AR, robotics and vision system

TESI DI LAUREA MAGISTRALE IN BUILDING ENGINEERING

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Abstract

This thesis proposes a digital fabrication workflow for aluminium façade components, integrating computational design, collaborative robotics, augmented reality (AR), and a compact automated mini-factory environment. Aluminium is examined for its mechanical behaviour and its relevance within sustainable façade systems, with emphasis on recyclability and material efficiency. Material and fabrication constraints are derived from common industrial practices in sheet-metal processing.

A dedicated mini-factory is developed to automate the production of façade elements, combining a collaborative robotic arm with a sheet-metal bending machine. The system employs a custom end effector featuring a vacuum-based handling mechanism and an additional rotational axis driven by a compact motorised unit. This extra degree of freedom enables the suction module to rotate around its own axis, improving the robot's ability to orient and manipulate aluminium sheets during pick-and-place and machine-tending operations. The robotic setup is complemented by a visual sensing apparatus for object detection and adaptive manipulation, and by an AR interface designed to support operators during tending tasks. The AR layer visualises work sequences, alignment tolerances, and robot–machine interactions, enhancing clarity, safety, and process reliability. A procedural programming pipeline coordinates robotic actions, synchronises bending operations, and ensures safe human–machine collaboration.

A computational design framework discretises façade geometries, encodes fabrication logic, and generates machine-ready instructions. Using a parametric modelling environment, the workflow translates geometric definitions into bending sequences, robotic movements, and production files. A case study demonstrates the complete digital-to-physical chain, from design to fabricated prototypes. The results highlight the feasibility of integrating collaborative robotics and AR-assisted operations into small-scale industrial processes, reducing repetitive labour while improving precision, transparency, and reproducibility. The thesis concludes with an evaluation of system performance and outlines future developments, including closed-loop feedback, expanded AR functionalities, and scalability toward fully automated façade production.

Key-words: Digital Fabrication; Robotics; Aluminium Façade Systems; Metal Sheet Bending.

Abstract in italiano

Questa tesi propone un flusso di fabbricazione digitale per componenti di facciata in alluminio, integrando design computazionale, robotica collaborativa, realtà aumentata (AR) e una mini-fabbrica automatizzata. L'alluminio è analizzato per il suo comportamento meccanico e per il ruolo nei sistemi di facciata sostenibili, con attenzione a riciclabilità ed efficienza materiale. I vincoli di progetto derivano da pratiche industriali diffuse nella lavorazione della lamiera.

È sviluppata una mini-fabbrica dedicata che automatizza la produzione degli elementi di facciata, combinando un braccio robotico collaborativo con una piegatrice per lamiera. Il sistema utilizza un end effector personalizzato dotato di presa a vuoto e di un asse di rotazione aggiuntivo, azionato da un'unità motorizzata compatta. Questo grado di libertà supplementare consente al modulo di aspirazione di ruotare attorno al proprio asse, migliorando la capacità del robot di orientare e manipolare le lamiere nelle operazioni di pick-and-place e di tending alla macchina. L'assetto robotico è completato da un apparato di visione per il rilevamento degli oggetti e la manipolazione adattiva, e da un'interfaccia AR che supporta l'operatore visualizzando sequenze operative, tolleranze di allineamento e interazioni robot-macchina, aumentando chiarezza, sicurezza e affidabilità. Una pipeline di programmazione procedurale coordina le azioni robotiche, sincronizza le operazioni di piega e garantisce una collaborazione sicura tra uomo e macchina.

Un framework di design computazionale discretizza le geometrie di facciata, codifica la logica di fabbricazione e genera istruzioni pronte per la produzione. Attraverso un ambiente parametrico, il flusso traduce le definizioni geometriche in sequenze di piega, movimenti robotici e file di produzione. Un caso studio dimostra l'intera catena digitale-fisica, dai modelli ai prototipi realizzati. I risultati evidenziano la fattibilità dell'integrazione tra robotica collaborativa e operazioni assistite da AR in processi industriali di piccola scala, riducendo il lavoro ripetitivo e migliorando precisione, trasparenza e riproducibilità. La tesi si conclude con una valutazione delle prestazioni del sistema e con una discussione sugli sviluppi futuri, tra cui feedback in ciclo chiuso, funzionalità AR estese e scalabilità verso una produzione completamente automatizzata.

Parole chiave: Fabbricazione Digitale; Robotica; Sistemi di Facciata in Alluminio; Piegatura Lamiera Metallo.

Contents

1 Introduction

1.1. Background and Motivation

The architectural façade has increasingly become a locus of technological convergence; performance requirements, material efficiency, and aesthetic expression now intersect in ways that challenge conventional construction practices. As contemporary buildings demand higher levels of customisation and environmental responsiveness, the fabrication of façade components has grown correspondingly more complex. Traditional manufacturing workflows; often reliant on manual labour, repetitive operations, and rigid production chains; struggle to accommodate the precision, variability, and responsiveness required by advanced façade systems. In parallel, the fields of computational design and digital fabrication have matured significantly. Parametric modelling, robotic automation, and augmented reality (AR) interfaces now offer new opportunities to rethink how façade elements are conceived, produced, and assembled; enabling workflows that are more flexible, data driven, and capable of embedding design intent directly into fabrication logic.

This research is situated within this evolving landscape and is developed at Indexlab, the computational design and digital fabrication laboratory of Politecnico di Milano. Indexlab provides the methodological and infrastructural framework for integrating algorithmic modelling, robotic control, and machine communication into a coherent system; fostering a research culture in which design computation, material experimentation, and hybrid human–machine workflows operate in close synergy. Within this context, aluminium emerges as a particularly compelling material: its favourable strength to weight ratio, corrosion resistance, and recyclability make it a staple of façade construction; while its malleability and compatibility with bending based forming techniques render it well suited to robotic manipulation and digitally assisted production environments.

This thesis positions itself at the intersection of these technological and material developments. It investigates how collaborative robotics, computational design, and AR assisted operations can be orchestrated into a compact mini factory capable of producing customised aluminium façade components with improved precision, repeatability, and safety. At its core, the research seeks to elevate a manual Schechtl UK 100 S bending machine to a level of automation approaching that of a fully automatic industrial system; achieving comparable operational efficiency and reliability, but at a fraction of the financial investment typically required for high end automated machinery.

1.2. Research Objectives

The primary objective of this thesis is to design, construct, and validate a compact digital fabrication environment capable of automating key stages in the production of aluminium façade components. While the initial scope included the discretisation of façade geometries, this aspect became secondary as the research evolved. The core focus shifted toward the development of a functional mini-factory, where collaborative robotics, machine tending, and augmented-reality-assisted operations converge into a coherent and affordable fabrication system.

The research therefore centres on the following goals:

- To design and implement a collaborative robotic cell capable of manipulating aluminium sheets with precision, including the development of a custom end effector equipped with a seventh axis of rotation for improved orientation control.
- To integrate a manual Schechtl UK 100 S bending machine into a semi-automated tending workflow, enabling it to perform with a level of efficiency and repeatability approaching that of a fully automatic bending machine, but at a fraction of the cost.
- To establish a robust mini-factory layout, incorporating safety protocols, calibration procedures, and coordinated communication between robot, sensors, and bending equipment.
- To develop a streamlined digital-to-physical workflow, translating design intent into robotic trajectories and bending sequences with minimal manual intervention.
- To fabricate a series of physical mock-ups, demonstrating the operational capabilities of the mini-factory and validating the system's performance in real production scenarios.

Together, these objectives aim to demonstrate how small-scale, flexible automation can meaningfully enhance the fabrication of façade elements, offering an accessible alternative to high-cost industrial machinery while maintaining precision, repeatability, and process transparency.

1.3. Methodological Approach

The methodological approach adopted in this thesis follows an iterative, practice-based research model in which digital development and physical prototyping evolve in parallel. Rather than advancing through a rigid linear sequence, the project unfolds through cycles of design, testing and refinement, each shaped by the constraints and opportunities encountered within the mini-factory environment.

The research begins with an examination of the material and industrial context. Aluminium is analysed for its mechanical behaviour, forming characteristics and suitability for robotic manipulation. The collaboration with Alpewa provides a real production benchmark, offering insight into existing workflows and the limitations of manual bending processes.

The second phase marks the beginning of the original contribution of this thesis, as it focuses on the design and construction of the MetaBend mini-factory. Central to this phase is the integration of the ABB GoFa 5 collaborative robot, whose safety-rated design supports close human–robot interaction without the need for traditional industrial barriers. Alongside the robot, a custom end effector with a seventh rotational axis is developed to enhance sheet manipulation capabilities, and a vacuum-based handling system is implemented to ensure reliable gripping. The mini-factory also incorporates an augmented-reality layer designed to support the tending of the Schechtl UK 100 S bending machine by guiding operators through alignment, positioning and sequencing tasks. Importantly, all hardware and software components are conceived as interchangeable modules, allowing the system to be adapted to different products, geometries and operational requirements. This modularity and adaptability constitute a core aspect of the project's original contribution.

The third phase concerns the development of the digital workflow that governs the system. While façade discretisation informed the early stages of the research, the focus progressively shifted toward creating a reliable pipeline capable of translating design intent into robotic trajectories and bending sequences. This involves the use of Grasshopper for parametric modelling, custom scripts for data structuring and simulation tools to anticipate robot behaviour before physical execution.

The final phase consists of producing and evaluating a series of physical mock-ups. These prototypes serve as tangible demonstrations of the system's capabilities, allowing the performance of the mini-factory to be assessed in terms of accuracy, repeatability and operational efficiency. The mock-ups also reveal practical limitations and inform the discussion on how such a system could be scaled or adapted for industrial use.

A brief declaration regarding the use of Artificial Intelligence is appropriate here. Throughout the project, AI tools were employed strictly under the researcher's direction and exclusively in supportive roles. In the computational domain, AI assisted in refining Python scripts and resolving syntactic or structural issues within code that was conceptually defined and authored by the researcher. In the writing process, AI was used as a rephrasing and clarity-enhancing tool to improve linguistic precision. At no stage did AI generate design concepts, methodological decisions or technical claims; intellectual authorship and projectual intent remain entirely with the researcher. In this sense, AI functioned as an auxiliary instrument comparable to a coding assistant or editorial aid, without influencing the substance of the research.

Through this methodology, the thesis aims to demonstrate the feasibility of a compact, collaborative and AR-enhanced fabrication environment capable of elevating a manual bending machine to near-automated performance.

1.4. Thesis Structure

The thesis is organised into six chapters; together, they trace the development of a semi-automated mini factory for aluminium façade fabrication, from conceptual foundations to physical validation. The structure reflects the iterative and interdisciplinary nature of the research; each chapter builds upon the previous one, gradually integrating geometric logic, material behaviour, robotic manipulation, and augmented reality guidance into a unified workflow.

Chapter 1 introduces the motivation for the research; it situates aluminium within contemporary façade systems and outlines the industrial context provided by Alpewa. The chapter frames the central challenges addressed by the thesis; the need for flexible, precise, and scalable fabrication methods that can bridge digital design and physical production. It also introduces the conceptual pillars that guide the work; the use of elastic relaxation as a low-energy strategy for generating curvature from planar pieces, and the integration of AI-assisted tools to support human–machine collaboration.

Chapter 2 reviews the state of the art in digital fabrication, sheet-metal forming, collaborative robotics, and augmented reality. It identifies the limitations of existing bending-based workflows and highlights the gap between industrial automation and small-scale architectural production. This chapter establishes the theoretical and technological background that informs the design of the mini factory.

Chapter 3 represents the beginning of the personal contribution and presents the physical components of the system; the ABB GoFa 5 collaborative robot, the custom end effector with vacuum gripping and seventh-axis rotation, the Schechtl UK 100 S bending machine, the vision apparatus, and the AR interface. The chapter describes how these elements are integrated spatially and operationally; it explains the calibration procedures, the safety considerations, and the logic of human–robot collaboration during bending operations.

Chapter 4 introduces the digital workflow and computational framework; it details the bottom-up geometric strategy used to discretise façade surfaces, the extraction of fabrication data, the generation of bending sequences, and the robotic programming pipeline. The chapter also describes the communication architecture linking Grasshopper, Python, Arduino, and the robot controller; it concludes with the implementation of the AR demonstrator, which provides a first step toward AI-mediated cognitive support during manual bending.

Chapter 5 documents the physical mock-ups that validate the system; from early paper models to aluminium prototypes and a full-scale application for the Alpewa headquarters. Each mock-up tests a different aspect of the workflow; geometric feasibility, bending constraints, assembly tolerances, digital precision, and robotic integration. The chapter culminates with the public demonstration at CaseItaly 2026, which provided external validation and revealed the system's potential for industrial adoption.

Chapter 6 concludes the thesis; it summarises the achievements, discusses the limitations, and outlines future developments. Particular emphasis is placed on the potential for deeper AI integration; closed-loop feedback, automated bending-sequence generation, real-time angle verification, and expanded AR functionalities. The chapter also reflects on the broader implications of the research; the role of elastic relaxation in architectural fabrication, and the emergence of hybrid manufacturing environments where human skill, robotic precision, and computational intelligence operate in synergy.

Together, these chapters articulate a coherent trajectory; from conceptual framing to technical implementation, from digital logic to physical prototypes, and from manual craftsmanship to semi-automated fabrication. The structure mirrors the ethos of the mini factory itself; modular, iterative, and grounded in the interplay between material behaviour and digital intelligence.

2 State of the art - Material and Industrial framework

2.1. Aluminium: Properties, Applications, and Sustainability

Aluminium occupies a central position in contemporary façade construction due to its unique combination of mechanical, aesthetic, and environmental qualities. Its high strength-to-weight ratio enables the production of lightweight yet structurally robust components, making it particularly suitable for cladding systems, shading devices, and architectural envelopes that demand both performance and visual refinement. The material's inherent corrosion resistance, derived from the formation of a stable oxide layer, ensures long-term durability even in demanding environmental conditions, reducing maintenance requirements and extending service life.

From a fabrication perspective, aluminium offers a high degree of malleability, enabling it to be bent, folded, and shaped with relative ease. This characteristic makes it compatible with both manual and automated forming processes, including the bending operations central to this research. Its predictable behaviour under deformation is especially advantageous when integrating robotic manipulation, where repeatability and controlled force application are essential. The material's elastic relaxation (springback) remains a critical parameter in bending workflows, influencing the accuracy of the final geometry and requiring compensation strategies—an aspect that becomes particularly relevant in the context of future AR-based predictive systems discussed later in the thesis.

Beyond its mechanical attributes, aluminium is increasingly valued for its sustainability profile. It is one of the most recyclable industrial materials, capable of being reprocessed indefinitely without significant loss of quality. The energy required to recycle aluminium is a fraction of that needed for primary production, making closed-loop material cycles both economically and environmentally compelling. In the context of façade systems; where large surface areas and long lifespans are typical, these sustainability advantages contribute meaningfully to reducing the environmental impact of the built environment.

The combination of mechanical versatility, formability, and circularity positions aluminium as an ideal material for exploring digitally integrated fabrication workflows. Its compatibility with bending-based forming and robotic handling provides a robust foundation for the development of the mini-factory presented in this thesis.

2.2. Industrial partner: Alpewa and the façade supply chain

Alpewa is a long-established Italian company based in Bolzano, operating as a key player in the field of building envelopes, with a particular focus on metal roofing and façade systems. Founded in the mid-1940s as a family business, it has progressively evolved from a small sheet-metal workshop into a reference point for high-quality cladding solutions, combining technical expertise with a strong orientation toward innovation. Over the decades, Alpewa has consolidated its position not only as a supplier of materials, but also as a technical partner for designers, installers, and contractors.

The company's core activity lies in the distribution and technical promotion of advanced systems for roofs and ventilated façades. Its product portfolio includes aluminium profiles (such as Montana and Prefa systems), copper (TECU), titanium-zinc (Rheinzink), stainless steel (Roofinox, Uginox), aluminium composite panels (e.g. Stacbond), high-pressure laminates (Trespa), and three-dimensionally deformed sheet metal (Fielitz). This broad range allows Alpewa to address both highly prestigious architectural projects and more standard applications, maintaining consistent quality across different market segments.

Within the façade supply chain, Alpewa occupies a hybrid position between material supplier, technical consultant, and innovation driver. The company supports designers in the selection of appropriate systems, provides detailing and technical assistance, and collaborates with installers to ensure correct on-site implementation. This role gives Alpewa a privileged vantage point on the practical challenges of façade construction: tolerance management, installation logistics, coordination between trades, and the impact of fabrication constraints on design decisions.

For this thesis, Alpewa's production and consulting environment offers a realistic framework in which to situate the mini-factory concept. The presence of manual bending equipment, such as the Schechtl UK 100 S, reflects a common condition in many small and medium-sized workshops: robust, versatile machines that are not fully automated but remain central to everyday production. The research therefore does not attempt to replace such machinery with high-end industrial lines; instead, it explores how collaborative robotics and augmented reality can be layered onto existing tools to enhance precision, repeatability, and throughput, while keeping investment costs comparatively low.

By aligning the mini-factory with Alpewa's operational reality, the project positions itself as a plausible evolution of current practice rather than a purely speculative prototype. The system is conceived as something that could, in principle, be integrated into a company like Alpewa to support the production of customised aluminium façade elements, mock-ups, and small series, bridging the gap between bespoke design and efficient fabrication.

2.3. State of the art in aluminium-based façade components

The contemporary landscape of aluminium-based façade systems is shaped by a dynamic interplay between standardised industrial products and increasingly bespoke, digitally driven approaches. On one side, the market continues to rely on modular solutions such as cassettes, standing seam profiles and ventilated façade panels, all optimised for repeatability, ease of installation and cost control. These systems operate within well-defined tolerance ranges and construction sequences, drawing on a limited repertoire of profiles, bending geometries and fastening strategies. Aluminium's lightness, durability and compatibility with these modular logics have contributed to its widespread adoption in both new-build and refurbishment contexts.

At the same time, advances in computational design and digital fabrication have expanded the formal and performative ambitions associated with aluminium cladding. Parametric modelling environments allow designers to articulate complex geometries, gradient patterns and locally differentiated components that respond to environmental, structural or visual criteria. Parallel developments in CNC cutting, robotic forming and automated bending have made it feasible to produce non-standard elements with high precision. This expansion of design space introduces new demands on fabrication workflows, tolerance management and the coordination between digital models and physical production. As façade systems depart from standardised panel logics, the relationship between design tools, machines and assembly procedures becomes increasingly critical.

Within this broader context, a number of research and practice-based projects have explored how thin-sheet materials can be transformed into spatially complex systems through bending, folding and incremental assembly. The metal cladding system developed by Indexlab for the Pesaro façade demonstrates how parametric rules, controlled bending sequences and flat-pattern logic can produce non-standard geometries without relying on heavy industrial infrastructures. Wood-Skin's façade for the Poste Italiane headquarters in Milan extends this logic through a hybrid system in which CNC-cut modules, flexible hinges and manual folding operations generate a three-dimensional surface from a planar pattern. These projects illustrate how geometric richness can emerge from the interplay between digital definition, material behaviour and sequential assembly.

In parallel, high-profile architectural works by Foster and Partners, Zaha Hadid Architects and BIG have pushed aluminium cladding toward levels of precision and complexity that require close integration between design, engineering and industrial fabrication. The monolithic aluminium panels of the Apple Store in San Francisco, the freeform envelope of the Heydar Aliyev Centre and the torsional metal skin of The Twist at Kistefos all demonstrate the potential of aluminium when supported by advanced manufacturing infrastructures. These projects foreground issues such as tolerance accumulation, panel alignment, installation sequencing and the translation of digital geometry into buildable systems. Although they operate at a scale and level of refinement distinct from experimental fabrication environments, they provide valuable insights into the challenges of constructing differentiated metal surfaces.

Beyond the architectural domain, industrial applications of robotics in sheet-metal manufacturing offer further perspectives on automation, precision and workflow orchestration. Machina Labs' die-less robotic forming platform exemplifies toolpath-driven deformation and flexible automation, while facilities such as the TRUMPF Smart Factory in Chicago reveal how bending, alignment and assembly can be coordinated across multiple machines and robotic stations. These environments are optimised for high-volume production and rely on substantial capital investment, yet they highlight strategies for managing tolerances, synchronising operations and integrating sensing and feedback that are instructive for smaller-scale, semi-automated setups.

Positioned between these poles are hybrid workflows that combine digital design, accessible fabrication tools and manual assembly. Projects such as Indexlab's Superframes and the Pesaro cladding system, as well as Wood-Skin's aluminium façade in Milan, occupy this intermediate territory. In these cases, flat-pattern geometries are generated parametrically, fabricated through CNC cutting and controlled bending, and assembled through flap-based or hinge-based logics that rely on both digital precision and human intervention. They demonstrate that geometrically expressive and materially efficient aluminium surfaces can be achieved without the infrastructure of large industrial lines, provided that the relationship between design intent, fabrication constraints and assembly procedures is carefully negotiated.

The mini-factory proposed in this thesis is situated within this hybrid domain. It does not seek to replicate the throughput or automation level of industrial sheet-metal production, nor does it remain confined to the limitations of purely manual workshop practice. Instead, it investigates how collaborative robotics, augmented reality and a computational design pipeline can be layered onto existing bending equipment to support the production of customised aluminium components in a controlled yet flexible manner. The following subsections examine a selection of architectural, research and industrial projects that collectively define the state of the art relevant to this investigation, highlighting specific aspects such as bending logic, sheet discretisation, robotic handling and flap-based assembly that inform the development of the proposed mini-factory.

2.3.1. Indexlab – Superframes (Politecnico di Milano)

Superframes, developed at Indexlab (Politecnico di Milano), is a research project exploring the fabrication of large-scale spatial structures through the incremental assembly of planar components. The system is based on a logic of discretisation in which flat elements are cut, folded, and joined to generate three-dimensional frames with high geometric variability. The project's strength lies in its ability to translate computational design strategies into a fabrication workflow that remains accessible and materially efficient, relying on CNC cutting and manual folding rather than complex moulds or heavy tooling. The assembly logic, based on local bending and flap-to-flap connections, creates a structural depth that emerges from the accumulation of thin components, demonstrating how planar sheets can be transformed into spatially expressive systems. Although the material used in Superframes differs from aluminium, the project shares several conceptual affinities with the present research, particularly in its use of flat-pattern logic, incremental assembly, and the negotiation between digital geometry and manual fabrication. These parallels highlight the relevance of hybrid workflows that combine computational precision with accessible fabrication techniques.

Figure 2.1: Superframes night view

Figure 2.2: Superframes night view

2.3.2. Indexlab – Metal Cladding System (Pesaro, Italy)

The metal cladding system developed by Indexlab for a building in Pesaro represents a built application of digitally driven sheet-metal fabrication within an architectural context. The façade is composed of custom-shaped metal panels whose geometry is derived from a parametric model that coordinates curvature, panelisation, and fastening logic. Each panel is produced through CNC cutting and bending, following a sequence that translates digital intent into manufacturable components while accommodating the constraints of sheet-metal behaviour. The project's strength lies in its integration of design computation with fabrication pragmatics: the geometry is articulated through a set of rules that ensure feasibility, repeatability, and alignment during installation. At the same time, the system demonstrates how non-standard metal cladding can be achieved without resorting to highly specialised industrial machinery, relying instead on controlled bending sequences and precise assembly. The Pesaro façade resonates with the themes of this thesis, particularly in its use of bending as a primary forming strategy, its reliance on flat-pattern logic, and its negotiation of tolerances across sequential operations.

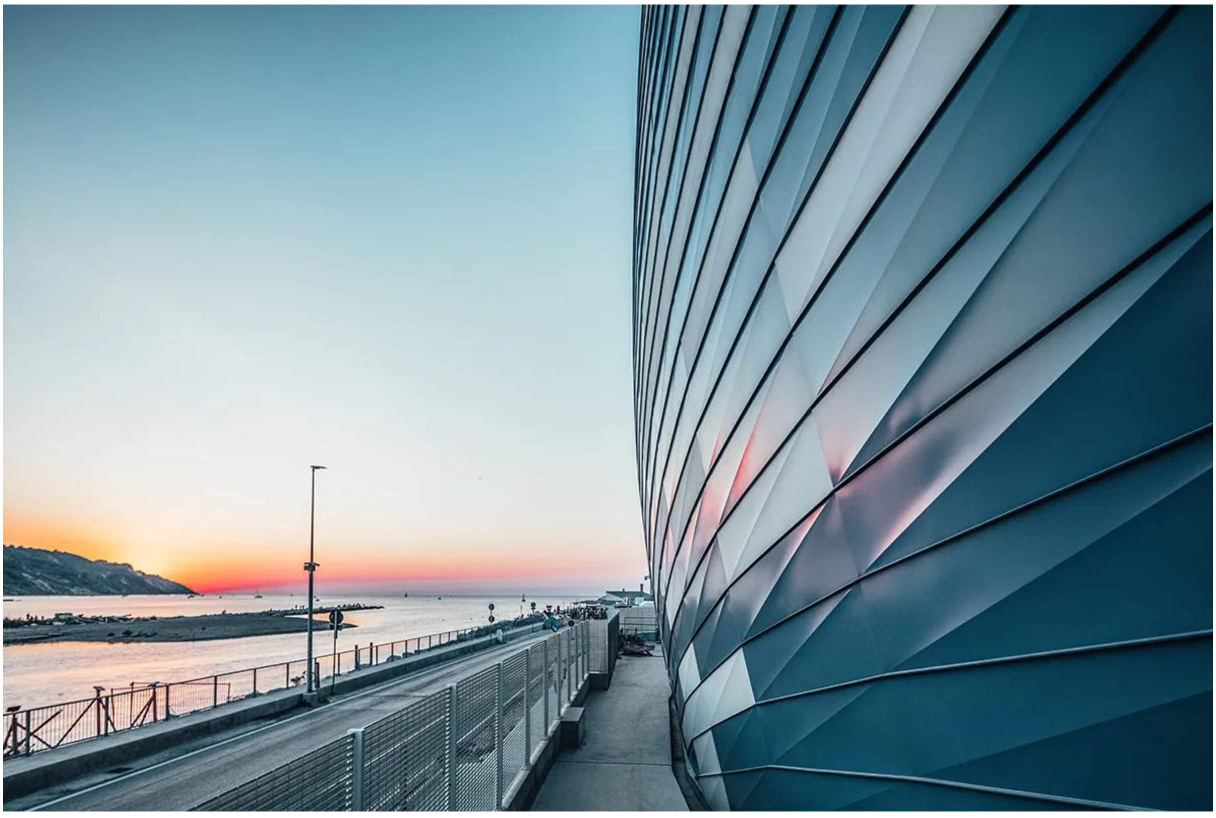


Figure 2.3: Pesaro project external view

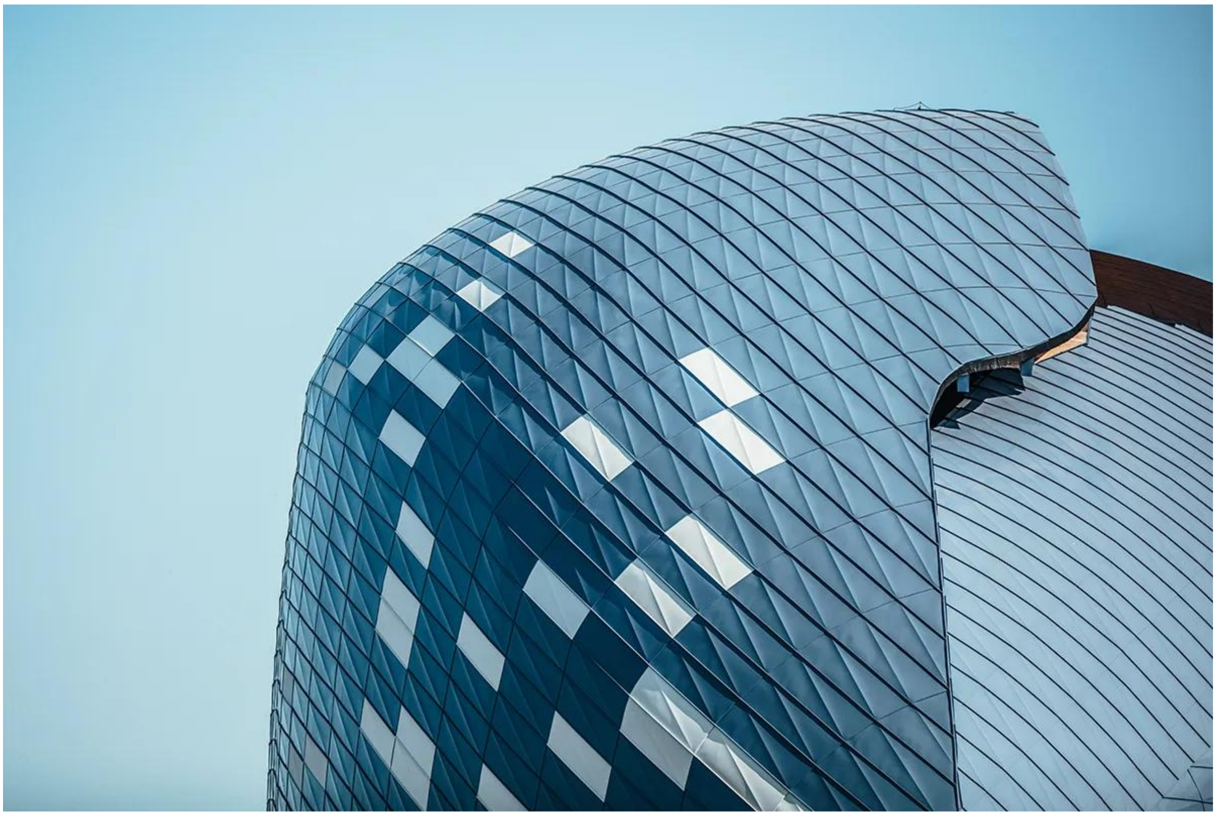


Figure 2.4: Pesaro project external cladding view

Figure 2.5: Pesaro project detail view

2.3.3. Wood-Skin – Poste Italiane Headquarters Façade (Milan, Italy)

The exterior façade intervention for the Poste Italiane headquarters in Milan represents one of Wood-Skin's most significant applications of its digitally fabricated surfaces in a fully outdoor, metal-clad architectural system. In this project, Wood-Skin's patented composite hinge technology—typically associated with interior partitions and acoustic surfaces—is adapted to support a continuous aluminium finishing layer capable of withstanding exterior environmental conditions. The façade is generated from a digitally defined flat pattern composed of rigid triangular modules connected by a flexible textile hinge, allowing the surface to fold along predetermined axes and assume a controlled three-dimensional articulation once installed. The aluminium outer skin is mounted onto this underlying flexible matrix, creating a façade that combines the geometric expressiveness of a folded surface with the durability and visual clarity of metal cladding. The project's strength lies in its hybrid fabrication logic: the geometry is parametrically defined, the components are CNC-cut with high precision, and the final form emerges through a sequence of manual folding operations that transform the planar sheet into a volumetric configuration. This flap-based assembly strategy resonates strongly with the themes explored in this thesis, particularly the translation of flat patterns into spatial structures through bending, alignment, and incremental joining. Although the material composition and hinge mechanism differ from the aluminium sheets manipulated within the mini-factory, the Poste Italiane façade provides a valuable precedent for understanding how digital fabrication, folding logic, and metal finishing layers can converge into a coherent architectural system that bridges design intent and fabrication constraints.

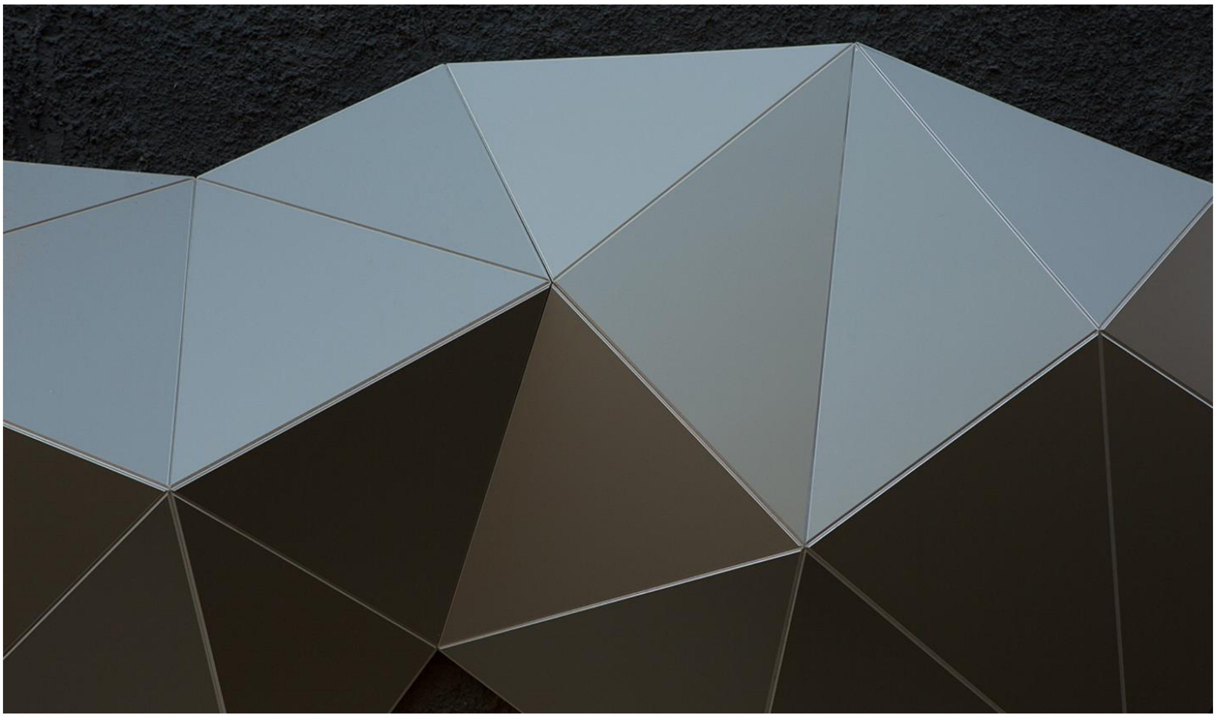


Figure 2.6: Cladding system close-up view

Figure 2.7: Post office external façade

Figure 2.8: Close-up façade detail

2.3.4. Foster + Partners - Apple Store, San Francisco (USA)

Completed in 2016, the Apple Store at Union Square in San Francisco represents one of Foster + Partners' most technically refined applications of aluminium cladding in a commercial setting. The building's façade is composed of large, monolithic aluminium panels characterised by exceptional surface continuity, minimal visible fixings and a level of manufacturing precision achieved through close collaboration with specialist fabricators. This pursuit of material perfection constitutes the project's primary strength, demonstrating how metal can be elevated to a near-seamless architectural finish through rigorous control of fabrication and assembly processes. Yet the same qualities also expose weaknesses: the system is costly, highly dependent on advanced industrial capabilities and offers limited geometric flexibility, making it unsuitable for contexts where adaptability or rapid prototyping is required. The project nonetheless illustrates the importance of tolerance management, alignment strategies and the coordination between digital models and physical components—issues that are equally relevant in workflows involving bent sheet metal and sequential assembly. While the Apple Store operates at a level of industrial refinement far beyond experimental fabrication environments, it provides a valuable benchmark for understanding the demands and constraints of high-precision metal cladding.

Figure 2.9: Apple store San Francisco street view

Figure 2.10: Apple store San Francisco street view

Figure 2.11: Apple store San Francisco external view

2.3.5. Zaha Hadid - Heydar Aliyev Centre (Baku, Azerbaijan)

The Heydar Aliyev Centre, completed in 2012 by Zaha Hadid Architects, is an internationally recognised example of large-scale freeform architecture realised through an intricate system of metal and composite cladding panels. The building's sweeping curves and continuous surfaces required the coordination of thousands of uniquely shaped components, each fabricated through a combination of digital modelling, structural analysis and advanced manufacturing techniques. The project's strength lies in its demonstration of how digital workflows can orchestrate extreme geometric complexity at architectural scale, translating a highly expressive design into a buildable system. However, this ambition also reveals significant weaknesses: the fabrication process is expensive, time-consuming and heavily reliant on specialised industrial partners, making it difficult to replicate in more conventional construction contexts. The project highlights the challenges of tolerance accumulation, panel alignment and the sequencing of installation—issues that resonate with any workflow involving differentiated metal components and incremental assembly. Although the Centre operates at a vastly different scale and level of complexity, it provides a critical reference for understanding the logistical and geometric implications of constructing curved surfaces from discrete elements.

Figure 2.12: Heydar Aliyev Centre external view

Figure 2.13: Heydar Aliyev Centre external view

Figure 2.14: Heydar Aliyev Centre close-up faced cladding

2.3.6. BIG - The Twist (Kistefos Museum, Norway)

The Twist, completed by BIG in 2019 at the Kistefos Museum in Norway, is a hybrid bridge-museum whose defining feature is a continuous torsion expressed through a complex metal cladding system. The structure is enveloped in aluminium and steel panels, each subtly different to accommodate the building's geometric deformation as it rotates across the river. The project's strength lies in its ability to translate a sculptural concept into a buildable system through careful segmentation, precise fabrication and rigorous coordination between digital models and physical components. Yet the reliance on a large number of unique panels introduces weaknesses, particularly in terms of cost, production time and the need for highly accurate on-site assembly. The project foregrounds issues such as tolerance management, panel alignment and the sequencing of installation—concerns that are equally relevant in workflows involving bent sheet metal and incremental assembly. While The Twist operates at a scale and level of refinement distinct from experimental fabrication environments, it offers valuable insights into the challenges and opportunities associated with constructing continuous surfaces from differentiated metal elements.

Figure 2.15: The Twist rendered view

Figure 2.16: The Twist external view

Figure 2.17: The Twist external view

2.3.7. Barkow Leibinger - TRUMPF Smart Factory (Chicago, USA)

The TRUMPF Smart Factory in Chicago, completed in 2017 by Barkow Leibinger, is a fully realised industrial facility designed to showcase TRUMPF's advanced sheet-metal fabrication technologies. The building integrates production spaces, demonstration areas and automated machining lines, forming an architectural expression directly informed by the processes it houses. Its façade and interior elements employ metal surfaces and folded geometries that echo the logic of industrial sheet-metal processing, establishing a clear dialogue between architectural form and fabrication identity. The project's strength lies in its ability to translate the precision and efficiency of industrial manufacturing into an architectural language, demonstrating how metal can be deployed at building scale with clarity and rigour. However, the system remains closely tied to standardised industrial machinery, which limits geometric flexibility and constrains experimentation. Despite this, the Smart Factory offers valuable insights into the relationship between bending, alignment and assembly in metal-based construction, providing a relevant precedent for workflows that seek to integrate digital design with fabrication processes. Its emphasis on sequencing, tolerances and the coordination of automated and manual operations subtly parallels the challenges encountered in hybrid robotic–manual fabrication environments.

Figure 2.18: TRUMPF smart factory external view

Figure 2.19: TRUMPF smart factory internal view

Figure 2.20: TRUMPF smart factory internal view

2.3.8. Machina Labs - Robotic Sheet-Metal Forming (Los Angeles, USA)

Machina Labs, founded in Los Angeles in 2019, is one of the most advanced industrial initiatives exploring the use of collaborative robotics for flexible sheet-metal forming. The company has developed a die-less manufacturing platform in which two large robotic arms equipped with specialised end effectors incrementally deform metal sheets through a process often described as "robotic blacksmithing". Unlike conventional stamping, which requires expensive, geometry-specific tooling, Machina Labs employs a toolpath-driven approach: the robots apply localised pressure along digitally defined trajectories, gradually shaping the sheet into complex three-dimensional forms. This method's principal strength lies in its adaptability, as the same robotic cell can produce a wide variety of geometries without retooling, making it particularly suited to prototyping, small-batch production and industries where rapid iteration is essential. However, the system's sophistication also introduces limitations, including the need for advanced sensing, real-time feedback and high-precision calibration to ensure consistent results. The workflow foregrounds issues such as material springback, tolerance accumulation and the coordination between digital simulation and physical forming—concerns that are central to any fabrication process involving thin metal sheets. Although Machina Labs operates at an industrial scale and focuses on forming rather than bending, its emphasis on flexible automation, toolpath-driven deformation and hybrid human–robot workflows provides a relevant technological parallel to research exploring semi-automated sheet-metal fabrication.

Figure 2.21: Machina Lab logo forming

Figure 2.22: Machina Lab sheet metal forming

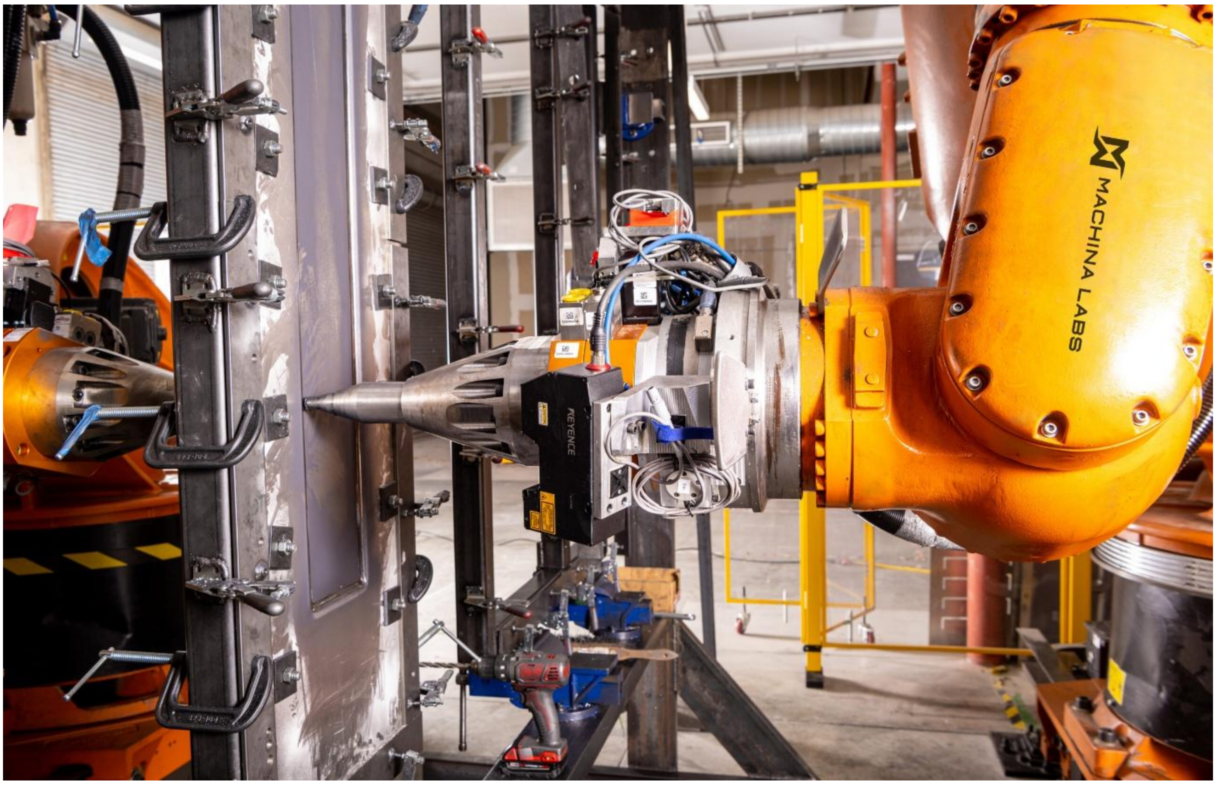


Figure 2.23: Machina Lab sheet metal forming

2.3.9. Integrated Robotic Cells for Sheet-Metal bending

Automated bending cells developed by integrators such as Tiesse Robot in combination with Gasparini press-brakes represent one of the most established solutions for robotic manipulation and forming of metal sheets. These systems typically employ a high-payload industrial robot equipped with vacuum or mechanical grippers to pick flat blanks, orient them precisely, and execute multi-step bending sequences in full coordination with the press-brake. The robot manages repositioning, flipping, and unloading operations autonomously, enabling continuous production with high repeatability and minimal human intervention. While this level of automation delivers exceptional throughput and precision, it also requires substantial investments, dedicated floor space, and highly specialised integration work. For this reason, such systems lack the lightness and versatility that characterise more compact, hybrid approaches. Nevertheless, they remain an important industrial benchmark for understanding the capabilities and constraints of fully automated sheet-metal bending workflows.

Figure 2.24: Automated robotic cell

Figure 2.25: Automated robotic cell

2.4. State of the art in AR guided fabrication systems

Augmented Reality has become a significant interface technology in both construction and manufacturing, providing a direct and intuitive bridge between digital models and physical operations. In construction, AR is increasingly used to superimpose BIM information onto the built environment, enabling workers to perform layout, assembly and tolerance verification with real-time spatial guidance. The introduction of wearable devices such as the Microsoft HoloLens has further expanded these possibilities, allowing operators to visualise full-scale models directly on site and to carry out tasks such as façade alignment, rebar placement and clash detection with improved accuracy and reduced reliance on traditional drawings. In manufacturing, AR functions as an operator-support layer that visualises part orientation, bending sequences and inspection checkpoints directly on the workstation, a capability that proves particularly valuable in high-mix, low-volume production where rapid changeovers and non-standard geometries are common. HoloLens-based interfaces have been shown to enhance comprehension of complex assembly steps and to support workers in maintaining consistent quality across variable tasks. Recent research extends these applications to hybrid human–robot workflows, using AR to visualise robot trajectories, safe zones and task sequences while assisting operators in performing precise, geometry-dependent actions that remain difficult to automate reliably. Although challenges persist in terms of tracking robustness, calibration and device ergonomics, AR is evolving toward deeper integration with robotic systems, CNC pipelines and vision-based feedback. As a result, it is emerging as a key enabler of adaptive, human-centred fabrication environments and provides an important conceptual foundation for the hybrid mini-factory developed in this thesis.

3 Original Contribution - MetaBend Architecture and Physical Components

This chapter presents the physical and operational foundations of the semi-automated mini-factory developed in this thesis and marks the point at which the original contribution of the research begins. Building on the motivations, precedents and methodological framework outlined in the previous chapters, the focus now shifts to the concrete implementation of MetaBend, a fabrication platform conceived to explore adaptive and digitally mediated workflows for customised sheet-metal production. The system is centred on an ABB GoFa collaborative robot and a Schechtl UK 100 S bending machine, supported by a set of hardware and software components that have been deliberately designed to remain interchangeable. This modularity allows the mini-factory to be reconfigured for different products, geometries and operational requirements, ensuring that the workflow is not tied to a single setup but can evolve alongside changing design objectives. Within this environment, a bespoke end effector for vacuum gripping and rotational manipulation, a vision apparatus and an augmented-reality interface work together to support the handling, positioning and bending of thin metal sheets with controlled precision and repeatability. The following sections describe how each component of MetaBend was designed, calibrated and integrated, establishing the technical basis upon which the subsequent workflow, experiments and results are constructed.

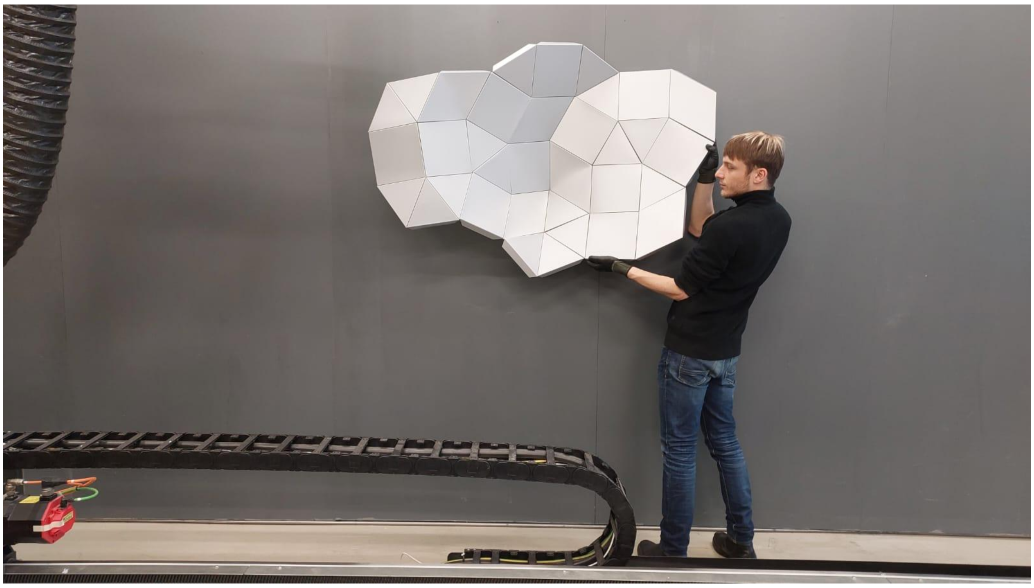


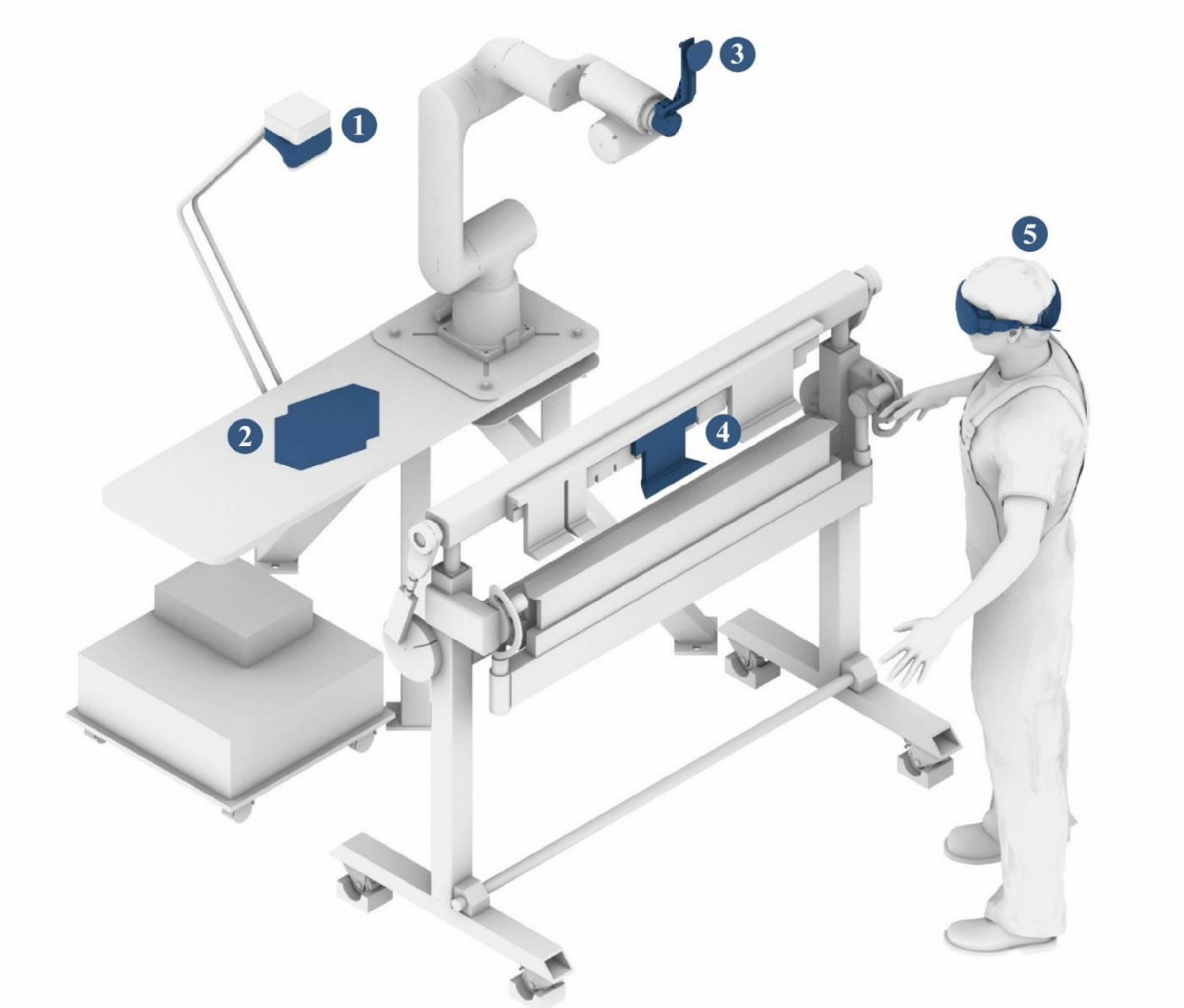
Figure 3.1: Bottom-up approach mock-up

Figure 3.2: Robotic sheet metal handling at Indexlab

3.1. Collaborative Robotic Cell

The core of the mini factory developed in this research is a collaborative robotic cell designed to automate the handling and positioning of aluminium sheets during bending operations; it functions as the operational centre of the system, where digital instructions are translated into precise physical actions. The cell is conceived as a compact, flexible, and accessible fabrication environment that can be integrated into small workshops without the need for industrial scale infrastructure; its layout, components, and control logic are intentionally designed to minimise spatial footprint while maximising operational versatility. At the centre of the cell is the ABB CRB 15000 5, commonly known as the GoFa 5; this collaborative robot enables safe and direct interaction with human operators, making it particularly suitable for hybrid workflows in which manual and automated tasks coexist. Its safety-rated joints, force-sensing capabilities, and inherently compliant behaviour allow the robot to operate without physical barriers, a condition that is essential for the compact and open nature of the mini factory.

The robotic cell is organised around a series of coordinated components that collectively support the manipulation of aluminium sheets with high precision. The robot arm provides the primary kinematic structure; a custom end effector equipped with a seventh axis of rotation extends its dexterity, allowing the suction unit to reorient the sheet without requiring complex arm repositioning. A vacuum based gripping system ensures reliable adhesion to the aluminium surface; its performance is calibrated to accommodate variations in sheet size, stiffness, and surface finish. Complementing these mechanical elements is a visual sensing apparatus responsible for object detection, alignment, and positional verification; this system enables the robot to adapt to small deviations in sheet placement and ensures that each bending operation begins from a known and controlled reference state. Together, these components form an integrated robotic environment capable of picking, orienting, and positioning aluminium sheets with a level of precision and repeatability that would be difficult to achieve manually, especially for repetitive, multi-step, or geometrically sensitive tasks.



1. Vision system

2. Pick-up area

3. Custom 3D-printed end effector

4. Bending positioning area

5. AR guidance system

Figure 3.3: MetaBend system main components diagram

3.1.1. ABB CRB 15000 5 (GoFa 5): Technical and Industrial Overview

ABB is one of the global leaders in industrial automation; its history spans more than forty years of continuous innovation in robotics, electrification, and digital technologies. The company emerged from the merger of ASEA (Sweden) and Brown, Boveri & Cie (Switzerland) in 1988; since then, ABB has played a decisive role in shaping the evolution of industrial robotics across sectors such as automotive manufacturing, electronics, logistics, and advanced fabrication. Its reputation is built on reliability, precision, and the development of systems that integrate seamlessly into human centred production environments; this combination of technological robustness and operational accessibility has made ABB a reference point for both large industrial plants and research-driven laboratories.

Within ABB’s portfolio, the CRB (Collaborative Robotics) series represents a strategic shift toward accessible automation; these robots are designed to operate safely in close proximity to human operators without the need for cages or physical barriers. The GoFa family is part of ABB’s next generation of collaborative robots; it is engineered for tasks requiring dexterity, repeatability, and intuitive interaction. The CRB 15000 5 (GoFa 5) is a six axis collaborative robot with a payload capacity of 5 kg and a reach of 950 mm; it incorporates safety rated torque sensors in every joint, enabling it to detect unexpected contact and react immediately. This capability allows the robot to work in open environments and makes it particularly suitable for compact fabrication setups such as the mini factory developed in this thesis; its collaborative nature ensures that human operators can remain close to the robot during tending operations without compromising safety.

Figure 3.4: ABB Gofa 5

The GoFa 5 offers a repeatability of ±0.02 mm; this level of precision is essential when handling thin aluminium sheets that must be aligned accurately with the bending machine's clamping line. The robot's motion profile is smooth and continuous; this reduces vibration during transport and ensures stable positioning of the sheet, especially during multi-step bending sequences where cumulative error must be minimised. In collaborative mode, the robot can reach speeds up to 2.2 m/s; this balance between performance and safety supports efficient workflows while maintaining operator comfort and situational awareness.

A major advantage of the GoFa platform is its integration with ABB RobotStudio; this software environment enables offline programming, simulation, and trajectory optimisation. RobotStudio allows the entire workflow to be tested virtually before execution; this reduces the risk of collisions, validates reachability, and accelerates the iterative development of the fabrication logic. For a research driven project such as this mini factory, the ability to simulate and refine robotic behaviour before physical testing is invaluable; it ensures that the robot's movements are both efficient and compatible with the spatial constraints of the workshop.

In this thesis, the GoFa 5 acts as the central actuator of the mini factory; it is responsible for picking, orienting, and positioning aluminium sheets with high consistency. Its collaborative nature allows the operator to remain close to the robot during tending operations; its precision elevates the performance of the manual Schechtl UK 100 S machine to a level approaching semi automation. The robot therefore serves not only as a handling device but as a key enabler of a hybrid fabrication workflow in which digital intent, robotic precision, and human supervision coexist within a compact and accessible production environment.

3.1.2. Custom End Effector with Seventh Rotational Axis

The custom end effector developed for this research incorporates a dedicated seventh axis of rotation; this additional degree of freedom is fundamental for orienting aluminium sheets around their normal axis with the precision required for bending operations. Although the ABB GoFa robot provides six degrees of freedom, relying exclusively on its arm kinematics for rotational alignment would introduce unnecessary complexity into trajectory planning; it would also reduce accuracy when the robot operates near singularities or within the spatial constraints imposed by the bending machine. More importantly, without a rotational axis at the gripping interface, every manual bend would require the robot to place the sheet on the table, reorient its entire arm, and pick the sheet up again before continuing the sequence. This approach would be slow, mechanically inefficient, and prone to cumulative positioning errors. By embedding rotation directly at the suction cup, the system bypasses this limitation entirely; the robot can reorient the sheet instantly and continue the bending process without interrupting the workflow.

Figure 3.5: Custom 3D printed end effector

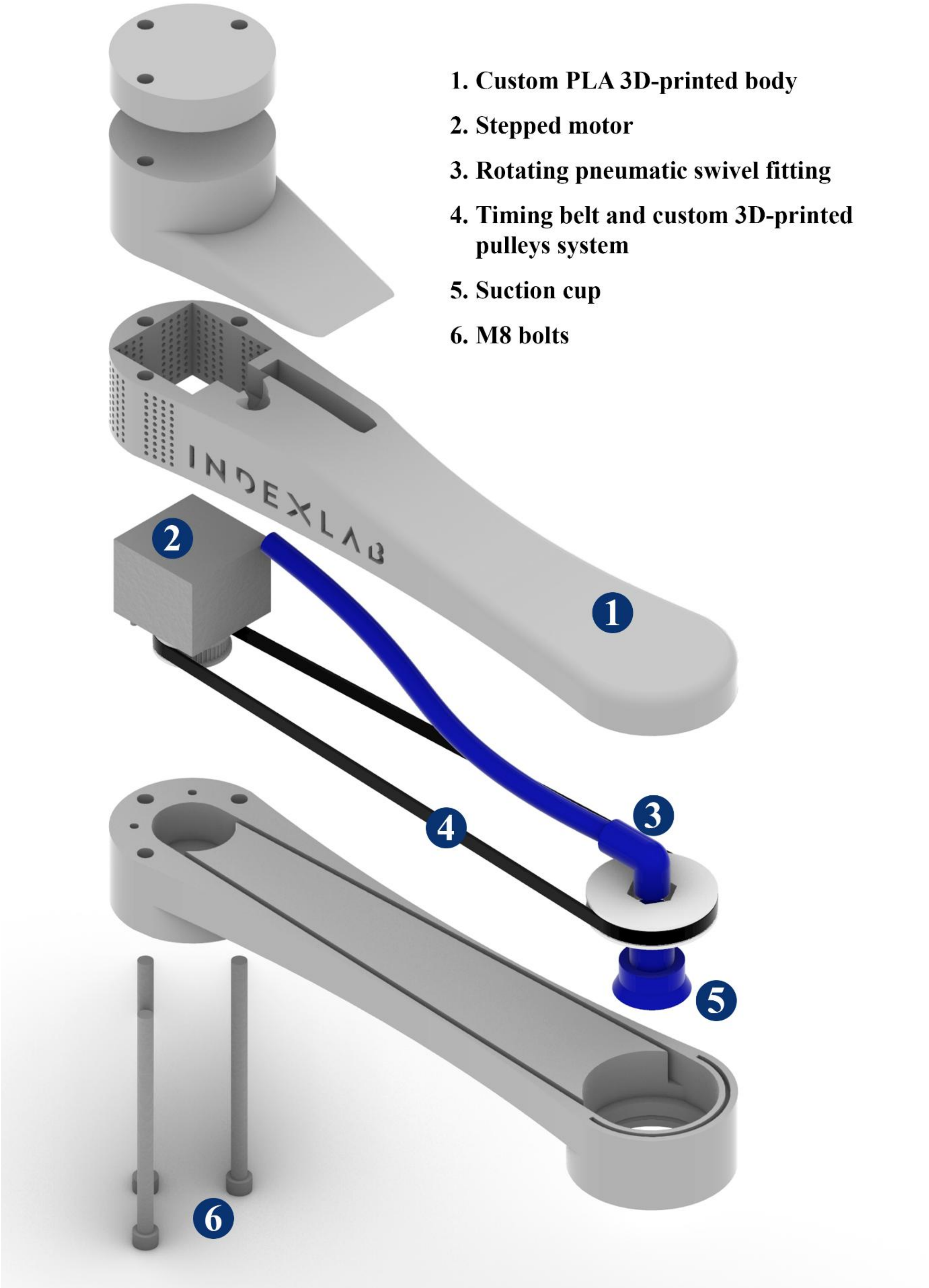


Figure 3.6: Exploded view of end effector and subsystems

The rotational axis is actuated by a NEMA 17 stepper motor; the motor is driven by a dedicated stepper driver configured to divide a full revolution into 1600 microsteps. This microstepping resolution provides the fine angular granularity required for precise sheet alignment. The Arduino microcontroller does not operate autonomously; instead, it receives rotation commands from a Python component embedded in the Grasshopper environment. Communication between Grasshopper and the Arduino is established through a pysocket interface; this enables real time transmission of rotation values, direction commands, and microstepping instructions. The Arduino interprets these values, computes the corresponding number of steps, and actuates the motor accordingly; once the rotation is complete, it sends a confirmation signal back to the robot, ensuring synchronisation between the seventh axis and the robot's motion logic.

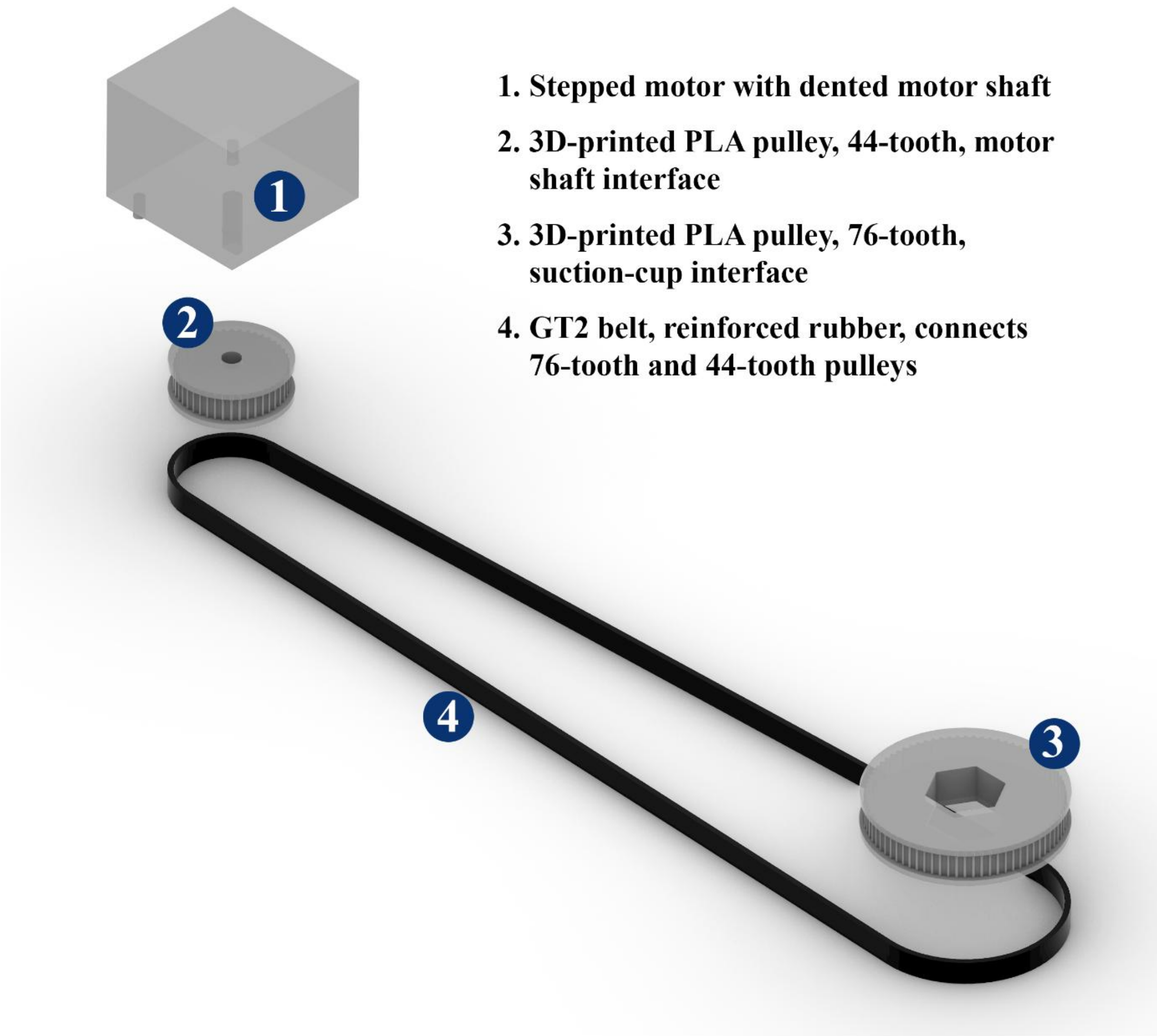


Figure 3.7: Stepped motor, pulleys and belt subsystem diagram

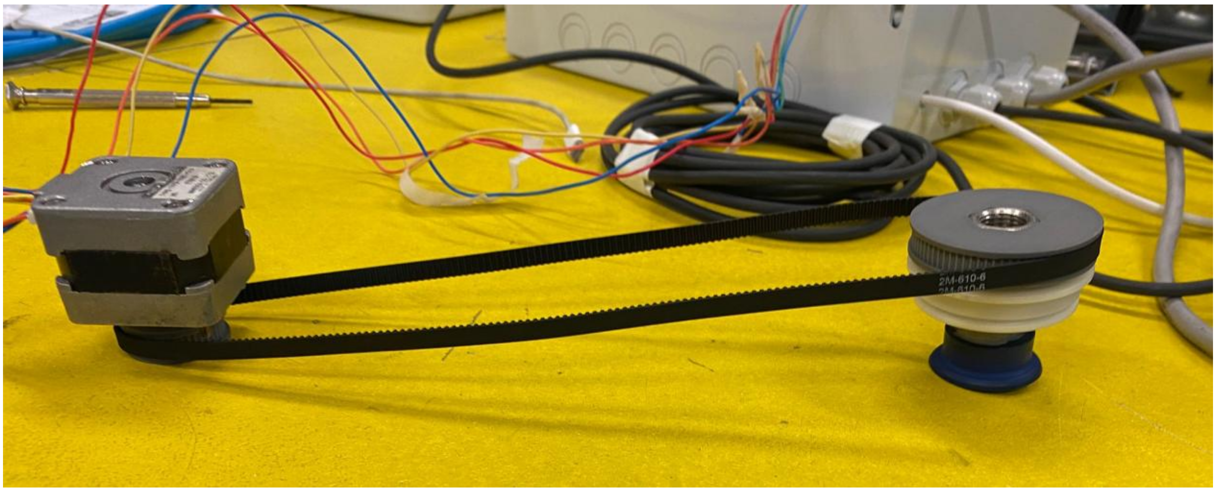


Figure 3.8: Stepped motor, pulleys and belt subsystem

The mechanical transmission of the rotational axis is achieved using a 610 mm GT2 timing belt and two custom 3D printed pulleys with 44 and 76 teeth. The dimensioning of these pulleys follows the standard relationship between tooth count and pitch diameter; for a GT2 profile, the pitch diameter D is given by:

$$\boldsymbol{D} = \frac{N.p}{\pi} \tag{3.1}$$

Where N is the number of teeth and p is the belt pitch (2 mm).

For the 44 tooth pulley:

$$\boldsymbol{D_{44}} = \frac{N.p}{\pi} = \frac{4.2}{\pi} \approx 28.0\ mm \tag{3.2}$$

For the 76 tooth pulley:

$$\boldsymbol{D_{76}} = \frac{N.p}{\pi} = \frac{76.2}{\pi} \approx 48.4\ mm \tag{3.3}$$

The mechanical reduction ratio is therefore:

$$\boldsymbol{R} = \frac{D_{76}}{D_{44}} = \frac{76}{44} \approx 1.727 \tag{3.4}$$

This means that one full revolution of the motor produces approximately:

$$\frac{360°}{1.727} \approx 208.4° \tag{3.5}$$

of rotation at the suction cup. Conversely, one degree of rotation at the suction cup requires approximately 1.727 degrees of motor rotation. This reduction increases torque at the rotating axis; it also improves angular resolution by distributing the motor's microsteps over a larger circumference. With 1600 microsteps per motor revolution, the effective angular resolution at the suction cup becomes:

$$\boldsymbol{Resolution} = \frac{360°}{1600\,.\,R} \approx 0.13°\, per\ microstep \tag{3.6}$$

This level of precision is essential when inserting aluminium sheets into the bending machine's clamping line; even small angular deviations can compromise the accuracy of the fold or cause collisions during insertion.

The Arduino firmware incorporates the pulley ratio directly into its step calculation; the following excerpt illustrates the logic used to convert a target rotation angle into the corresponding number of microsteps:

```
// ---------------------------
// Pulley ratio
// ---------------------------
const float TARGET_BIG_DEG = 120.0;
const float MOTOR_PER_BIG  = 76.0 / 44.0;
const float TARGET_MOTOR_DEG = TARGET_BIG_DEG * MOTOR_PER_BIG;
```

```
// ---------------------------
// Stepper configuration
// ---------------------------
const int MICROSTEP = 16;
const int STEPS_PER_REV = 200 * MICROSTEP;
const float STEPS_PER_DEG = (float)STEPS_PER_REV / 360.0;
const float TARGET_STEPS_FLOAT = TARGET_MOTOR_DEG * STEPS_PER_DEG;
```

The suction cup assembly is mounted directly on the rotating axis; this configuration allows the aluminium sheet to be oriented precisely without requiring complex multi axis robot movements. The rotational axis can perform continuous or incremental rotation depending on the bending sequence; this flexibility supports a wide range of façade components and geometries. The combination of microstepping, pulley reduction, and low backlash transmission ensures that the end effector can achieve fine angular adjustments with high repeatability; this is particularly important during multi fold operations where cumulative error must be minimised.

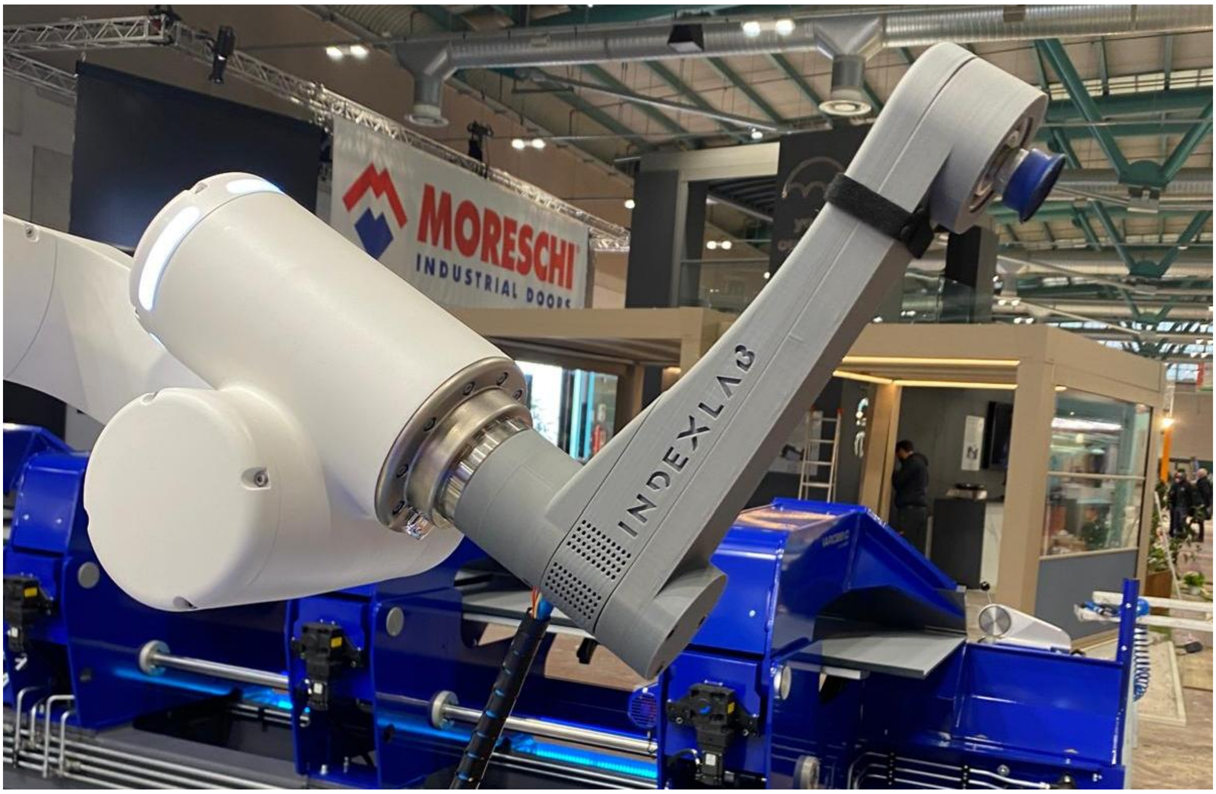


Figure 3.9: End effector mounted on Gofa 5

By integrating this seventh axis, the end effector becomes a highly adaptable tool; it enhances the robot's ability to position sheets accurately, reduces operator intervention, and eliminates the inefficient cycle of placing, reorienting, and regripping the sheet after every manual bend. This improvement supports the broader objective of transforming a manual bending machine into a semi-automated system with improved precision, repeatability, and workflow continuity. The seventh axis therefore plays a central role in bridging the gap between the flexibility of collaborative robotics and the geometric constraints of sheet metal bending; it enables the mini factory to operate with a level of control and efficiency that would be difficult to achieve through the robot's native kinematics alone.

Figure 3.10: Metal sheet pick-up operation at CaseItaly 2026

3.1.3. Signal Architecture of the Seventh Axis of Rotation

The seventh axis of rotation is driven by a dedicated electromechanical subsystem composed of a NEMA 17 stepper motor, a stepper motor driver, and an Arduino microcontroller; together, these components generate the controlled rotational motion required to orient the aluminium sheet between bending operations. This subsystem is fully integrated into the end effector and operates as an autonomous rotational module that complements the robot’s native kinematics.

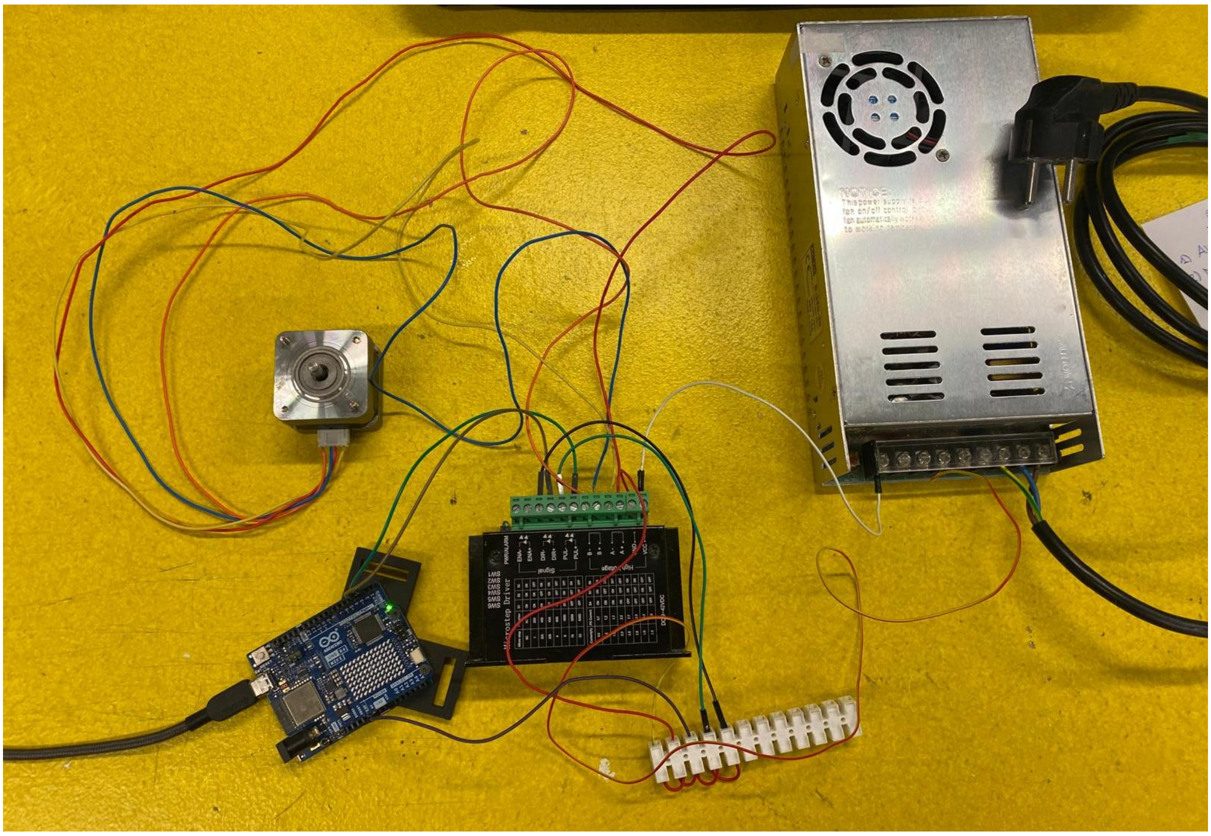


Figure 3.11: Seventh axis of rotation subsystem

The NEMA 17 stepper motor provides the torque necessary to actuate the GT2 belt and pulley assembly; stepper motors operate through discrete angular increments and therefore require a sequence of electrical pulses to rotate. Because the Arduino cannot supply the current needed to energise the motor coils directly, the motor is connected to a stepper driver; the driver acts as an intermediary between the low voltage logic signals generated by the Arduino and the higher current required by the motor phases. This separation ensures that the motor receives stable and sufficient power without overloading the microcontroller.

The stepper driver receives two essential control signals from the Arduino; the STEP signal, which determines the number of microsteps the motor performs, and the DIR signal, which sets the direction of rotation. These signals are transmitted at 5 V logic level and are interpreted by the driver, which then generates the appropriate multi phase current patterns required to rotate the motor. The driver is powered through a dedicated external supply; this guarantees that the motor receives a stable current source and prevents voltage drops that could compromise rotational accuracy.

The Arduino functions as the control unit of the seventh axis; it generates the STEP and DIR pulses according to the rotation commands it receives from the digital workflow. The microcontroller is powered via USB-C, which provides both power and communication. A shared ground between the Arduino and the driver ensures that the logic signals are interpreted consistently and without electrical noise; this is essential for maintaining precise timing of the STEP pulses, which directly affects the angular resolution of the rotational axis.

The wiring architecture can be summarised as follows:

- The Arduino outputs STEP and DIR signals to the driver;
- The driver powers and controls the NEMA 17 motor, while sharing a common ground with the Arduino;
- The driver receives its own external power supply to energise the motor coils.

This architecture provides a clear separation between logic level control and motor level power; it ensures reliable operation of the seventh axis while maintaining electrical safety and signal integrity. In future developments, the Arduino may be triggered directly by the robot’s digital outputs; this will require a relay or optocoupler to convert the robot’s 24 V signals into the 5 V logic required by the Arduino, enabling tighter integration between the robot controller and the rotational subsystem.

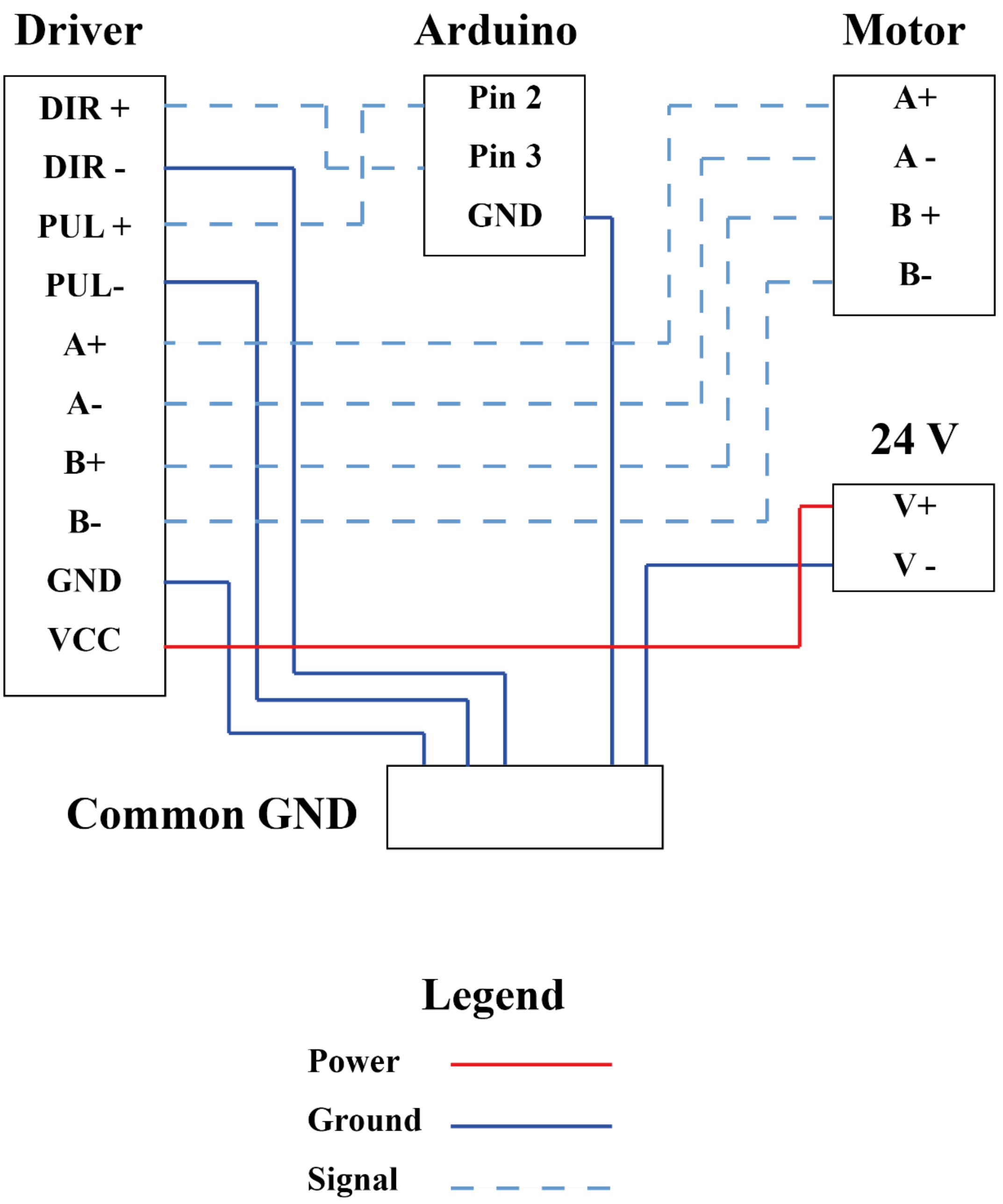


Figure 3.12: Signal architecture diagram of seventh axis of rotation

3.1.4. Vacuum System Integration

The gripping mechanism of the end effector relies on a vacuum based system designed to handle aluminium sheets securely and without surface damage; the system is engineered to provide reliable adhesion, rapid response times, and stable performance throughout the bending workflow. At the core of this subsystem is a Schmalz compact ejector (SCPI 15 NC VD M12.5); this component integrates vacuum generation, flow regulation, and monitoring functions within a compact housing, making it particularly suitable for lightweight robotic applications where space and weight constraints are critical. The ejector operates using compressed air supplied through a dedicated pneumatic line; its Venturi based mechanism converts the airflow into negative pressure, which is then transmitted to the suction cup mounted on the rotating axis of the end effector.

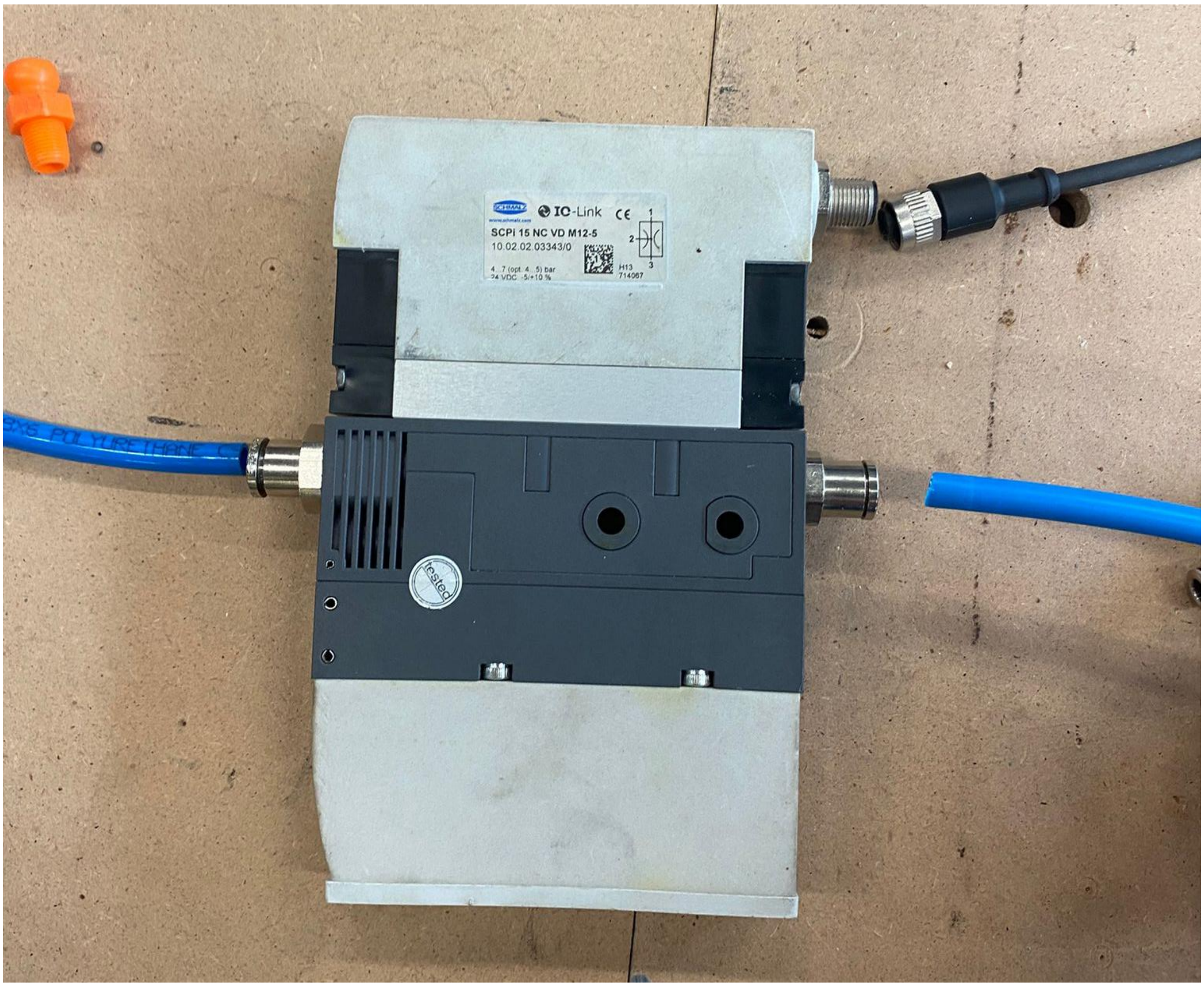


Figure 3.13: Schmalz SCPI 15 NC VD M12.5 compact ejector

A crucial element enabling this configuration is a rotating pneumatic swivel fitting, positioned between the suction cup and the vacuum line. This component allows the suction cup to rotate freely around its own axis while maintaining an airtight connection to the compact ejector through a flexible plastic tube. Without this swivel fitting, the vacuum hose would twist and coil as the seventh axis rotates, eventually causing mechanical interference, air leakage, or complete obstruction of the vacuum flow. The swivel fitting therefore plays an essential role in the mechanical architecture of the end effector; it ensures continuous vacuum supply during rotation and allows the seventh axis to operate without constraints or risk of damaging the pneumatic line.

Figure 3.14: Pneumatic swivel fitting, suction cup and 76 tooth pulley

The system employs a single suction cup, selected to match the typical surface area, stiffness, and mass of the aluminium sheets processed in the mini factory. The suction cup is connected directly to the swivel fitting, which in turn is connected to the output port of the compact ejector; this configuration minimises pressure losses and ensures fast switching between gripping and release. The compact ejector is also integrated into the robot's electrical I/O architecture; it is controlled as a digital output (DO) of the GoFa, allowing the robot controller to activate or deactivate the vacuum at specific points in the workflow. To guarantee stable operation, the ejector is powered through a dedicated 24 V supply; this ensures consistent voltage delivery independent of other electrical loads within the system and prevents fluctuations that could compromise vacuum performance.

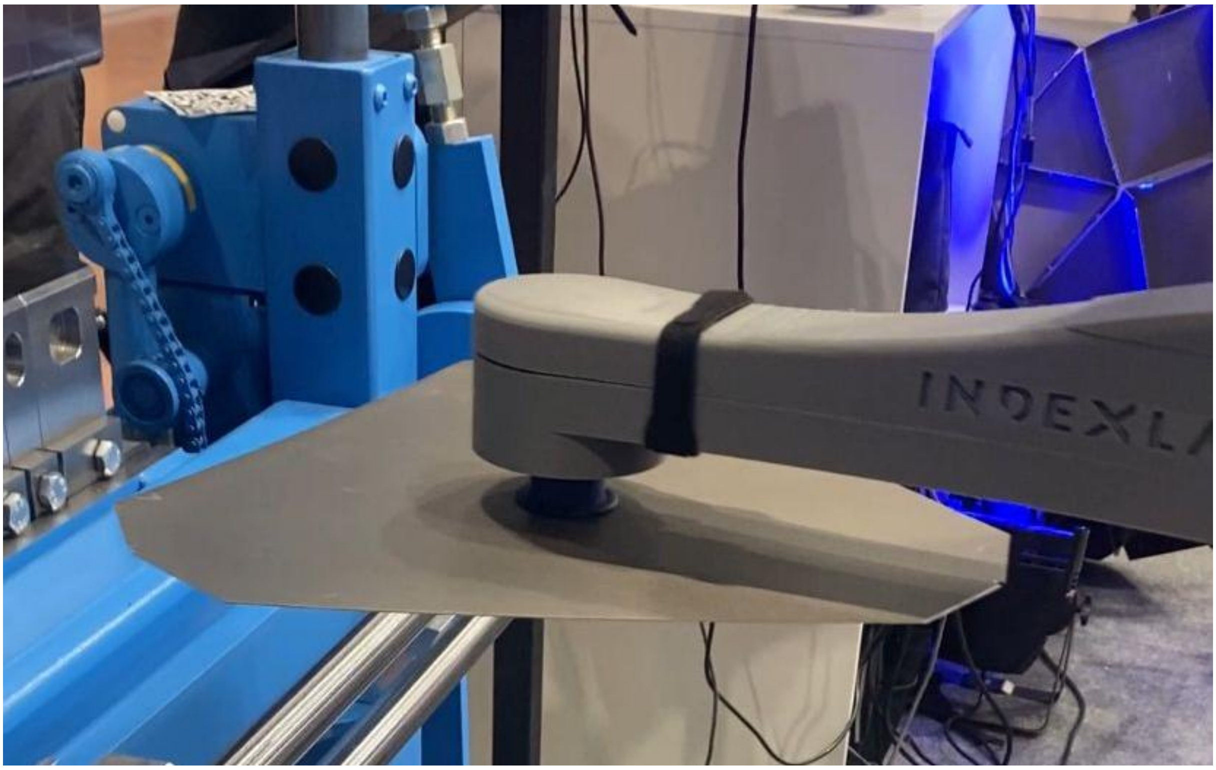


Figure 3.15: End effector gripping a piece

The integration of the vacuum ejector into the robot's control logic enables precise synchronisation between gripping actions and robot motion; before initiating any movement, the robot can verify that the vacuum is active, reducing the risk of accidental drops or incomplete gripping. The compact ejector also incorporates internal sensors capable of monitoring vacuum level and flow rate; this diagnostic information can be used to detect leaks, misalignment, or insufficient surface contact, further enhancing the reliability of the gripping process. Although this feedback is not yet fully integrated into the real time control loop, it provides a foundation for future improvements in adaptive gripping and error detection.

The combination of a Schmalz compact ejector, a single optimised suction cup, a rotating pneumatic swivel fitting, and direct digital control through the GoFa results in a robust and responsive gripping system; it ensures that aluminium sheets remain stable during transport, rotation, and insertion into the bending machine. This stability is essential for maintaining the precision and repeatability of the mini factory workflow, particularly during multi step bending sequences where cumulative errors must be minimised. The vacuum system therefore plays a central role in enabling the robot to handle sheets safely and efficiently within the compact spatial constraints of the fabrication environment.

3.1.5. Visual Sensing and Object Recognition

The mini factory incorporates a vision based detection system that assists the robot in identifying the position and orientation of aluminium sheets before gripping. The system is designed to operate reliably under workshop lighting conditions; it uses contrast based recognition to distinguish the sheet from the background. A depth sensing camera is mounted above the pick-up area; the aluminium piece is placed on a white surface that provides a uniform, high contrast background. This configuration allows the camera to isolate the sheet's silhouette with high accuracy.

The vision algorithm analyses the captured image to detect the sheet's contour; it then computes the geometric centre of the piece and identifies the main direction of its first flap. This directional information is extracted by evaluating the longest edge or the dominant axis of the detected contour; the system then calculates the orientation angle relative to the camera's reference frame. Once the centre point and orientation are determined, the camera communicates these coordinates to the robot controller; the robot uses this information to position the TCP of the end effector precisely at the centre of the sheet.

This process ensures that the robot grips the piece in a stable and balanced manner; it also compensates for small variations in how the sheet is placed on the table. By providing real time positional data, the vision system reduces the need for manual alignment and increases the repeatability of the workflow. The combination of contrast based detection, geometric analysis, and direct communication with the robot controller enables a robust and efficient pick up procedure; it forms an essential component of the mini factory's semi-automated handling pipeline.

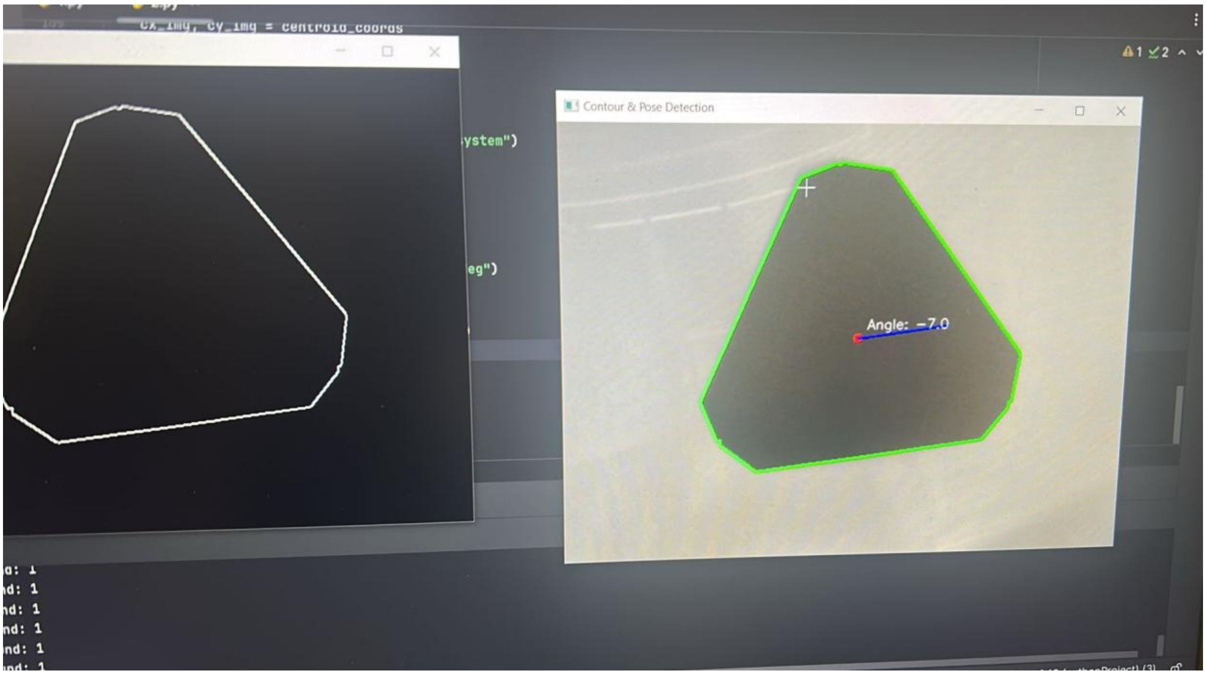


Figure 3.16: Object recognition

3.1.6. Robotic Workflow During the Bending Process

The GoFa robot plays an active role throughout the entire bending sequence; rather than releasing the sheet after the first clamping operation, the robot remains engaged until all flaps of the component have been bent. This continuous involvement ensures precise alignment, reduces handling errors, and allows the seventh axis of rotation to be used effectively between bending steps. By maintaining control of the sheet from the initial pick-up to the final placement, the robot eliminates unnecessary repositioning cycles and preserves geometric consistency across the entire workflow.

The process begins with the robot picking up the flat sheet from the designated pick-up area using the vacuum end effector. The vision system provides the centre point and orientation of the sheet; the robot aligns the suction cup with this detected pose and lifts the sheet from the table. It then moves through a sequence of intermediate waypoints designed to avoid collisions with the surrounding environment and to maintain the sheet in a stable, vibration-free orientation. These waypoints are optimised to ensure that the sheet remains fully visible to the operator and clear of the bending machine's moving elements.

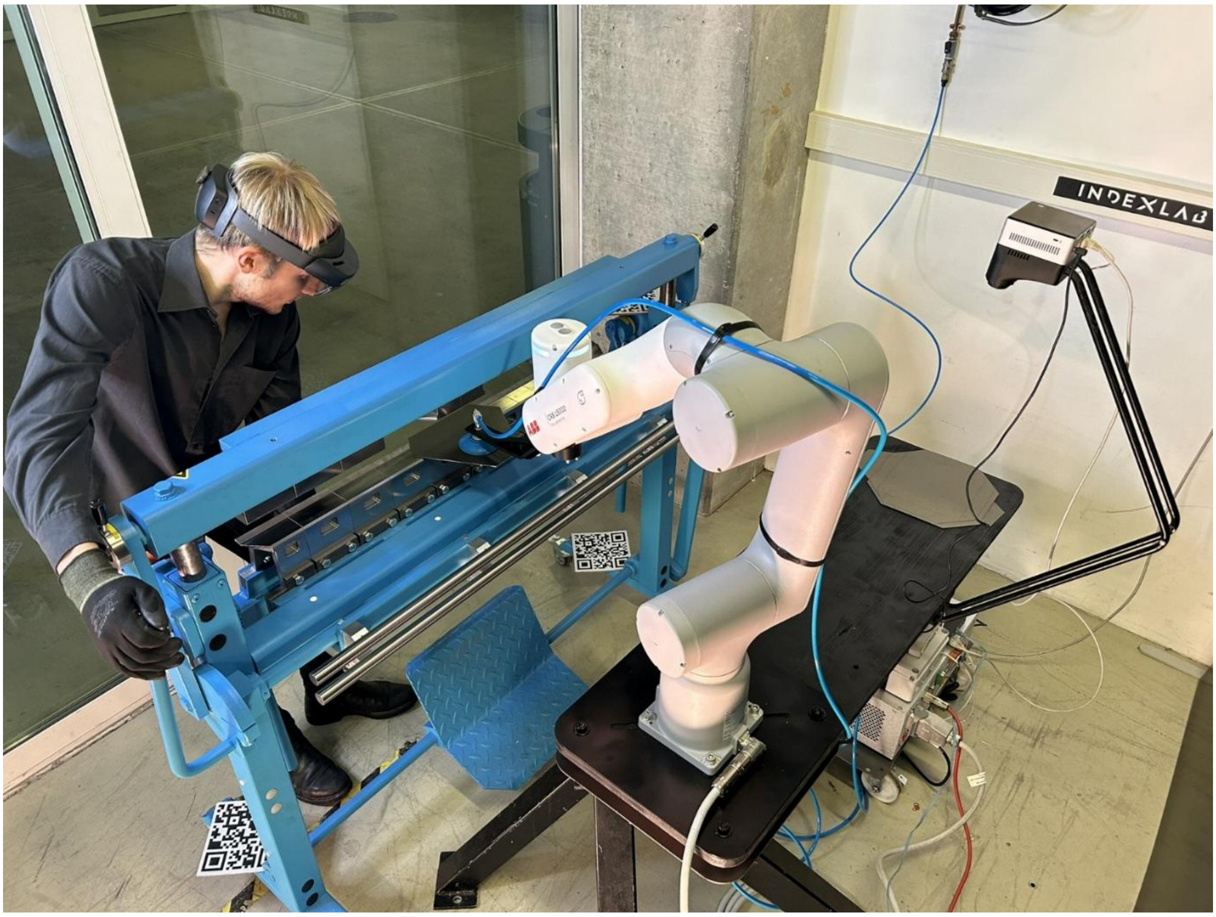


Figure 3.17: Lecco Indexlab laboratory system set-up

Upon reaching the Schechtl UK 100 S, the robot positions the sheet precisely against the clamping line. The operator then manually clamps the sheet; during this phase, the robot maintains its grip and holds the sheet firmly in place, ensuring that the material does not shift during clamping. Once the sheet is secured, the operator performs the bending operation guided by the augmented reality interface. The robot remains stationary throughout the bend, providing a stable reference frame that prevents misalignment or unintended movement of the sheet.

After the first flap is bent, the operator releases the clamp. At this point, the robot lifts the sheet away from the machine and moves to a safe intermediate position. The seventh axis of rotation is then activated; the robot rotates the sheet by the required angle so that the next flap is correctly oriented for bending. This rotational capability is essential for maintaining workflow continuity; without it, the robot would be forced to place the sheet on the table, reorient its entire arm, and pick it up again before each bend. The seventh axis therefore eliminates unnecessary handling steps and significantly improves the efficiency and accuracy of the bending sequence.

Once the sheet has been rotated, the robot repositions it against the clamping line for the next bend. The operator clamps the sheet again and performs the subsequent bending operation. This cycle repeats until all flaps of the component have been bent in the correct order and orientation. Throughout the process, the robot ensures consistent alignment, compensates for cumulative tolerances, and reduces the physical workload on the operator.

When the bending sequence is complete, the robot transports the finished component back to the designated placement area. This iterative workflow not only guarantees that each flap is bent with the required precision; it also minimises manual handling, reduces the likelihood of errors, and maintains a stable and repeatable fabrication process within the compact environment of the mini factory.

3.2. Bending/Tending Subsystem

The bending/tending subsystem constitutes the second core element of the mini factory; it bridges the precision of robotic handling with the manual dexterity of a traditional folding machine. Rather than replacing the bending machine with an automated industrial line, this research integrates collaborative robotics, augmented reality guidance, and human expertise into a unified workflow. The subsystem demonstrates how existing workshop equipment can be enhanced through digital augmentation; it transforms a conventional manual process into a semi-automated fabrication sequence capable of producing façade components with improved accuracy, repeatability, and operator support.

3.2.1. Schechtl UK 100 S: Technical and Industrial Overview

Schechtl is one of the most established manufacturers of sheet metal bending machinery in Europe; the company has been producing folding machines, shears, and forming equipment for more than a century. Founded in Germany in the early twentieth century, Schechtl has built its reputation on robust mechanical engineering, reliability, and the ability to serve small and medium-scale workshops that require versatile equipment rather than fully automated industrial lines. Its machines are widely used in roofing, façade fabrication, HVAC ductwork, and general sheet metal processing; they are valued for their durability, mechanical precision, and ease of use.

The Schechtl UK series represents the company’s line of manual and semi-manual bending machines; these machines are designed for operators who need flexibility and control when producing customised sheet metal components. The UK 100 S, used in this research, is a manually operated folding machine with a bending length of approximately one metre; it is engineered to handle thin to medium thickness aluminium sheets with consistent accuracy. The machine consists of a clamping beam, a bending beam, and a counter beam; the operator positions the sheet manually, clamps it using a foot pedal or lever, and then performs the bend by lifting the bending beam to the desired angle.

The mechanical structure of the UK 100 S is built around a rigid steel frame; this ensures minimal deflection during bending and contributes to the repeatability of the process. The clamping beam applies uniform pressure along the entire length of the sheet; this prevents slippage and ensures that the bend line remains straight. The bending beam is equipped with adjustable angle stops; these allow the operator to repeat specific angles with reasonable consistency. Although the machine is manually operated, its mechanical tolerances and structural stability make it suitable for producing façade components such as flashings, cassettes, drip edges, and corner profiles.

In traditional workshop settings, the performance of the UK 100 S depends heavily on operator skill; precise alignment of the sheet before clamping is essential, and the bending angle must be judged visually or with the aid of simple mechanical gauges. This introduces variability; it also limits the speed at which repetitive or geometrically sensitive components can be produced. Despite these limitations, the UK 100 S remains a popular choice because it is affordable, compact, and capable of handling a wide variety of bending tasks without the need for specialised tooling.

In the context of the mini factory developed in this thesis, the UK 100 S is not replaced but augmented; the collaborative robot positions the sheet with high precision, while the operator performs the bending action following augmented reality guidance. This hybrid configuration elevates the machine's performance to a level approaching that of automated bending lines; however, it does so at a fraction of the cost and without sacrificing the flexibility that makes manual machines attractive to small workshops. The UK 100 S therefore becomes a key component of the semi-automated workflow; it demonstrates how existing equipment can be enhanced through digital integration rather than replaced by expensive industrial systems.

Figure 3.18: Schectl UK 100 S bending machine

3.2.2. Augmented Reality Guidance System

The augmented reality system is designed to support the manual bending operations performed on the Schechtl UK 100 S; its primary function is to reduce the cognitive load on the operator by providing real time, spatially aligned visual guidance. Instead of relying on printed drawings, angle indicators, or repeated visual checks, the operator receives precise instructions directly within their field of view through an AR visor. This transforms the bending process from a memory-driven task into a guided, visually assisted workflow.

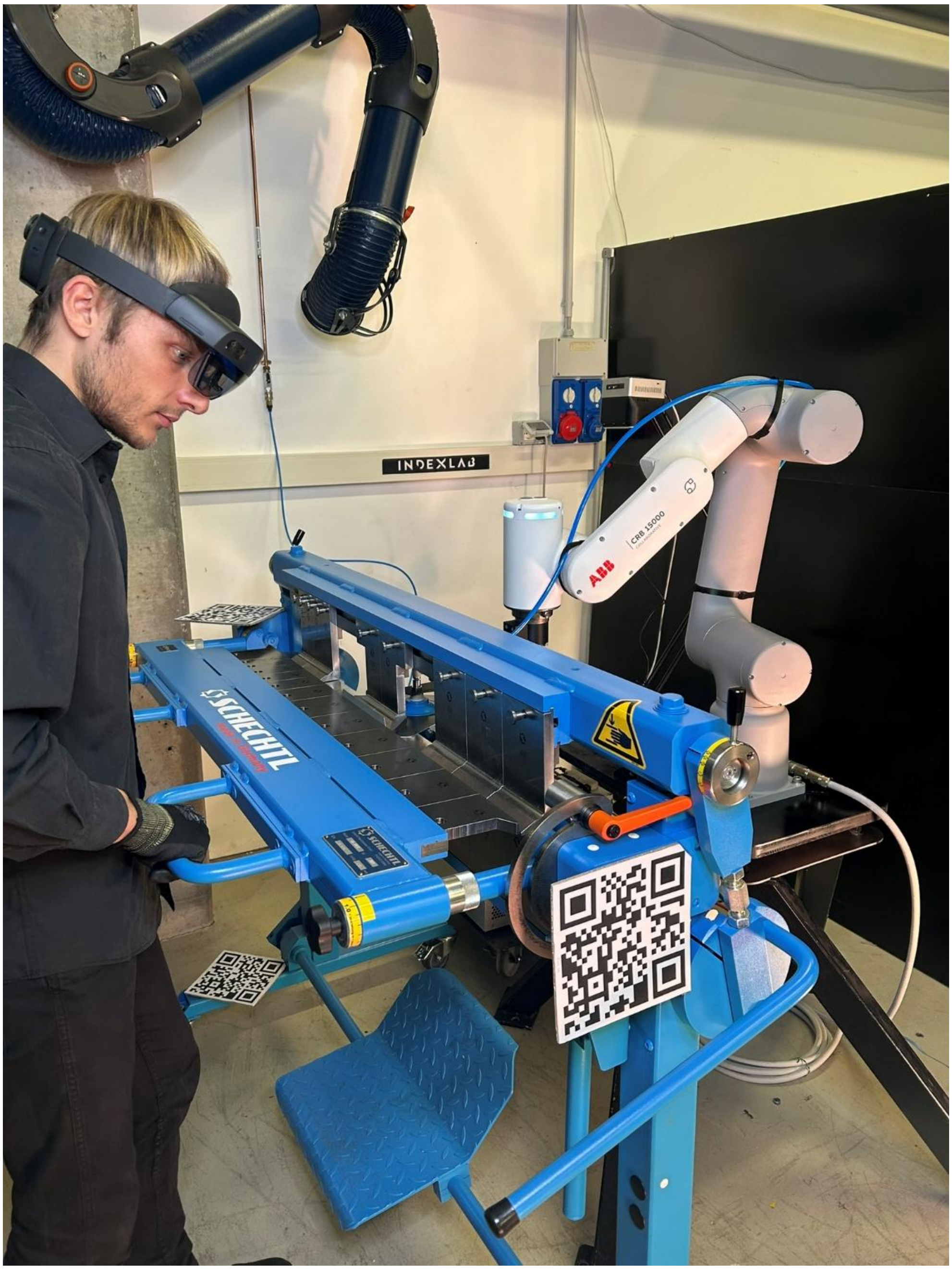


Figure 3.19: AR-assisted bending operations

The AR interface operates by superimposing a wireframe model of the digital bending machine onto the physical one; this alignment is achieved through spatial anchoring, ensuring that the virtual geometry remains fixed in place relative to the real machine. When the operator looks at the bending station through the visor, the digital model appears perfectly juxtaposed with the physical structure; this creates a stable reference frame in which instructions can be delivered with clarity and precision. The spatial anchoring process is robust to small head movements and changes in viewpoint; the virtual elements remain locked to the machine, enabling the operator to move naturally without losing alignment.

This system is particularly valuable because bending sequences vary significantly between pieces; even when starting from sheets of identical shape, the order of operations, the required angles, and the orientation of each flap can differ depending on the final façade component. The AR interface highlights the flap that must be bent, indicates the correct orientation of the sheet, and displays the sequence of operations step by step. By following the digital cues, the operator avoids common errors such as bending a flap prematurely, misreading the intended angle, or misaligning the sheet before clamping.

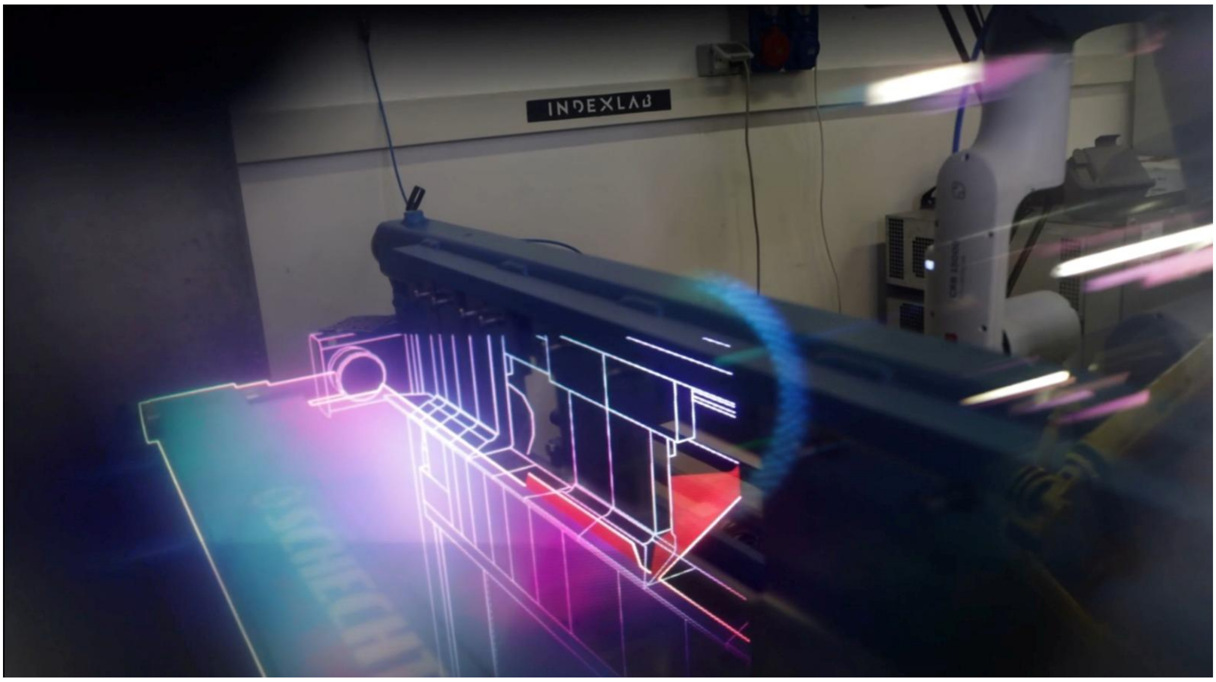


Figure 3.20: AR visor internal view

A key advantage of the AR system is its ability to guide the operator in achieving accurate bending angles without the need to monitor the mechanical angle indicators on the machine. The visor displays a digital representation of the bending leaf; as the operator lifts the physical bending leaf, they simply ensure that its movement coincides with the digital overlay. When the physical and virtual bending leaves align, the bend angle corresponds exactly to the value defined in the digital model. This method eliminates the need for visual estimation or repeated checking; it ensures that the bend matches the designed angle with high precision and reduces the variability typically associated with manual bending.

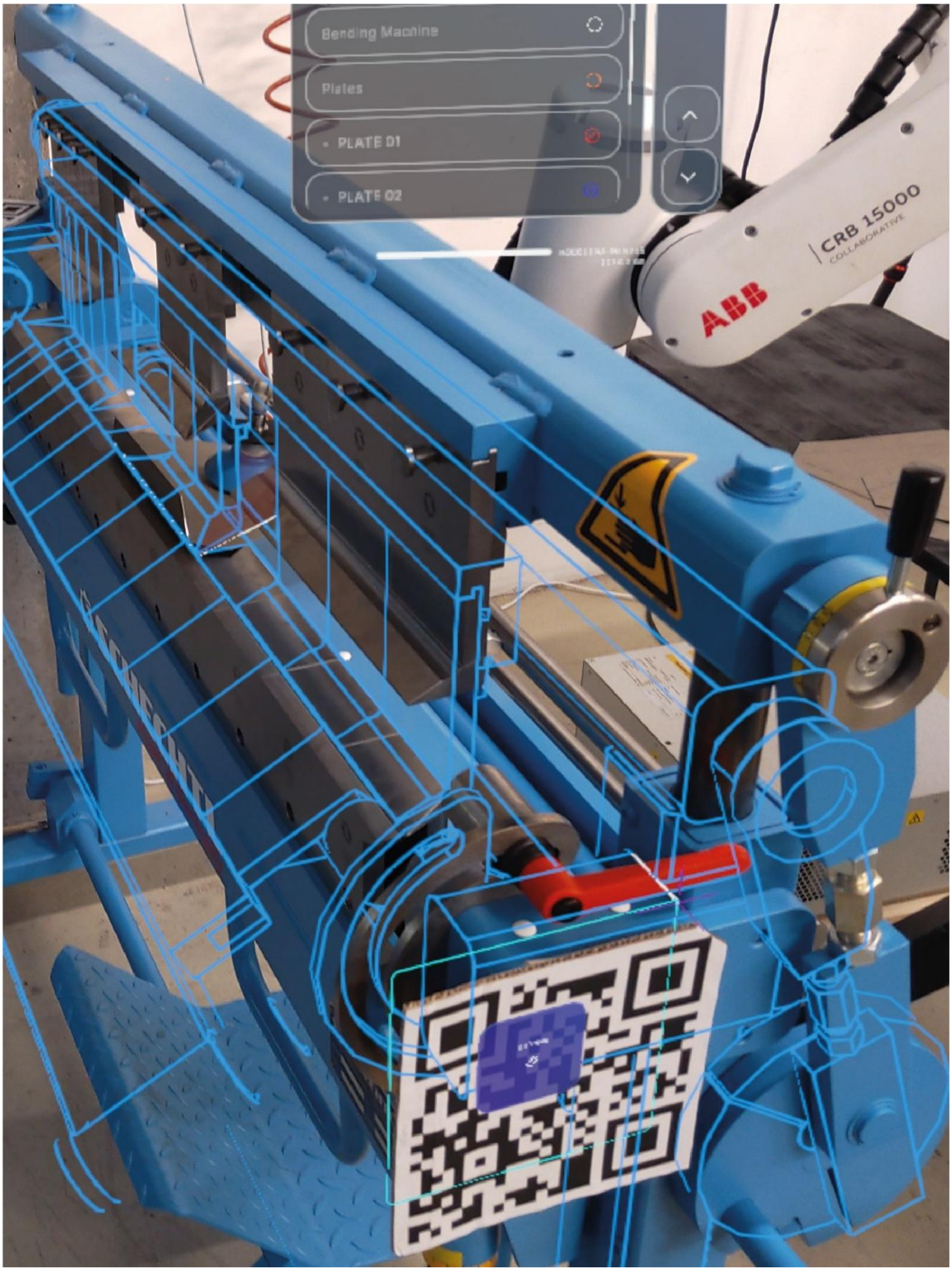


Figure 3.21: Digital and physical bending machines overlapping

The AR system also supports the operator during sheet positioning. Before each bend, the visor displays the correct orientation of the sheet relative to the clamping line; this is particularly important when the robot rotates the sheet using the seventh axis, as the operator must confirm that the new orientation matches the digital instructions. The AR overlay therefore acts as a verification layer, ensuring that the robot's positioning and the operator's clamping actions remain synchronised.

By combining spatial alignment, digital sequencing, and real time visual feedback, the AR system transforms the manual bending process into a guided, semi-automated workflow. It enhances accuracy, reduces the likelihood of human error, and enables operators with varying levels of experience to produce consistent results. Within the mini factory, augmented reality acts as a crucial bridge between digital fabrication logic and manual machine operation; it allows the Schechtl UK 100 S to perform with a level of precision and repeatability approaching that of automated bending systems, while preserving the flexibility and affordability of manual equipment.

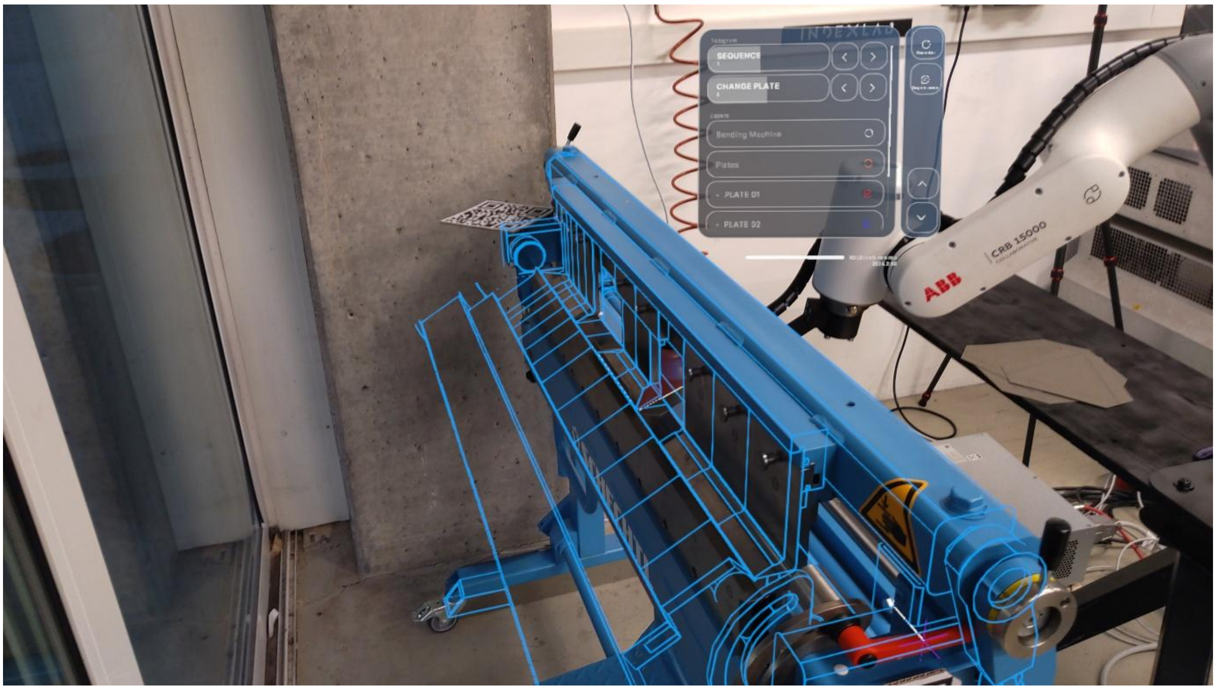


Figure 3.22: Digital and physical bending machines overlapping

3.3. Calibration and Spatial Layout of the Mini Factory

The spatial configuration of the mini factory is designed to ensure a continuous and efficient workflow between the robot, the pick-up area, and the bending machine; the layout must allow the GoFa to operate within its optimal reach while maintaining a safe and ergonomic working environment for the operator. The arrangement of the components is therefore not arbitrary; it is the result of a calibration process that establishes a shared geometric framework across all elements of the system. Only by aligning the physical and digital environments can the robot, the vision system, the bending machine, and the operator function as a coherent whole.

The first step in the calibration procedure consists of defining the robot's base frame within the physical workspace. This reference frame is aligned with the coordinate system used in Grasshopper and RobotStudio; it ensures that the virtual simulation corresponds precisely to the real environment. The robot is positioned so that its working envelope covers both the pick-up table and the clamping line of the Schechtl UK 100 S; this placement minimises unnecessary arm extension, reduces cycle time, and ensures that the robot can approach the bending machine with stable and collision-free trajectories.

Once the robot's base frame is established, the tool centre point (TCP) of the custom end effector is calibrated. This step is essential because the TCP corresponds to the centre of the suction cup; all gripping, alignment, and insertion operations depend on its accuracy. The calibration is performed by touching known reference points in the workspace and adjusting the TCP parameters until the virtual and physical positions coincide. A precise TCP ensures that the robot can approach the sheet at the correct angle; it also guarantees that the sheet is inserted into the bending machine along the intended line, avoiding contact with the clamping beam or bending leaf.

The next stage involves calibrating the pick-up area. The vision system provides the robot with the centre and orientation of the sheet; however, the camera itself must be registered within the robot's coordinate system. This is achieved by identifying a set of calibration markers placed on the pick-up table; the camera detects these markers, and their positions are matched to known coordinates in the robot's frame. This procedure ensures that the positional data sent by the vision system corresponds accurately to the robot's spatial logic; it allows the robot to grip the sheet at its true centre even when the sheet is placed with slight variations in position or orientation.

A further calibration step concerns the alignment with the bending machine. The Schechtl UK 100 S does not provide digital feedback; therefore, the robot must rely on a precisely defined reference frame that describes the position of the clamping line, the bending leaf, and the sheet insertion path. This frame is established by manually probing key points on the machine with the robot's TCP; once these points are recorded, the bending machine becomes fully integrated into the robot's spatial model.

This alignment is crucial because even small deviations in the insertion path can result in misaligned bends, collisions with the clamping beam, or inconsistent bending angles.

The final aspect of the spatial layout concerns the operator's working area. Because the GoFa is a collaborative robot, no physical barriers are required; however, the layout must ensure that the operator can access the bending machine comfortably while remaining outside the robot's immediate motion path. The AR system reinforces this separation by guiding the operator through the bending sequence only when the robot has completed its positioning task; this temporal coordination prevents interference and maintains a smooth workflow.

Through this multi-layered calibration process, the mini factory becomes a coherent and integrated system; the robot, the vision apparatus, the bending machine, and the operator all operate within a shared spatial logic. This alignment is essential for achieving the precision, repeatability, and efficiency that define the semi-automated fabrication workflow developed in this thesis.

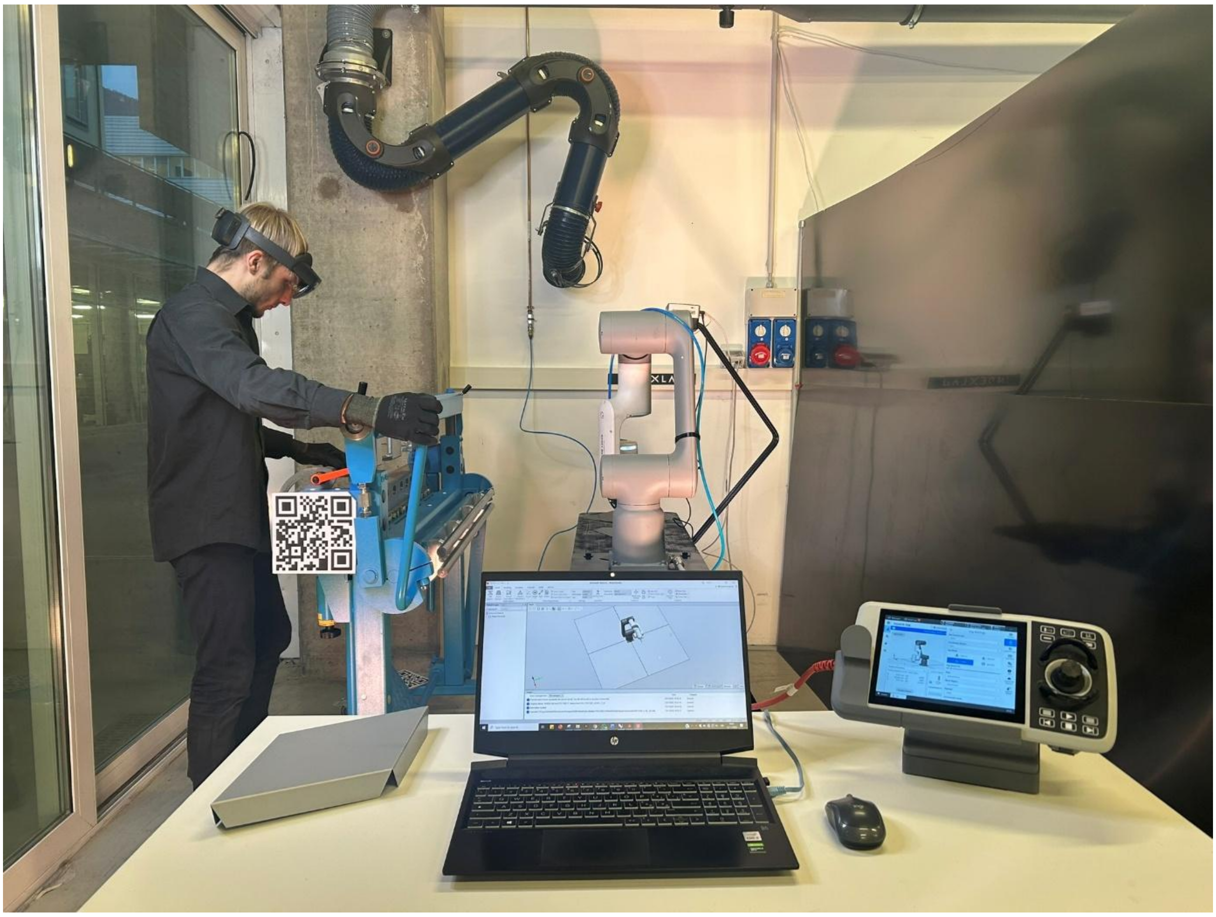


Figure 3.23: Lecco laboratory system set-up with RobotStudio interface

Figure 3.24: Robotic gripping and placing operations

4 Digital Workflow and Computational Framework

4.1. Introduction

The digital workflow developed in this thesis provides the organisational logic that connects geometric design, fabrication data, robotic manipulation, and augmented reality guidance; it acts as the central coordinating layer through which all components of the mini factory communicate. Unlike top-down approaches that begin with a continuous surface and subsequently discretise it, this workflow adopts a bottom-up strategy; the system starts from a set of predefined sheet-metal pieces and builds the final geometry by assembling them into a double-curvature configuration. This approach aligns more directly with the constraints of bending-based fabrication; it ensures that each piece is geometrically feasible, robotically manipulable, and compatible with the manual bending operations performed on the Schechtl UK 100 S.

Grasshopper serves as the central computational environment; it hosts the geometric logic, the fabrication calculations, the robotic programming pipeline, and the communication protocols that control the seventh axis of the end effector. The workflow is modular; each stage operates as an independent block that can be modified without disrupting the entire system. This modularity is essential for a research-driven fabrication process, where the geometry, the robotic logic, and the AR instructions evolve iteratively.

The following sections describe the structure of this workflow; they explain how the pieces are defined, how bending information is extracted, how robotic trajectories are generated, and how external devices such as the Arduino-controlled seventh axis are integrated into the system.

4.2. Bottom Up Geometric Strategy

The geometric logic of the mini factory is based on a bottom-up approach; instead of discretising a continuous surface, the workflow begins with a catalogue of predefined sheet-metal pieces. These pieces include triangles, squares, and rhomboids; although their internal angles vary, they all share the same edge length of 260 mm. This uniformity simplifies fabrication; it ensures that the robot handles pieces of comparable size and that the bending machine receives sheets that fall within a predictable dimensional range. It also reduces the number of suction-cup positions, insertion paths, and bending configurations that must be encoded in the robotic logic.

Each piece is defined parametrically; its geometry is not stored as a static mesh but generated from a set of rules that describe its topology, edge lengths, and internal angles. This allows the system to regenerate the entire catalogue automatically if the design intent changes. The pieces are then assembled into larger configurations; curvature emerges from the angular relationships between adjacent pieces rather than from deformation of the sheet itself. A small deviation from planarity along the longer axis of rhomboids is tolerated, but the workflow ensures that this deviation remains within the bending machine's operational limits.

This strategy is particularly suited to bending-based fabrication; each piece remains planar before bending, and curvature is achieved through assembly rather than forming. It also aligns with the logic of the mini factory; each piece is treated as an independent fabrication unit with its own bending sequence, robotic handling path, and AR-guided operations. The bottom-up method therefore mirrors the physical logic of the system: discrete pieces, discrete operations, and a controlled assembly process that produces continuous curvature through local angular variation.

4.3. Fabrication Data Extraction

Once the pieces are defined, the workflow computes the bending information required to fabricate each element. The bending angle is derived from the geometric relationship between adjacent faces; the system calculates the dihedral angle between the two faces, divides it by two, and then computes the bending angle using the formula:

$$\boldsymbol{Bending\ angle} = 180° - \frac{dihedral\ angle}{2} \qquad (2.1)$$

This ensures that the flap is bent to the correct inclination so that the assembled pieces meet at the intended spatial angle. The workflow also checks whether the resulting angle falls within the mechanical limits of the Schechtl UK 100 S; if not, the piece is flagged as non-fabricable.

After computing the bending angles, the workflow orients each piece on the XY plane; this orientation corresponds to the flat-sheet configuration used for cutting and bending. The system generates a "flattened" representation of each piece, including its flaps, bend lines, and metadata. Each piece is tagged with:

- its ID number
- its bending angles

These fabrication files serve as the bridge between geometric design and physical production; they encode all the information needed to move from digital geometry to material execution.

The workflow also embeds the rotational requirements for the seventh axis; the angle by which the sheet must be rotated between bends is stored alongside the bending data. This ensures that the robot and the seventh axis operate in synchrony during the fabrication sequence.

4.4. Robotic Programming Pipeline

The robotic programming environment is built around Grasshopper and the Robots plug-in; together, they define the relationship between the GoFa robot, the custom end effector, the digital bending machine, and the vision system.

In Robots, the GoFa is selected from the library and the custom end effector is assigned with its calibrated TCP. The workflow then defines the target points for the robot; these include:

- The pick-up position
- The approach vector
- The intermediate waypoints
- The insertion path into the bending machine
- The retreat path after each bend

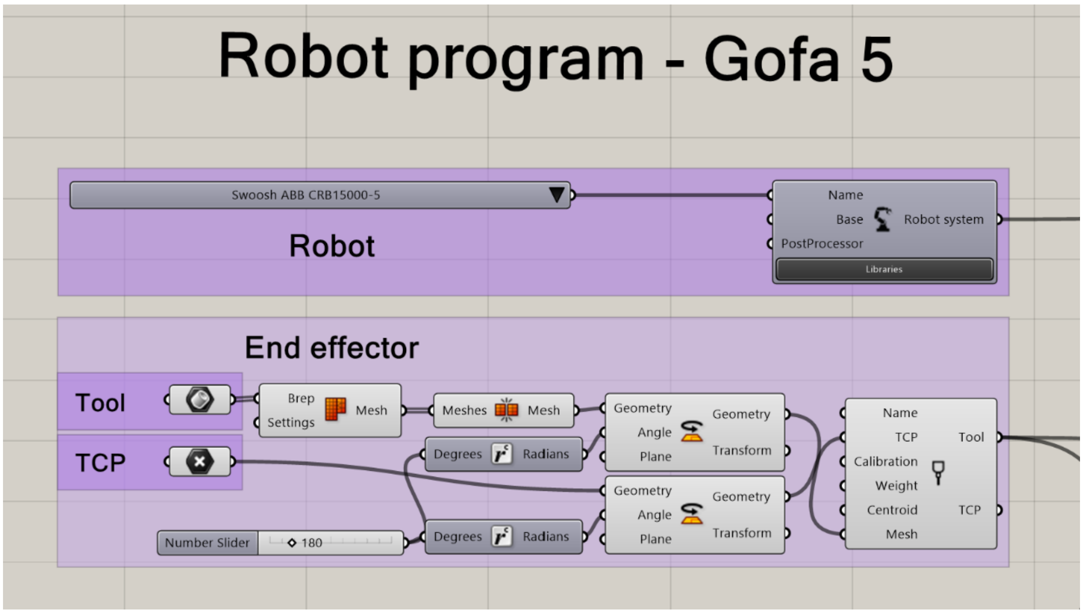


Figure 4.1: Robot selection and TCP definition

Each point is assigned a zone value; small zones enforce precise positioning, while larger zones allow smoother trajectories. The system also defines the robot's speed profile; slower speeds are used near the bending machine, while faster speeds are used during transport.

Digital outputs (DOs) are defined to control the vacuum ejector; wait times are inserted to ensure synchronisation with the bending machine and the operator. The digital bending-machine model is used to generate the trajectories that describe how the aluminium sheet must be positioned; the vision system provides the coordinates of the sheet's centre and orientation.

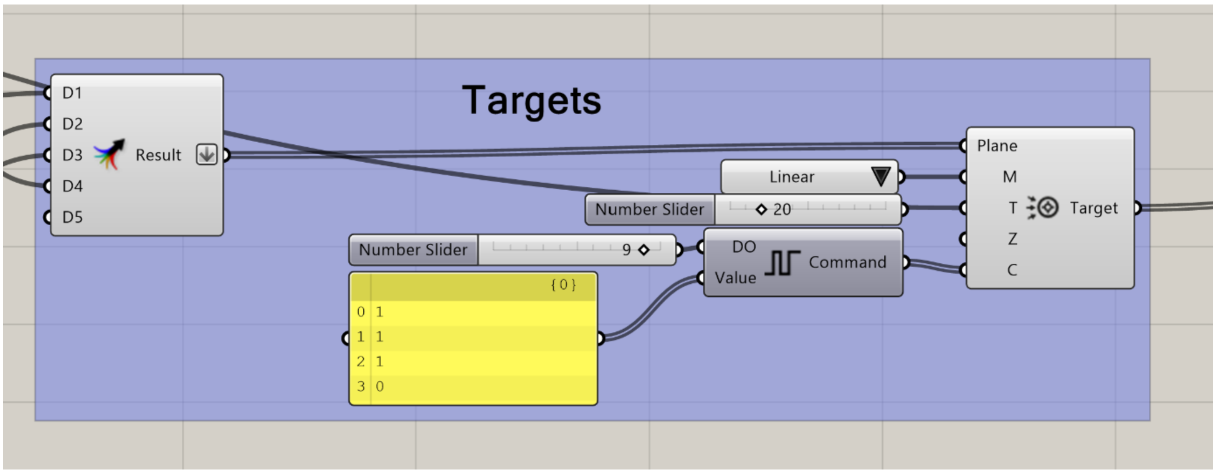


Figure 4.2: Targets and DO definition

Once the sequence is complete, Robots generates the RAPID code; this code is imported into RobotStudio, where it is debugged. RobotStudio allows the correction of DO names, the adjustment of timing, and the verification of reachability; once validated, the code is deployed to the physical robot. This pipeline ensures that the virtual simulation and the physical execution remain aligned throughout the process.

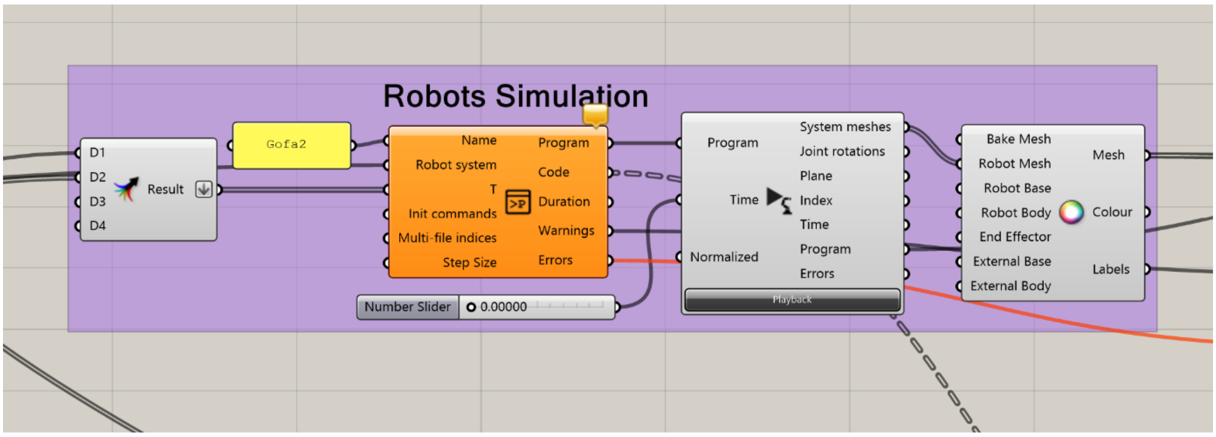


Figure 4.3: Robot simulation within Rhino environment

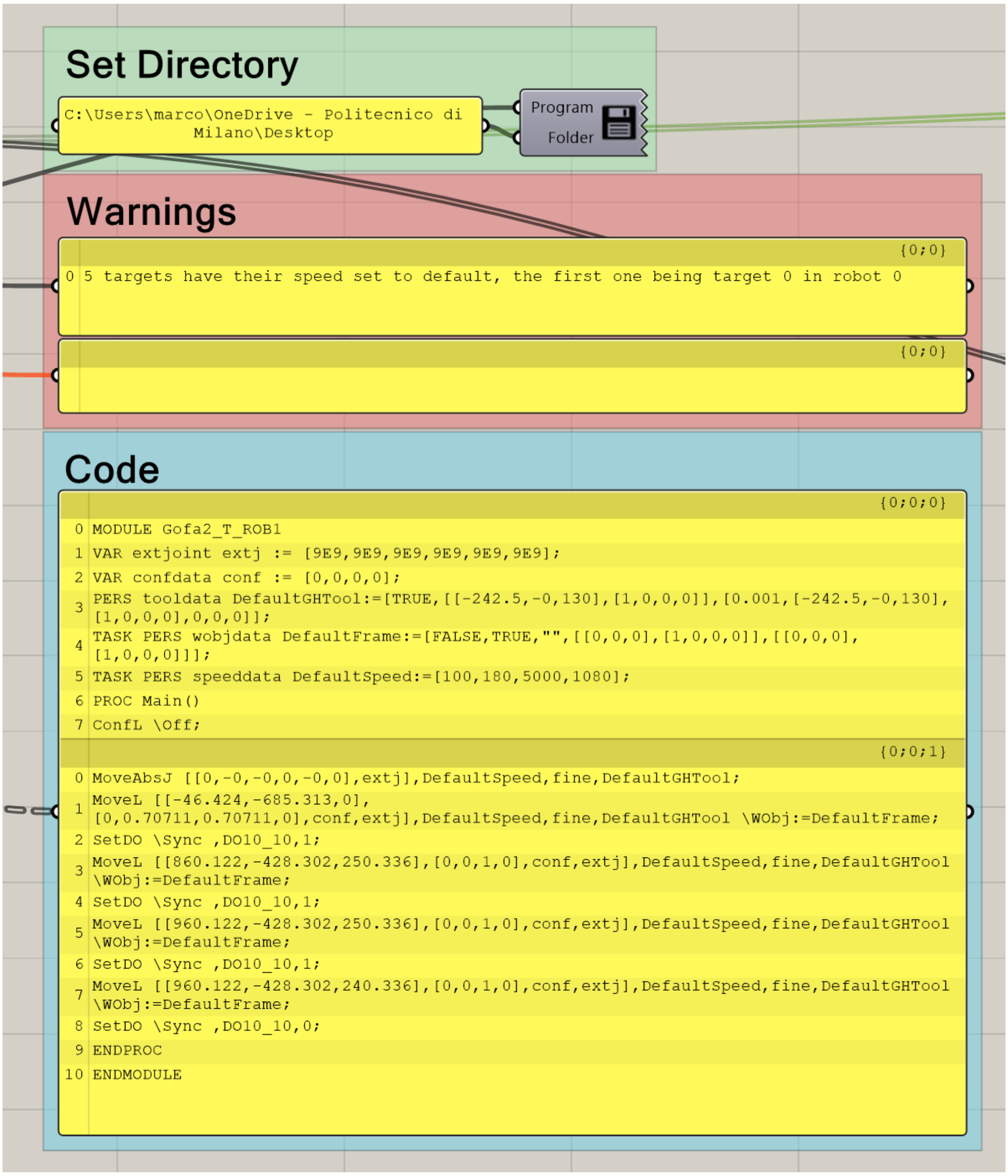


Figure 4.4: RAPID code generated from Grasshopper's Robots plug-in

4.5. Communication with External Devices

The seventh axis of rotation is controlled through a Python component in Grasshopper; the component sends rotation commands to the Arduino via USB-C serial communication. A custom server file manages the communication protocol; it ensures that the Arduino receives clean, correctly formatted signals that drive the NEMA 17 stepper motor.

The communication protocol is intentionally simple; each command consists of:

- A rotation angle
- A direction flag
- A confirmation request

The Arduino interprets these values, computes the corresponding number of microsteps, and actuates the motor. Once the rotation is complete, the Arduino sends a confirmation message back to Grasshopper; this ensures synchronisation between the seventh axis and the robot's motion logic.

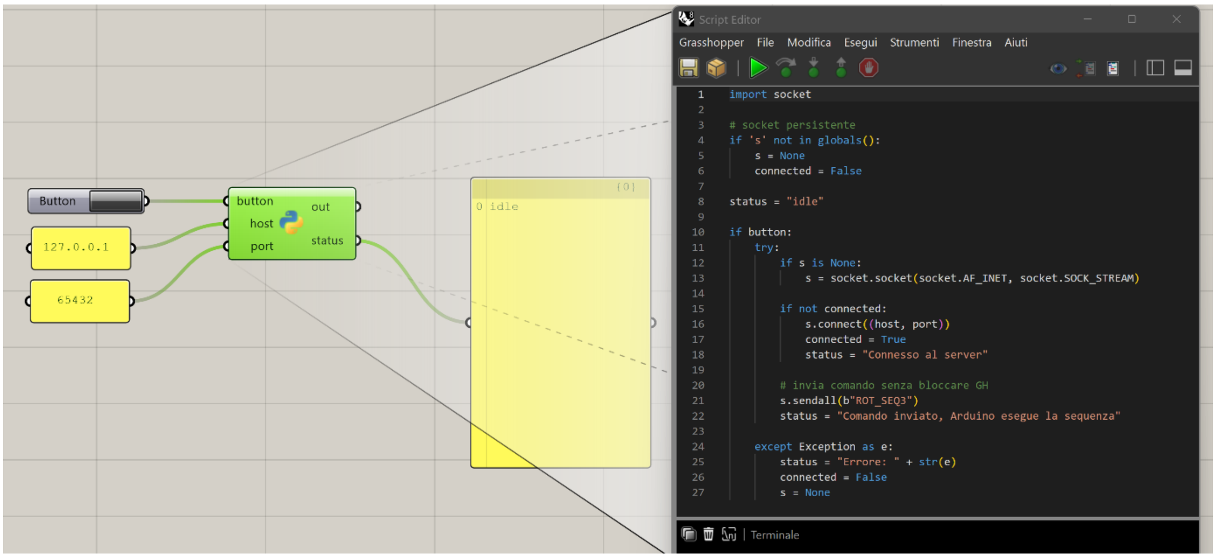


Figure 4.5: Grasshopper component for Arduino comunication

At present, the seventh axis is not controlled directly by the robot; however, a future development foresees integrating it into the GoFa's I/O architecture. Since the robot's digital outputs operate at 24 V and the Arduino logic operates at 5 V, a relay or optocoupler will be required to bridge the two systems. This upgrade would allow the robot to trigger rotation commands autonomously, reducing latency and simplifying the communication chain.

The communication architecture therefore reflects the hybrid nature of the mini factory; it combines real-time robotic control with external microcontroller-based actuation, all coordinated through the Grasshopper environment.

4.6. Augmented Reality Integration

The augmented reality system developed for this project represents an initial but functional step toward integrating digital fabrication logic with manual bending operations. Although the current implementation operates as a demonstrator rather than a fully automated production tool, it already provides a clear indication of how AR can support and enhance the bending workflow within the mini factory.

At this stage, the AR system is capable of displaying digital overlays of randomly selected sheet-metal pieces; these overlays are aligned with the physical bending machine and allow the operator to visualise the intended bending sequence directly within the working environment. The system uses a wireframe representation of the bending machine and the sheet; this wireframe is anchored spatially so that it coincides with the real machine when viewed through the AR visor. This alignment enables the operator to perceive both the physical and digital geometries simultaneously; it also provides a stable reference frame for interpreting the bending instructions.

The current AR demonstrator is not yet connected to the production files generated in the digital workflow; instead, it uses a set of predefined or randomly selected pieces to test the visualisation pipeline. Despite this limitation, the system already demonstrates the core principles that will underpin the full integration. The operator can follow a sequence of bending steps displayed in the visor; the digital bending leaf is shown in the correct position for each step, and the operator lifts the physical bending leaf until it coincides with the virtual one. This ensures that the bending angle corresponds to the intended design without requiring the operator to monitor mechanical angle indicators or rely on visual estimation.

The AR system therefore acts as a cognitive support tool; it reduces the mental effort required to interpret drawings, calculate angles, or remember sequences. Even in its current prototype form, it shows how AR can guide the operator through complex bending operations, especially when dealing with pieces that differ from one another despite sharing the same initial geometry. The system also demonstrates how AR can help maintain consistency across multiple operators; by providing a standardised visual reference, it reduces variability and improves repeatability.

Future development will focus on connecting the AR system directly to the fabrication files generated in Grasshopper; this will allow the bending sequences, angles, and piece identifiers to be transmitted automatically to the AR environment. Once this integration is complete, the AR system will become a fully operational component of the mini factory; it will provide real-time, piece-specific guidance that aligns perfectly with the robotic handling and the digital workflow described in this chapter.

5 Physical models fabrication

5.1. Introduction

This chapter presents a series of application case studies that document the progressive development of the mini factory through physical mock-ups. Each mock-up served as a testbed for different aspects of the system: geometric feasibility, bending constraints, assembly logic, digital workflow accuracy, and the integration of robotic and augmented reality tools. The sequence of prototypes reflects an iterative research process in which insights from one stage informed the next, gradually refining both the physical and digital components of the workflow.

The mock-ups also played a crucial role in validating the bottom-up fabrication strategy. By moving from paper to aluminium, from manual assembly to digitally informed bending, and finally to robotic handling and AR guidance, the prototypes allowed the research to evolve in a controlled and evidence-based manner. Each physical model exposed limitations, revealed opportunities, and clarified the operational boundaries of the system. Together, they form a coherent narrative of how the mini factory matured from a conceptual framework into a functional fabrication environment.

5.2. Preliminary Paper Mock-Up

The first mock-up was intentionally simple: a paper model used to explore the geometric logic of the bottom-up approach. Paper offered a fast and inexpensive medium for testing how triangular, square, and rhomboid pieces could be combined to generate double curvature. Although the material properties differ significantly from aluminium, the paper mock-up allowed early evaluation of adjacency relationships, flap configurations, and the emergence of curvature through assembly rather than deformation.

Working with paper made it possible to rapidly test multiple configurations, adjust internal angles, and observe how curvature accumulated across the surface. The mock-up also revealed how the orientation of flaps influenced the assembly sequence and how small variations in angle could significantly affect the global geometry. These insights were essential for defining the catalogue of pieces and for understanding how local geometric decisions propagate through the surface.

This preliminary exercise validated the conceptual foundation of the system. It demonstrated that a surface composed of planar pieces with identical edge lengths could approximate double curvature through controlled variation of internal angles.

It also revealed early constraints related to assembly order and the spatial behaviour of flaps, which informed the subsequent physical prototypes.

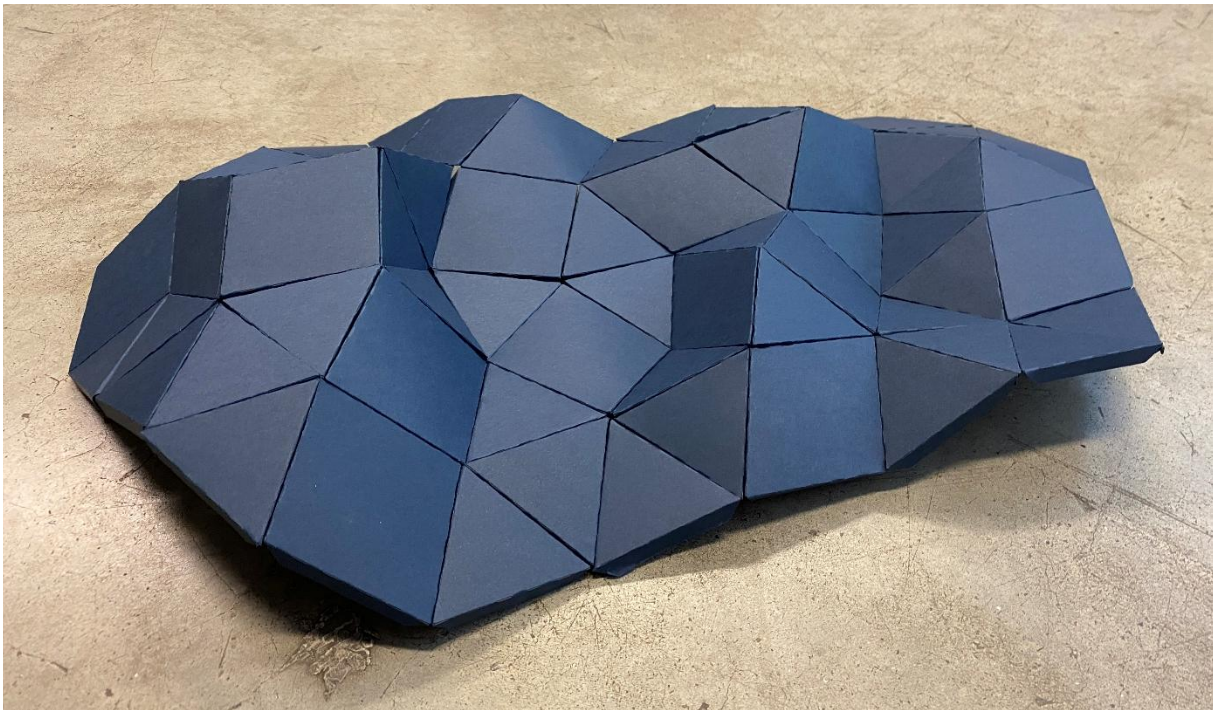


Figure 5.1: Paper mock-up view

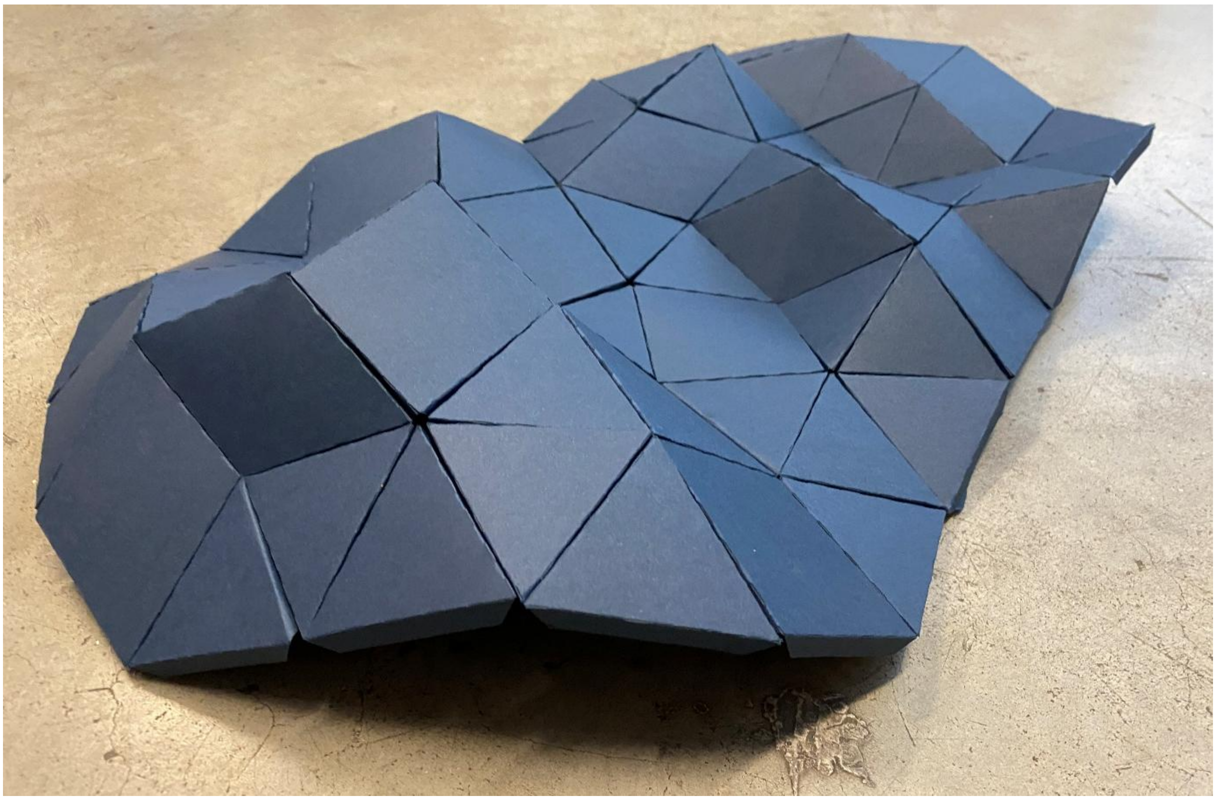


Figure 5.2: Paper mock-up view

5.3. Assembly Process

Before moving to the larger aluminium prototypes, it is necessary to clarify the assembly logic that governs the transition from the flat-pattern geometry to the final three-dimensional surface. This process follows a sequence of operations that reflects both the material constraints of aluminium sheet and the practical requirements of manual fabrication. The assembly workflow can be summarised in four main phases: cutting, bending, joining, and fastening.

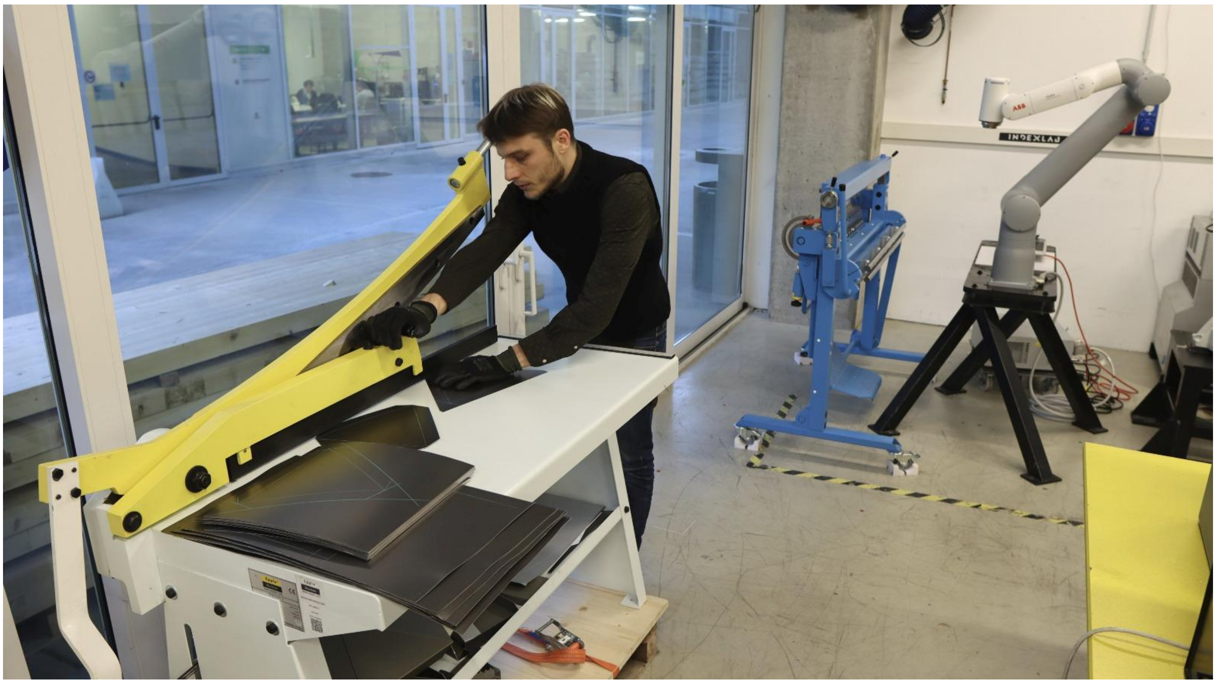


Figure 5.3: Aluminium pieces preparation and cutting from sheets.

Figure 5.4: Linear cutter use

5.3.1. Cutting

The first phase consists of cutting the individual pieces from the flat sheet. This operation is performed using a linear cutter, which ensures straight, clean edges and consistent dimensional accuracy across all components. The cutting stage establishes the geometric boundaries of each piece and prepares the flaps that will later be bent and joined. Because all pieces share the same edge length, the cutting process is highly repeatable and can be performed with minimal setup time.

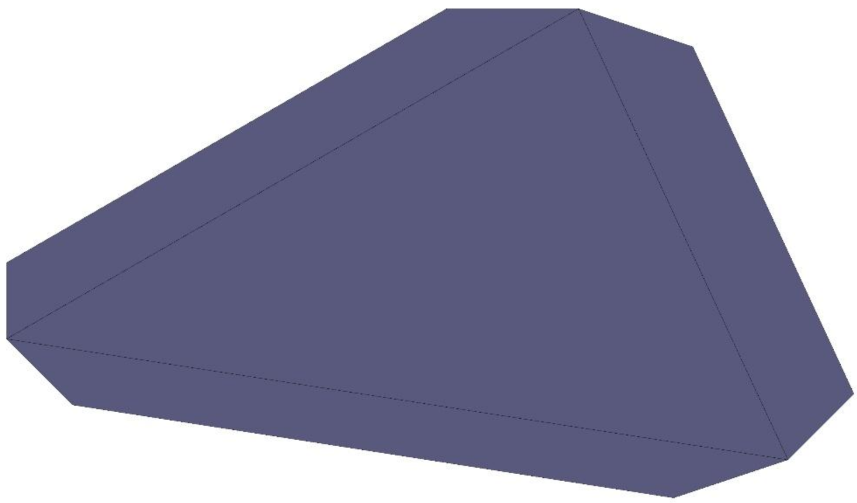


Figure 5.5: Phase 1 – cutting

5.3.2. Bending

Once the pieces are cut, the second phase involves bending the flaps along the predefined fold lines. These flaps serve both as structural stiffeners and as connection interfaces between adjacent pieces. The bending is carried out on the Schechtl UK 100 S, following the sequence derived from the digital workflow. The accuracy of this step is essential, as the bending angles directly influence the overall curvature and continuity of the assembled surface. Even small deviations can accumulate across the surface, making precise bending a critical requirement.

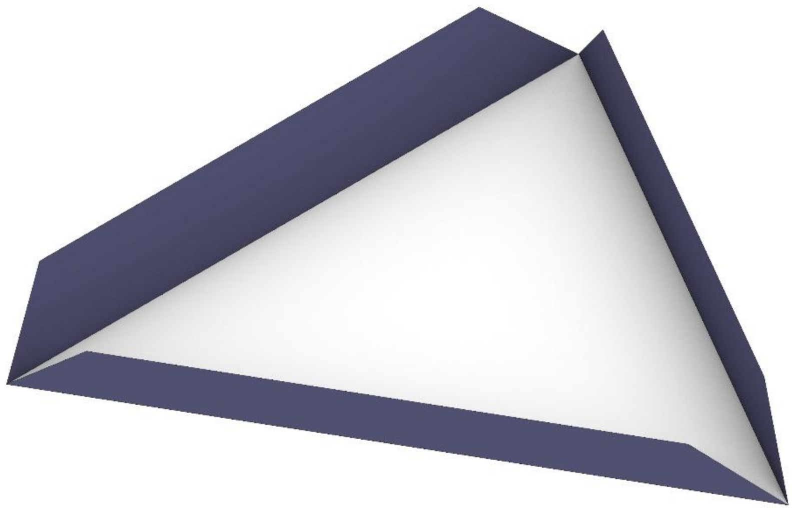


Figure 5.6: Phase 2 – bending flaps

5.3.3. Joining

The third phase focuses on joining two adjacent pieces. After bending, the flaps of neighbouring components are aligned and brought into contact, forming the local geometry of the surface. This step is guided by the assembly diagram, which clarifies the order in which pieces must be connected and the orientation required to maintain geometric coherence. The assembly logic ensures that the curvature is progressively built up through the accumulation of small, controlled connections. During this phase, the behaviour of the flaps—whether they overlap, interlock, or align edge-to-edge—becomes a key factor in achieving a smooth surface.

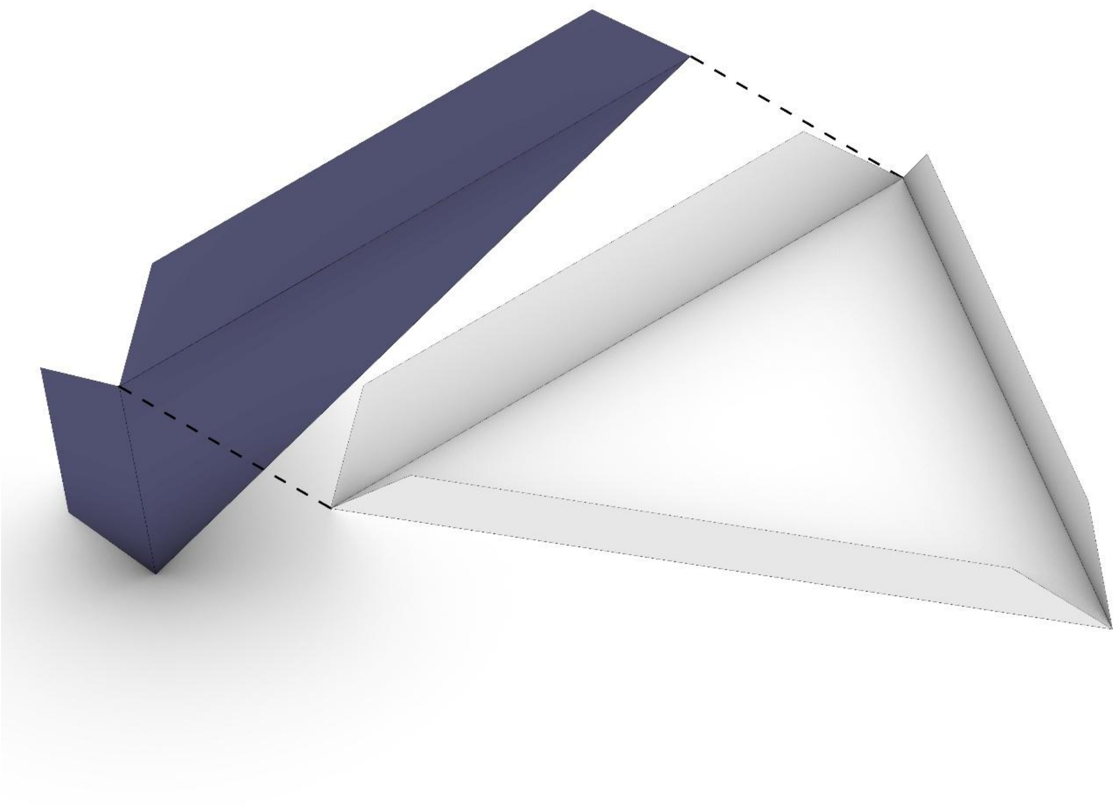


Figure 5.7: Phase 3 – joining pieces

5.3.4. Fastening

The final phase consists of fastening the pieces together. Holes are punched through the overlapping flaps, and the components are secured using aluminium rivets. Riveting provides a lightweight, mechanically reliable connection that is compatible with the thin-sheet nature of the material. This fastening method also allows for a degree of tolerance absorption, accommodating minor deviations that may arise during bending or alignment. Rivets also provide a consistent spacing pattern that contributes to the structural stability of the assembled surface.

Together, these four phases define a clear and repeatable assembly workflow that bridges the digital logic of the flat-pattern geometry with the physical reality of the fabricated surface. The diagram accompanying this section illustrates the sequence and interdependencies of the operations, providing a visual reference for understanding how the surface is constructed piece by piece.

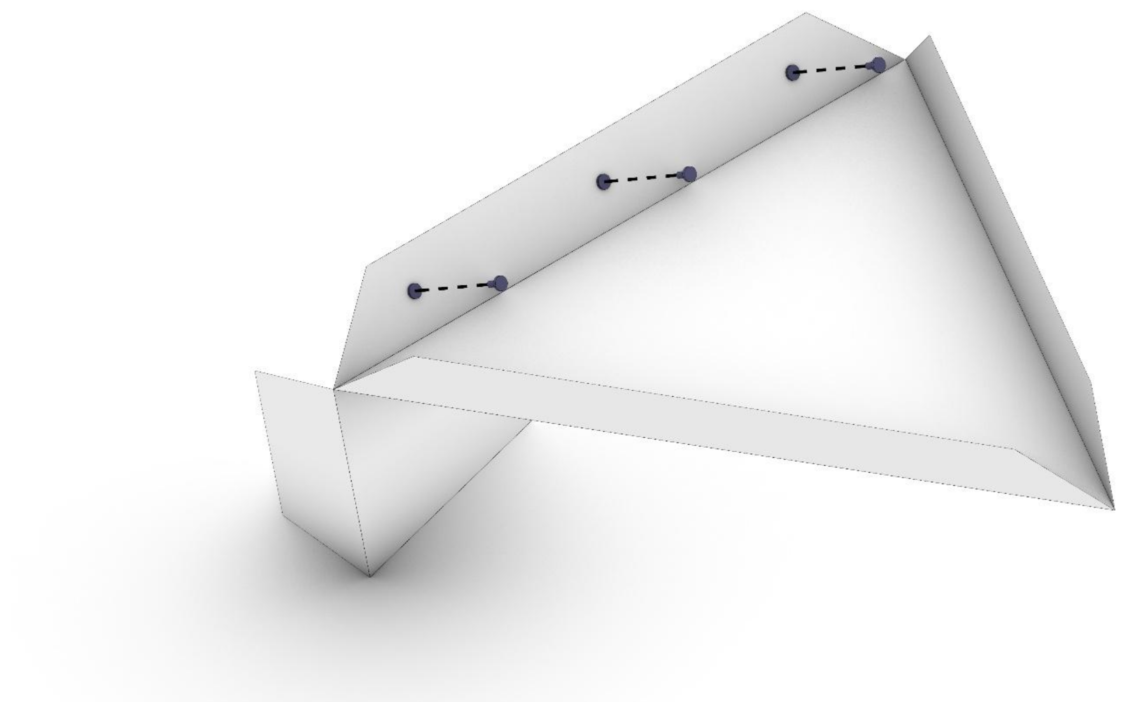


Figure 5.8: Phase 4 - fastening

5.4. Bottom-Up Surface Mock-Up Process

The second mock-up scaled up the bottom-up strategy to a larger physical surface. This prototype aimed to test the feasibility of bending and assembling a significant number of pieces, each with different internal angles but identical edge lengths. The focus was on understanding the practical limits of manual bending and assembly when working with aluminium sheets.

Several key aspects were evaluated:

- Bending feasibility: which pieces could be comfortably bent on the Schechtl UK 100 S according to the interchangeable physical blocks that compose the bending machine.
- Assembly tolerances: how rivet spacing, flap width, and bending precision affected the alignment of adjacent pieces.
- Achievable angles: the maximum and minimum angles between pieces that could be reliably produced.
- Rhomboid deviation: how far rhomboids could deviate from coplanarity while still assembling into a coherent double-curvature surface.

This mock-up revealed the geometric and ergonomic constraints of the system. It provided a realistic understanding of how curvature emerges from the assembly of planar pieces and highlighted the importance of precise bending angles for maintaining consistent gaps and surface continuity. It also clarified the limits of manual fabrication, showing which operations were robust and which required digital or robotic support.

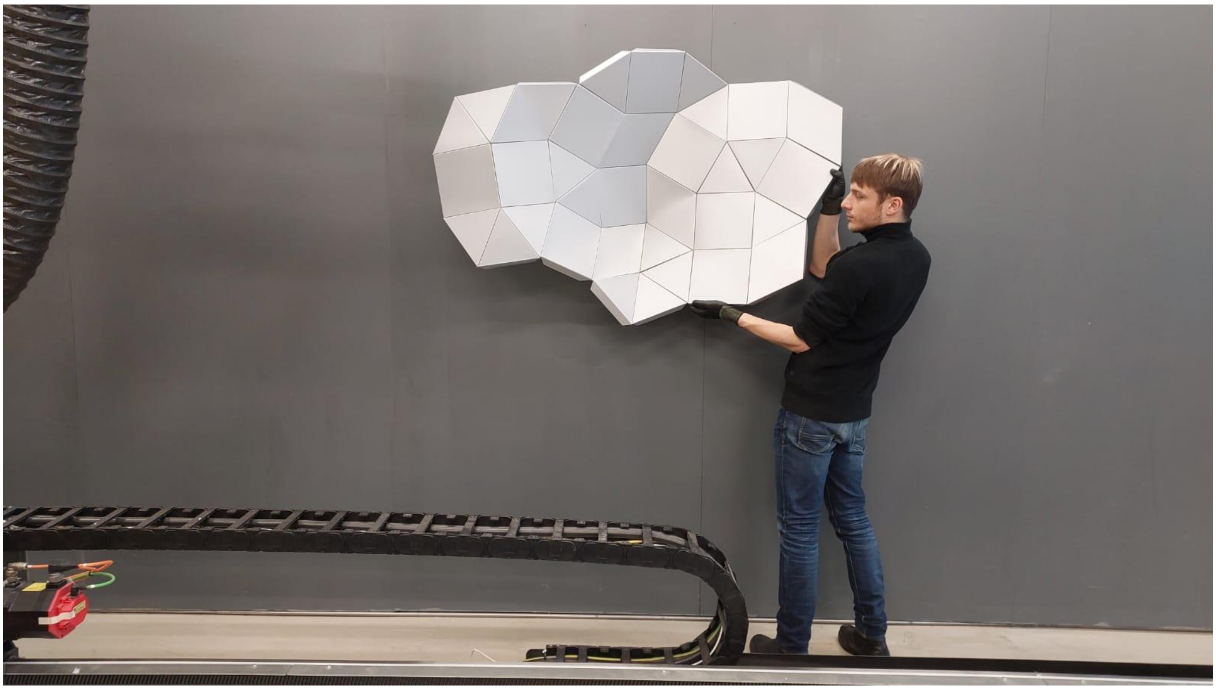


Figure 5.9: Bottom-up process mock-up in Lecco laboratory

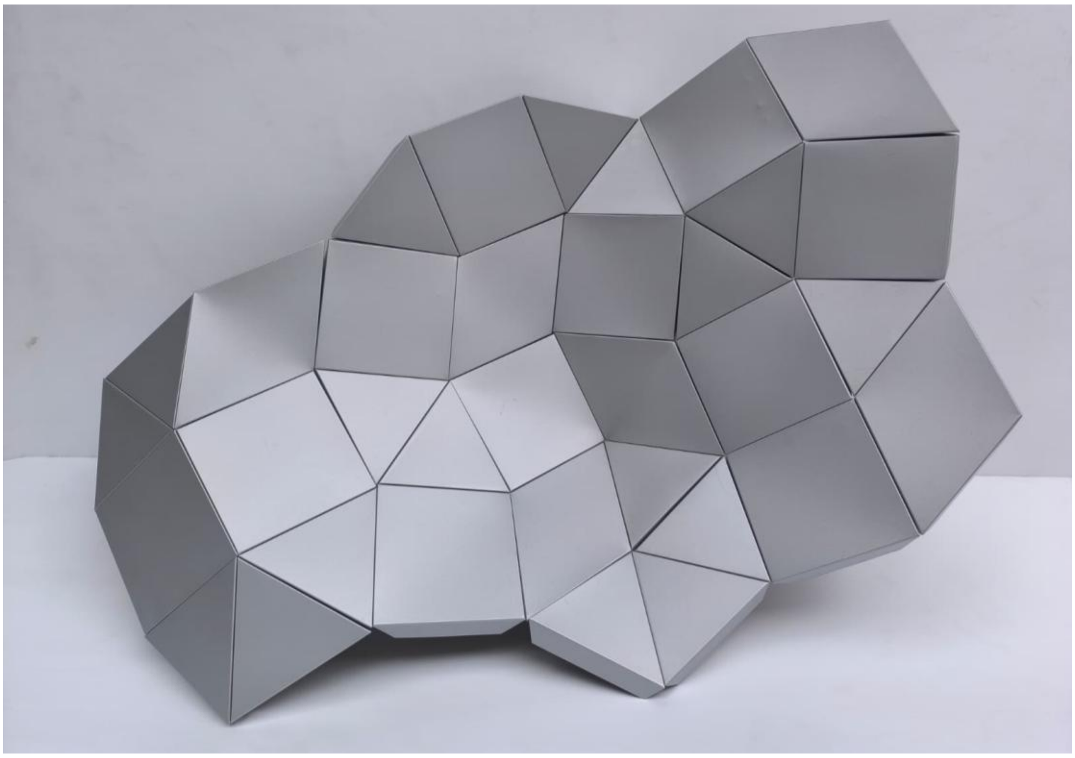


Figure 5.10: Bottom-up process mock-up

Figure 5.11: Bottom-up process mock-up close-up view

5.5. Digital Twin Driven Mock-Up

The third mock-up shifted the focus from geometric feasibility to digital precision. Starting from a digital twin of the mock-up, the goal was to test the production files generated by the digital workflow described in Chapter 4. This included the computation of bending angles, the orientation of pieces on the XY plane, and the tagging of flaps.

The results were significantly more precise than in the previous prototype. Because the bending angles were derived directly from the digital model, the flaps aligned more consistently, and the gaps between pieces were more uniform. This mock-up validated the bending-angle computation method and demonstrated the benefits of integrating geometric logic with fabrication data.

It also provided a controlled environment for testing the early stages of robotic handling, as the pieces were dimensionally consistent and predictable. The mock-up confirmed that the digital workflow could reliably generate fabrication-ready data and that the transition from digital geometry to physical bending was accurate enough to support assembly without corrective adjustments.

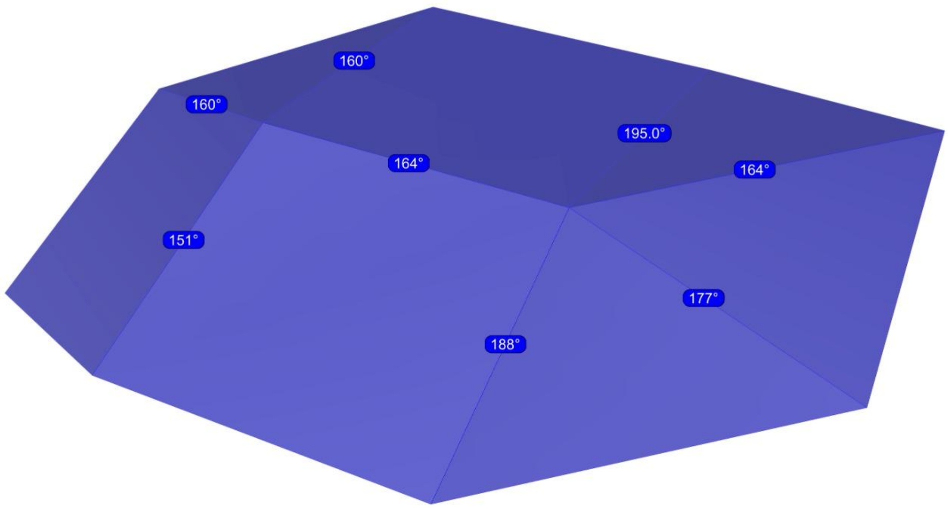


Figure 5.12: Digital twin

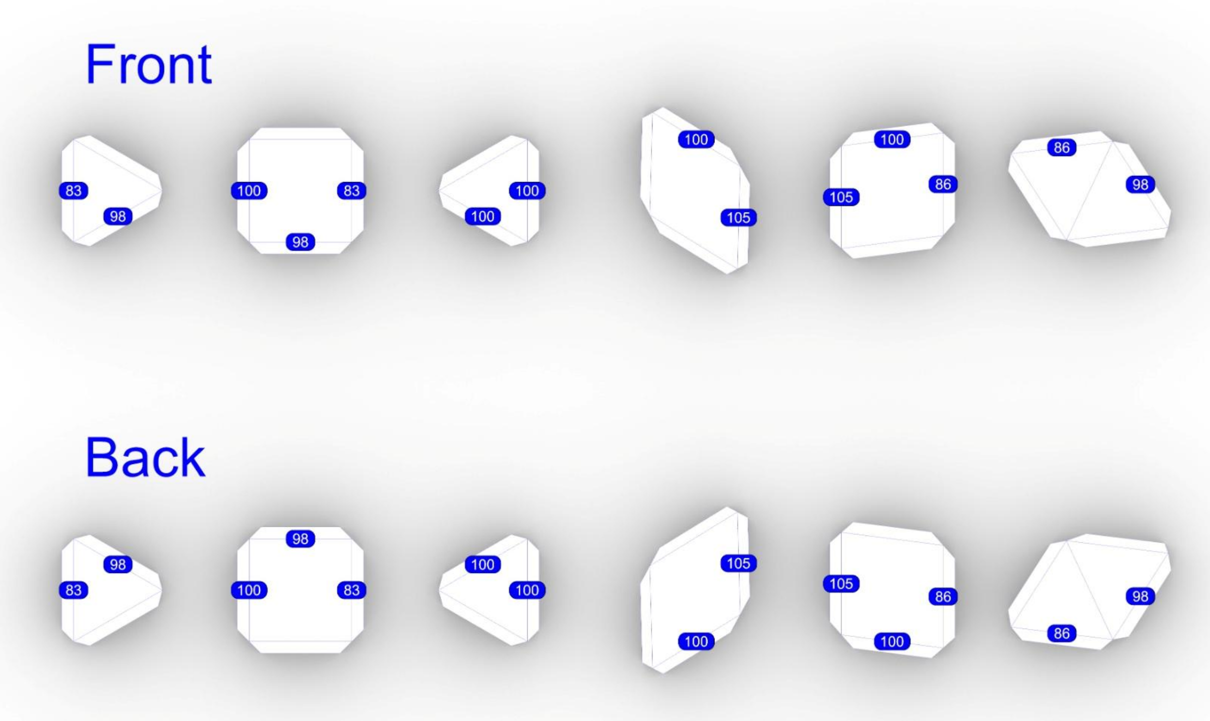


Figure 5.13: Production files

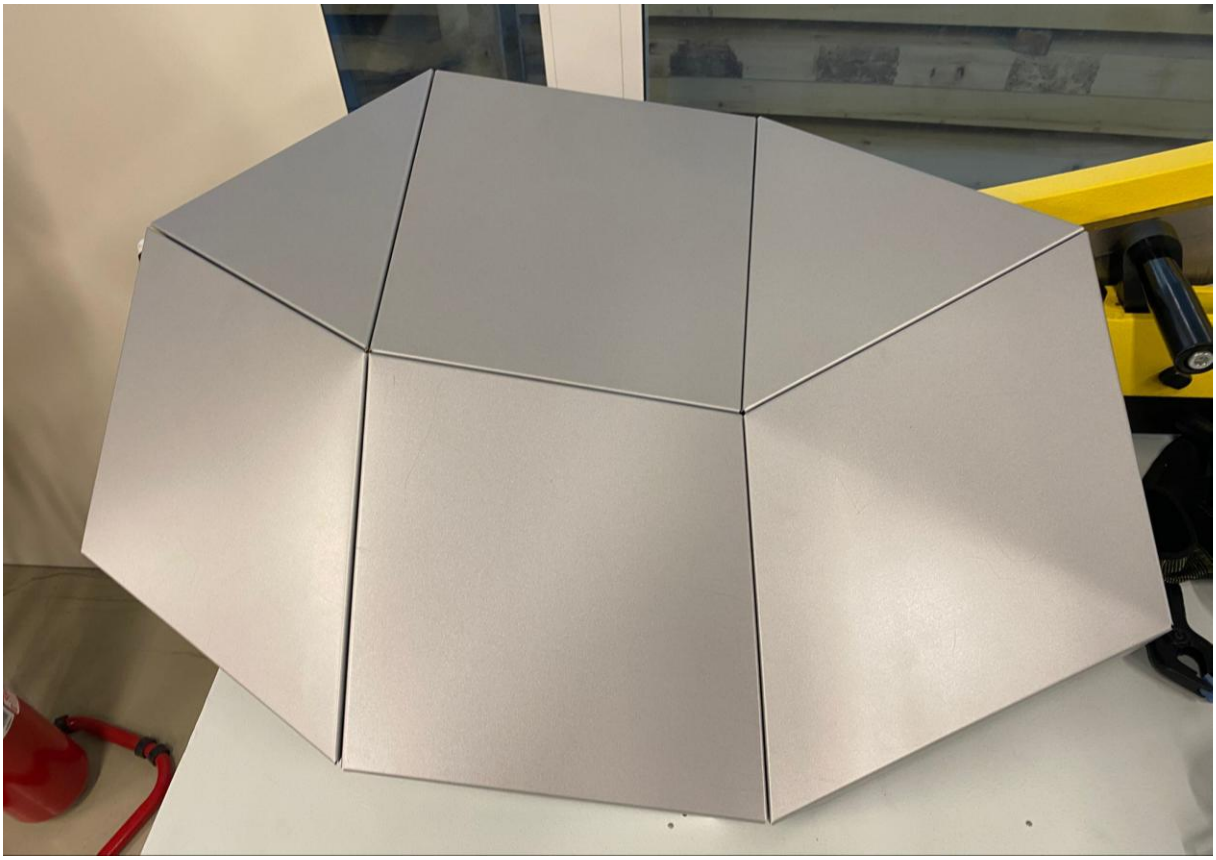


Figure 5.14: Digital twin driven mock-up

5.6. Alpewa Headquarters Mock-Up

The fourth mock-up applied the system to a real architectural context: a larger surface designed for the Alpewa headquarters. This prototype combined the strengths of the previous two approaches. It used the bottom-up geometric logic to define the overall surface while relying on digital-twin-based production files to compute bending angles and flap orientations.

This hybrid strategy allowed the fabrication of a larger, more complex surface while maintaining the precision achieved in the smaller digital-twin mock-up. The prototype demonstrated the scalability of the system and its potential for architectural applications. It also provided valuable insights into assembly logistics, bending sequences, and the handling of larger pieces within the mini factory.

The Alpewa mock-up served as a bridge between research-scale prototypes and real-world fabrication scenarios, showing that the system could be adapted to architectural dimensions without losing accuracy or workflow coherence.

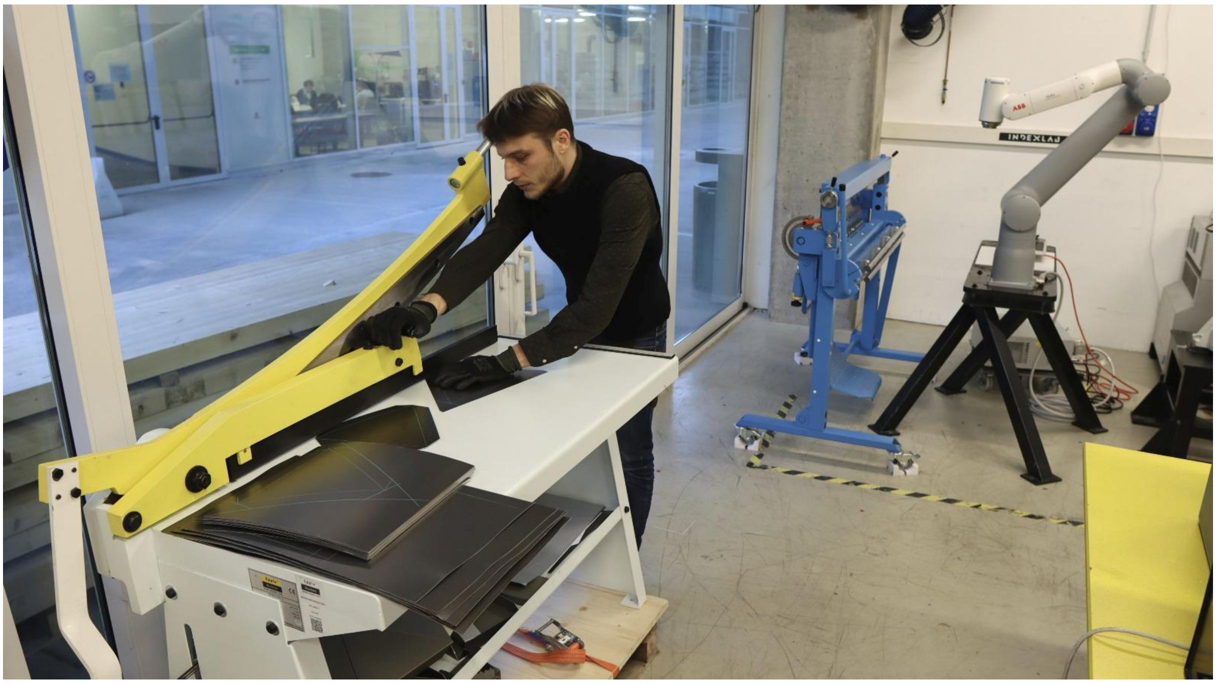


Figure 5.15: Alpewa mock-up pieces preparation

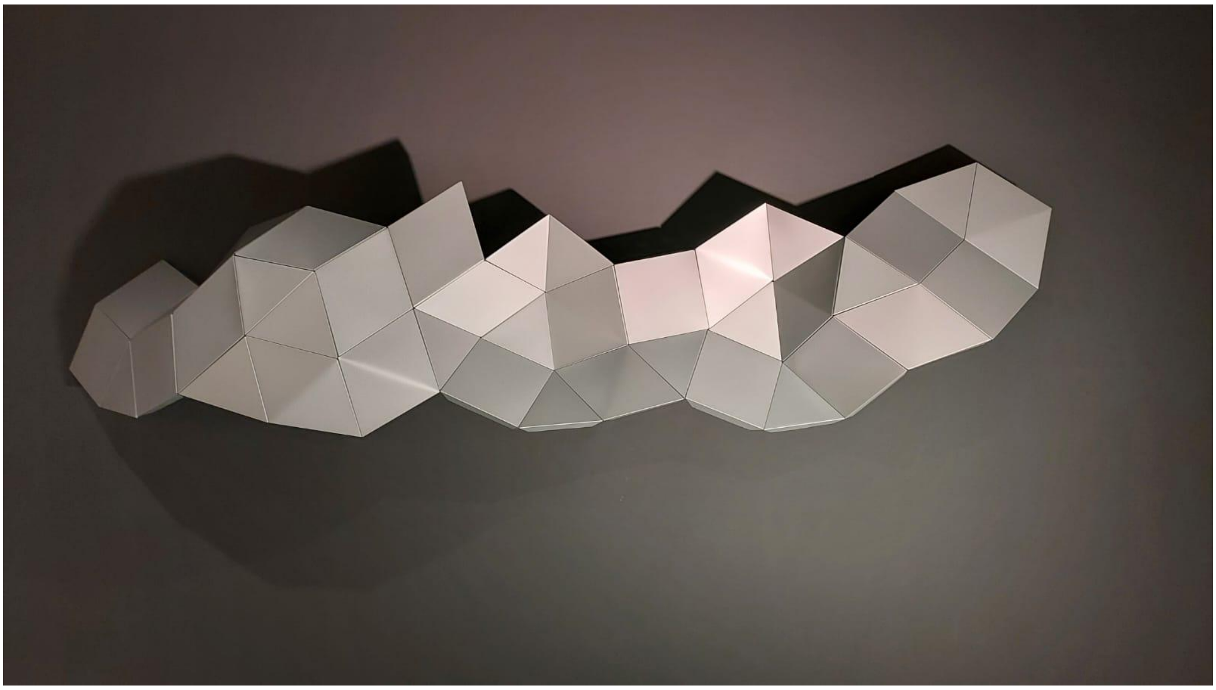


Figure 5.16: Alpewa mock-up

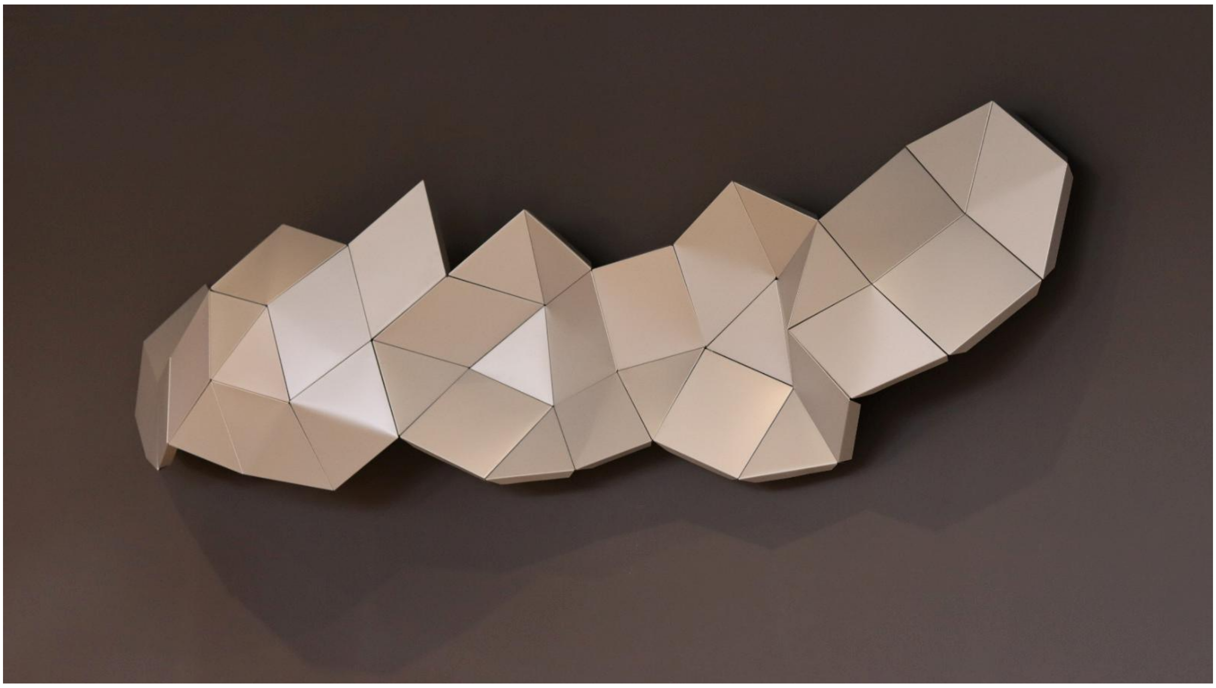


Figure 5.17: Digital and physical bending machines overlapping

5.7. Public Demonstration at CaseItaly 2026

The system was publicly presented at CaseItaly 2026, where both the robotic workflow and the augmented reality demonstrator were showcased. The robot performed a continuous loop that included the rotation of the seventh axis, illustrating the handling and orientation logic developed throughout the project. The AR system displayed bending sequences and wireframe overlays, allowing visitors to experience the manual guidance component of the workflow.

The demonstration attracted significant attention, including visits from Maria Schechtl, representing the manufacturer of the bending machine, and an ABB employee, who evaluated the robotic integration. Their interest provided external validation of the system's potential and highlighted its relevance to both industrial partners.

The public demonstration also served as a stress test for the workflow, confirming that the system could operate reliably in a non-laboratory environment and communicate its logic clearly to an external audience.

Figure 5.18: CaseItaly 2026 end effector setting-up

Figure 5.19: AR demonstration at CaseItaly 2026

Figure 5.20: MetaBend presentation at CaseItaly 2026

5.8. Discussion

The sequence of mock-ups illustrates the evolution of the mini factory from conceptual exploration to architectural application. Each prototype contributed specific insights:

- The paper mock-up validated the geometric logic.
- The large bottom-up mock-up revealed fabrication constraints and assembly tolerances.
- The digital-twin mock-up demonstrated the precision achievable through computational workflows.
- The Alpewa mock-up proved the scalability and architectural relevance of the system.
- The CaseItaly demonstration confirmed the system's potential for public engagement and industrial interest.

Together, these case studies show how iterative prototyping can bridge the gap between digital design, robotic fabrication, and manual craftsmanship. They also highlight the remaining challenges, such as full integration of AR with production files and direct robot control of the seventh axis, which will be addressed in future developments.

6 Conclusions and Future Developments

6.1. Achievements

This thesis presented the development of a semi-automated mini factory for sheet-metal fabrication; it integrated collaborative robotics, custom hardware, computer vision, and augmented reality into a unified workflow. The project demonstrated how digital design logic can be translated into physical operations through a hybrid system that combines robotic precision with human-guided bending; it also showed how curvature can emerge through elastic relaxation rather than through material deformation. This principle became a defining achievement of the research; it confirmed that double curvature can be produced by assembling planar pieces whose internal angles have been carefully calibrated, allowing the material to settle naturally into the intended geometry.

A major achievement was the design and implementation of a compact robotic cell centred on the ABB GoFa 5; the robot was equipped with a custom end effector and a seventh axis of rotation that enabled continuous orientation of the sheet during bending. This configuration allowed the robot to handle sheet-metal pieces, orient them for insertion into the bending machine, and collaborate safely with the operator; the seventh axis eliminated the need for repeated regripping cycles and significantly improved workflow continuity. The integration of a vacuum-based gripping system and a vision-assisted pick-and-place strategy further enhanced the reliability of the process; these components ensured that each sheet was detected, lifted, and positioned with consistent accuracy.

On the digital side, the project established a complete pipeline from geometric definition to fabrication; the bottom-up strategy for generating double-curvature surfaces was translated into fabrication data, bending angles, and robot programs through a modular Grasshopper workflow. This workflow coordinated the geometric logic, the bending sequences, the robotic trajectories, and the metadata required for assembly; communication between Grasshopper, Python, Arduino, and the robot controller enabled synchronised control of the seventh axis and the robotic movements. The augmented reality demonstrator provided an additional layer of cognitive support; it showed how digital bending instructions can be visualised directly in the physical workspace and how AR can serve as an early form of AI-mediated guidance for manual operations.

The system was validated through a sequence of mock-ups; these ranged from a preliminary paper model to larger aluminium prototypes. Each mock-up confirmed a different aspect of the workflow; the geometric logic, the precision of the digital pipeline, the feasibility of the bending sequences, and the scalability of the approach. The public demonstration at CaseItaly 2026 provided external validation; it attracted interest from industrial partners and highlighted the relevance of the system within contemporary manufacturing contexts.

6.2. Limitations

Despite the achievements, several limitations remain; these limitations define the boundaries of the current prototype and indicate the directions for future development.

The augmented reality system functions as a demonstrator and is not yet connected to the production files generated in the digital workflow; bending sequences and angles must therefore be manually selected rather than automatically transmitted to the visor. This prevents the AR system from acting as a fully integrated cognitive assistant; it also limits its ability to adapt instructions dynamically based on the piece being fabricated.

The seventh axis is controlled through an external Arduino rather than directly through the robot’s digital outputs; while functional, this introduces additional hardware, increases latency, and complicates the integration. A tighter coupling between the robot controller and the rotation mechanism would streamline the workflow; it would also enable more advanced synchronisation between robot movements and manual bending operations.

The vision system, although effective for detecting the position of sheet-metal pieces, remains sensitive to lighting conditions and requires manual calibration; this reduces robustness and limits applicability in industrial environments where conditions are less controlled. A more advanced detection strategy would be required for deployment at scale.

Finally, the system has been tested on relatively small surfaces and under controlled conditions; scaling to larger assemblies, different materials, or more complex geometries will require further refinement of both the physical and digital components. In particular, the behaviour of elastic relaxation at larger scales must be studied more deeply; while small assemblies naturally settle into the intended curvature, larger surfaces may require additional constraints or predictive simulation to ensure geometric fidelity.

6.3. Potential Expansion and Industrial Scalability

The mini factory developed in this thesis establishes a robust foundation for future research in hybrid robotic–manual fabrication and demonstrates how a compact, modular workflow can support the production of geometrically complex sheet-metal components. Several avenues for expansion emerge directly from the current prototype.

A fully integrated AR system connected to the fabrication files would enable real-time, piece-specific guidance during bending, reducing cognitive load and improving consistency across operators. Such a system could evolve into a more autonomous guidance layer capable of verifying bending angles, checking sequence order, and providing corrective feedback based on the geometry being handled.

On the hardware side, direct control of the seventh axis through the robot's digital outputs would eliminate the need for external microcontrollers, simplifying the architecture and reducing latency. This tighter integration would allow more precise synchronisation between robotic movements and manual bending operations, supporting a smoother and more predictable workflow.

The fabrication pipeline itself could be strengthened through the introduction of CNC laser cutting. Laser-cut blanks would ensure higher dimensional accuracy, cleaner edges, and more reliable bending behaviour, particularly for pieces with tight tolerances or complex geometries. Laser cutting would also make it possible to engrave coded identifiers—such as QR-like patterns or fiducial markers—directly onto the aluminium sheets. These markings would significantly improve the robustness of the vision system, enabling automatic recognition of each piece, its orientation, and its bending sequence.

Further improvements to the vision apparatus could enhance reliability and reduce operator intervention. Structured-light scanning, fiducial-marker tracking, or machine-learning-based detection could support automatic verification of flap orientation, bending angles, and geometric deviations before they propagate through the assembly.

From an industrial perspective, the system can be scaled to handle larger surfaces, different alloys, or multi-robot configurations. The bottom-up geometric logic and modular digital workflow make it adaptable to a wide range of architectural and manufacturing contexts. At larger scales, the principle of elastic relaxation becomes even more powerful, allowing curvature to emerge naturally from the assembly of many small, precisely bent components. The interest shown by industry representatives at CaseItaly 2026 indicates that this approach has potential for real-world adoption, particularly in environments where flexibility, precision, and customisation are essential.

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A Appendix A— Full Code Listings

A.1. Arduino Code.

The following listing contains the Arduino program developed to control the seventh rotational axis integrated into the robot's custom end effector. This additional degree of freedom, driven by a NEMA 17 stepper motor and a dedicated driver, enables the suction unit to rotate around its longitudinal axis; this capability is essential for reorienting aluminium sheets between bending operations without requiring complex regripping manoeuvres from the robot.

The code has been designed to ensure stable, repeatable, and synchronised actuation within the broader digital workflow described in Chapter 4. Communication with Grasshopper occurs via USB serial; upon receiving a specific command string, the Arduino triggers a continuous rotation sequence. The program manages several key functions:

- Configuration of the stepper driver control pins;
- Computation of the required number of microsteps based on pulley ratios and target rotation angles;
- A pre-excitation routine to reduce backlash and improve initial torque;
- A simple acceleration profile to ensure smooth motion;
- Timing logic that synchronises the rotational cycle with the robot's handling and the bending machine's operation.

To maintain long-term angular accuracy, the code incorporates a remainder-tracking mechanism that compensates for fractional steps accumulated over multiple rotations. The waiting intervals between rotations are calibrated to match the operational rhythm of the mini factory, ensuring that the seventh axis completes its movement before the robot proceeds to the next stage.

The version presented here corresponds to the implementation used during experimental testing and the public demonstration at CaseItaly 2026. It provides a reliable foundation for future enhancements, including direct integration with the robot's I/O system and the potential introduction of real-time angular feedback.

```
// --------------------------
// Pins
// --------------------------
const int STEP_PIN = 2;
const int DIR_PIN  = 3;
const int ENA_PIN  = -1;

// --------------------------
// Pulley ratio
// --------------------------
const float TARGET_BIG_DEG = 120.0;
const float MOTOR_PER_BIG  = 76.0 / 44.0;
const float TARGET_MOTOR_DEG = TARGET_BIG_DEG * MOTOR_PER_BIG;

// --------------------------
// Stepper configuration
// --------------------------
const int MICROSTEP = 16;
const int STEPS_PER_REV = 200 * MICROSTEP;
const float STEPS_PER_DEG = (float)STEPS_PER_REV / 360.0;
const float TARGET_STEPS_FLOAT = TARGET_MOTOR_DEG * STEPS_PER_DEG;

// --------------------------
// Motion timing
// --------------------------
const int BASE_STEP_DELAY_US   = 800;
const int START_STEP_DELAY_US  = 2000;
const int ACCEL_STEPS          = 100;

const unsigned long WAIT1_MS = 1000;
const unsigned long WAIT2_MS = 1000;
const unsigned long WAIT_AFTER_MS = 14000;   // <<< NUOVO WAIT AFTER

const unsigned long WAKE_MS = 80;

// --------------------------
const int JIGGLE_PAIRS = 6;
const int JIGGLE_STEP_US = 1600;
const int JIGGLE_GAP_US  = 600;

// --------------------------
```

```
String cmd = "";
static long remainder360 = 0;
bool loopActive = false;   // controlla il loop continuo
// --------------------------

inline void pulseStep(int delayUs) {
  digitalWrite(STEP_PIN, HIGH);
  delayMicroseconds(delayUs);
  digitalWrite(STEP_PIN, LOW);
  delayMicroseconds(delayUs);
}

void driverEnable(bool en) {
  if (ENA_PIN >= 0) {
    digitalWrite(ENA_PIN, en ? LOW : HIGH);
  }
}

void preExciteJiggle() {
  for (int i = 0; i < JIGGLE_PAIRS; i++) {
    digitalWrite(DIR_PIN, HIGH);
    pulseStep(JIGGLE_STEP_US);
    delayMicroseconds(JIGGLE_GAP_US);

    digitalWrite(DIR_PIN, LOW);
    pulseStep(JIGGLE_STEP_US);
    delayMicroseconds(JIGGLE_GAP_US);
  }
  digitalWrite(DIR_PIN, HIGH);
  delayMicroseconds(500);
}

int computeSteps() {
  long numer = (long)(TARGET_STEPS_FLOAT * 360.0f) + remainder360;
  const long denom = 360;
  int steps = numer / denom;
  remainder360 = numer % denom;
  return steps;
}

int rotateBigTarget() {
```

```
  driverEnable(true);
  delay(WAKE_MS);
  preExciteJiggle();

  int stepsToDo = computeSteps();

  int accelSteps = (ACCEL_STEPS < stepsToDo) ? ACCEL_STEPS : stepsToDo;
  for (int i = 0; i < accelSteps; i++) {
    int d = START_STEP_DELAY_US
          - ((START_STEP_DELAY_US - BASE_STEP_DELAY_US) * i
             / ((accelSteps > 1) ? (accelSteps - 1) : 1));
    pulseStep(d);
  }

  for (int i = accelSteps; i < stepsToDo; i++) {
    pulseStep(BASE_STEP_DELAY_US);
  }

  return stepsToDo;
}

// ---------------------------
void setup() {

  pinMode(STEP_PIN, OUTPUT);
  pinMode(DIR_PIN, OUTPUT);
  digitalWrite(DIR_PIN, HIGH);

  if (ENA_PIN >= 0) {
    pinMode(ENA_PIN, OUTPUT);
    driverEnable(true);
  }

  Serial.begin(9600);
  Serial.println("READY");
}

// ---------------------------
void loop() {

  // --- Ricezione comando da GH ---
```

```
  if (Serial.available()) {
    char c = Serial.read();
    cmd += c;

    // siccome GH manda solo ROT_SEQ3 senza newline,
    // controlliamo se la stringa contiene il comando
    if (cmd.indexOf("ROT_SEQ3") >= 0) {
      loopActive = true;
      cmd = "";
    }
  }

  // --- Loop continuo ---
  if (loopActive) {

    int s1 = rotateBigTarget();
    delay(WAIT1_MS);

    int s2 = rotateBigTarget();
    delay(WAIT2_MS);

    int s3 = rotateBigTarget();

    delay(WAIT_AFTER_MS);   // <<< WAIT AFTER

    // continua automaticamente
  }
}
```

A.2. Server Code

The following script implements the communication bridge between Grasshopper and the Arduino-controlled seventh axis. While the Arduino manages the low-level actuation of the stepper motor, Grasshopper must be able to trigger rotation sequences remotely and receive confirmation that each command has been executed. To achieve this, a lightweight TCP server is implemented in Python; it acts as an intermediary layer that translates network messages into serial commands for the Arduino.

The server listens on a local TCP port and waits for incoming connections from Grasshopper. Once connected, it receives command strings, forwards them to the Arduino via a serial interface, and returns any responses generated by the microcontroller. This architecture ensures a clean separation between the computational environment and the hardware control logic; Grasshopper communicates through a simple text-based protocol, while the Arduino remains dedicated to precise motor actuation.

The script performs the following functions:

Establishes a TCP socket server on the local machine;

- Opens a serial connection to the Arduino at the specified baud rate;
- Receives rotation commands from Grasshopper and forwards them to the Arduino;
- Waits for a confirmation message from the Arduino before returning feedback to Grasshopper;
- Maintains a persistent communication loop until manually interrupted.

This server was used throughout the development of the mini factory to coordinate the seventh-axis rotation with the robot's movements and the bending workflow. Its simplicity and reliability make it suitable for rapid prototyping and for integration into the modular digital pipeline described in Chapter 4. Future iterations may replace this intermediary layer with direct robot-to-Arduino communication, but the present implementation provides a robust and transparent foundation for synchronised multi-device control.

```
import socket
import serial

# CONFIGURAZIONE
HOST = '127.0.0.1'       # localhost
PORT = 65432             # porta TCP per Grasshopper
SERIAL_PORT = 'COM3'     # sostituire con la porta Arduino
BAUD = 9600

# Connetti Arduino
arduino = serial.Serial(SERIAL_PORT, BAUD, timeout=1)

# Avvia socket server
s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
s.bind((HOST, PORT))
s.listen(1)

print(f"Server TCP in ascolto su {HOST}:{PORT}...")

conn, addr = s.accept()
print(f"Connesso a {addr}")

try:
    while True:
        data = conn.recv(1024).decode().strip()
        if data:
            print(f"Ricevuto da GH: {data}")
            arduino.write((data + '\n').encode())

            # aspetta conferma da Arduino
            response = arduino.readline().decode().strip()
            if response:
                print(f"Arduino: {response}")
                conn.sendall(response.encode())
except KeyboardInterrupt:
    print("Server chiuso")
finally:
    conn.close()
    arduino.close()
    s.close()
```

A.3. Grasshopper Component Code for Arduino Control

The following script implements the Grasshopper-side client used to trigger the rotation sequence of the seventh axis. While the Arduino controls the stepper motor and the Python server manages the serial communication, Grasshopper acts as the high-level interface through which the user initiates the rotation command during the fabrication workflow. This component allows the digital environment to communicate with the physical hardware in a simple and non-blocking manner, ensuring that Grasshopper remains responsive while the seventh axis performs its motion.

The script establishes a persistent TCP connection to the local Python server; once connected, it sends a predefined command string that instructs the Arduino to execute the rotation sequence. The use of a persistent socket avoids repeated connection overhead and ensures fast communication during iterative bending operations. The component also provides basic status reporting, allowing the user to monitor whether the connection is active, whether the command has been sent, or whether an error has occurred.

The Grasshopper client performs the following functions:

- Creates and maintains a TCP socket connection to the Python server;
- Sends the rotation command (“ROT_SEQ3”) when the user activates the component;
- Avoids blocking Grasshopper’s execution thread by sending the command asynchronously;
- Provides feedback on connection status and error conditions.

This lightweight client completes the communication chain between Grasshopper, the Python server, and the Arduino-controlled seventh axis. It enables the digital workflow to trigger physical actuation reliably and with minimal overhead, forming an essential link in the semi-automated bending process described in Chapter 4.

```
import socket

# socket persistente
if 's' not in globals():
    s = None
    connected = False

status = "idle"

if button:
    try:
        if s is None:
            s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)

        if not connected:
            s.connect((host, port))
            connected = True
            status = "Connesso al server"

        # invia comando senza bloccare GH
        s.sendall(b"ROT_SEQ3")
        status = "Comando inviato, Arduino esegue la sequenza"

    except Exception as e:
        status = "Errore: " + str(e)
        connected = False
        s = None
```

A.4. RAPID Code

The following listing contains the RAPID program used to control the ABB GoFa 5 during the bending-tending workflow of the mini factory. This code represents the robot-side execution layer of the digital pipeline described in Chapter 4; it translates the trajectories generated in Grasshopper and RobotStudio into a structured sequence of movements, synchronisation points, and digital output operations.

The program is organised into three main procedures:

- FullCycle executes the complete sequence required for the first run; it includes the initial approach, the activation of the vacuum system through a digital output, the transport of the sheet to the bending machine, and the return to the intermediate position. This procedure also contains the final three movements that are performed only once at startup.
- LoopCycle contains a reduced version of the sequence; it omits the homing motion and the final targets, allowing the robot to repeat the core handling routine continuously.
- Main_Alp coordinates the execution; it performs the initial homing, calls the full cycle once, and then enters an infinite loop in which the reduced cycle is repeated.

The program defines all necessary robot data structures, including tool definitions, work objects, speed profiles, and zone parameters. These values correspond to the calibrated TCP of the custom end effector and the spatial reference frame used in the mini factory. The MoveL instructions specify the Cartesian targets generated by the digital workflow; each target includes position, orientation, configuration data, and external joint values. WaitTime instructions ensure synchronisation with the bending machine and the seventh-axis rotation.

A digital output is activated at the second target of the first cycle; this signal controls the vacuum ejector mounted on the end effector. The program is designed to operate safely within a collaborative environment; all motions are linear, speeds are limited, and zones are selected to balance precision and smoothness.

The version presented here corresponds to the program used during experimental testing and the public demonstration at CaseItaly 2026. It provides a stable and repeatable execution framework for the robot and forms the final link in the digital-to-physical chain of the mini factory.

```
MODULE Alpewa_program_01_T_ROB1

VAR extjoint extj := [9E9,9E9,9E9,9E9,9E9,9E9];
VAR confdata conf := [0,0,0,0];
PERS tooldata DefaultTool:=[TRUE,[[0,0,0],[1,0,0,0]],[0.001,[0,0,0.001],[1,0,0,0],0,0,0]];
PERS           tooldata           DefaultGHTool:=[TRUE,[[-245,0,124.5],[1,0,0,0]],[0.001,[-
245,0,124.5],[1,0,0,0],0,0,0]];
TASK PERS wobjdata DefaultFrame:=[FALSE,TRUE,"",[[0,0,0],[1,0,0,0]],[[0,0,0],[1,0,0,0]]];
TASK PERS speeddata Speed000:=[500,180,5000,1080];
TASK PERS speeddata Speed001:=[1000,180,5000,1080];
TASK PERS zonedata Zone001:=[FALSE,50,50,50,5,50,5];
TASK PERS zonedata Zone002:=[FALSE,20,20,20,2,20,2];
TASK PERS zonedata Zone003:=[FALSE,5,5,5,0.5,5,0.5];

PROC FullCycle()
    ! Full sequence for FIRST RUN ONLY

    ! ----- Target 1 -----
    MoveL [[-57.811,-621.244,56.626],[0,0.70711,0.70711,0],conf,extj],
          Speed000,fine,DefaultGHTool \WObj:=DefaultFrame;

    ! ----- Target 2 -----
    MoveL [[-57.811,-621.244,10],[0,0.70711,0.70711,0],conf,extj],
          Speed001,Zone001,DefaultGHTool \WObj:=DefaultFrame;
    WaitTime 2;

    ! ****** ACTIVATE DIGITAL OUTPUT AT SECOND TARGET ******
    SetDO ABB_Scalable_IO_0_DO1,1;

    ! ----- Target 3 -----
    MoveL [[-57.811,-621.244,56.626],[0,0.70711,0.70711,0],conf,extj],
          Speed000,fine,DefaultGHTool \WObj:=DefaultFrame;

    MoveL [[459.364,-615.108,100],[0,0.38268,0.92388,0],conf,extj],
          Speed001,Zone002,DefaultGHTool \WObj:=DefaultFrame;

    MoveL [[672.97,-559.918,350.0],[0,0,1,0],conf,extj],
          Speed001,Zone003,DefaultGHTool \WObj:=DefaultFrame;

    WaitTime 7;
```

```
    MoveL [[459.364,-615.108,100],[0,0.38268,0.92388,0],conf,extj],
          Speed001,Zone002,DefaultGHTool \WObj:=DefaultFrame;

    ! ----- Last 3 moves that will NOT be repeated -----
    MoveL [[-57.811,-621.244,56.626],[0,0.70711,0.70711,0],conf,extj],
          Speed000,fine,DefaultGHTool \WObj:=DefaultFrame;
    WaitTime 1;

    MoveL [[-57.811,-621.244,10],[0,0.70711,0.70711,0],conf,extj],
          Speed001,Zone001,DefaultGHTool \WObj:=DefaultFrame;
    WaitTime 2;

    MoveL [[-57.811,-621.244,56.626],[0,0.70711,0.70711,0],conf,extj],
          Speed000,fine,DefaultGHTool \WObj:=DefaultFrame;
    WaitTime 1;
ENDPROC


PROC LoopCycle()
    ! Reduced sequence repeated forever (NO home, NO last 3 targets)

    MoveL [[-57.811,-621.244,56.626],[0,0.70711,0.70711,0],conf,extj],
          Speed000,fine,DefaultGHTool \WObj:=DefaultFrame;

    MoveL [[-57.811,-621.244,10],[0,0.70711,0.70711,0],conf,extj],
          Speed001,Zone001,DefaultGHTool \WObj:=DefaultFrame;
    WaitTime 2;

    MoveL [[-57.811,-621.244,56.626],[0,0.70711,0.70711,0],conf,extj],
          Speed000,fine,DefaultGHTool \WObj:=DefaultFrame;

    MoveL [[459.364,-615.108,100],[0,0.38268,0.92388,0],conf,extj],
          Speed001,Zone002,DefaultGHTool \WObj:=DefaultFrame;

    MoveL [[672.97,-559.918,350.0],[0,0,1,0],conf,extj],
          Speed001,Zone003,DefaultGHTool \WObj:=DefaultFrame;

    WaitTime 7;

    MoveL [[459.364,-615.108,100],[0,0.38268,0.92388,0],conf,extj],
```

```
          Speed001,Zone002,DefaultGHTool \WObj:=DefaultFrame;
ENDPROC



PROC Main_Alp()
    ! ---------- FIRST RUN ----------
    ConfL \Off;
    MoveAbsJ [[0,0,0,0,0,0],extj],
             Speed000,fine,DefaultTool;

    FullCycle;   ! includes everything

    ! ---------- LOOP RUNS ----------
    WHILE TRUE DO
        LoopCycle;   ! skips home + last 3 targets
    ENDWHILE
ENDPROC

ENDMODULE
```

B Appendix B

This annex collects the essential technical sheets of the core machinery and components used in the mini factory. These documents provide reference specifications that support the descriptions in Chapters 3 and 4 without interrupting the narrative flow of the thesis.

B.1. ABB GoFa CRB 15000 (GoFa 5)

The following technical sheet provides the essential configuration data, tool definitions, speed profiles, and work-object parameters used by the ABB GoFa 5 within the mini factory. These values form the operational foundation for the RAPID programs presented in the main chapters; they ensure that the robot executes trajectories with the correct tool centre point, orientation, and motion characteristics.

The sheet includes calibrated tooldata for both the default tool and the custom end effector equipped with the vacuum gripping system; it also specifies the work object corresponding to the mini factory reference frame. Speed and zone parameters are defined to balance precision, safety, and fluidity during collaborative operation, while configuration and external joint variables support consistent robot posture throughout the bending and tending workflow.

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barriers or fencing. GoFa can continuously share workspace with people, giving it maximum flexibility and efficiency. Robot and human cooperate on the same tasks, without jeopardizing productivity or safety.

Strong yet safe

Designed for handling payloads up to 14 kg*, GoFa has integrated torque sensors in each of its six joints offering superior power and force limiting performance. Together, these prevent the risk of injury by bringing GoFa to an immediate stop if it senses any contact with a human worker.

Built-in Force control for advanced applications

The force control option enables GoFa to adjust its motion based on measured force input without the need of any additional hardware thanks to our unique architecture.
This capability allows the cobot to maintain a consistent force between itself and the objects it interacts with, while also adjusting its path and speed. This feature is essential for applications such as polishing, sanding, deburring, testing, and assembly.

* wrist down configuration

Easy set-up and operation

Set up and configuration is easy with intuitive, graphical Apps directly on the FlexPendant.
You can move your robot using lead through
in no time.

Faster performance for greater productivity

GoFa offers a maximum Tool Center Point (TCP) speed of up to 2,2 m/s,[1] faster than other cobots in its class. GoFa can perform more operations in a set period than competing robots.

Ultra Accuracy for high precision tasks

GoFa Ultra Accuracy feature ensures exceptional precision with path accuracy down to 0.03 mm and absolute position accuracy of 0.1 mm, perfect for high-stakes applications like gluing, sealing, laser welding, and precision cutting, delivering over 10 times greater path accuracy than other cobots.

Key features:

Collaborative safety
- Superior power and force limiting performance through integrated torque sensors,
- Safe design of robot, rounded geometry, no pinch/trap points,
- Safety certified Category 3, PL d.

Easy to use
- Enhanced interaction with arm side interface,
- Lead-through anywhere on the robot,
- Wizard easy programming,
- SafeMove configurator App on the FlexPendant.

Accuracy:
- With path accuracy down to 0.03mm, GoFa delivers over 10 times greater accuracy than other cobots*
- Absolute position accuracy of 0.1 mm maintains tight tolerances*
- Offline programming with RobotStudio® achieves up to 99% match between simulation and reality, reducing the need for adjustments and ensuring efficient deployment*
- * Available with GoFa Ultra Accuracy option

Productivity
- With a TCP speed of up to 2,2 m/s², GoFa is faster than other cobots in its class,
- Up to 1,62 m reach, 14% longer than other comparable robots,
- Up to 20% energy savings,
- Best-in-class repeatability of 0,02 mm on the market.

Applications
- Machine tending,
- Welding,
- Palletizing,
- Assembly,
- Screwdriving,
- And many more...

Specification			
	GoFa 5	GoFa 12	GoFa 10
Reach (mm)	950 (wrist) 1050 (flange)	1270 (wrist) 1370 (flange)	1520 (wrist) 1620 (flange)
Payload (kg)	5	up to 14kg*	up to 12kg*
Arm load (kg)	1 (mounted on axis 4)	1 (mounted on axis 2, 3, or 4)	1 (mounted on axis 2, 3 or 4)
Number of axes	6	6	6
Protection	IP54	IP67	IP67
Cleanroom class	ISO cleanroom 4	ISO cleanroom 4	ISO cleanroom 4
Mounting	Any angle, including table mounting, wall mounting, and ceiling mounting		
Controller	OmniCore C30		
Controller power needed to run the GoFa arm	100 – 230 VAC 50 – 60 Hz		
Customer power supply	M8, 3 pins connector, 24V/3A		
Customer signals	M8, 4 pins connector, CAT 5 cable, up to 4 digital signals availble for digital IOs,Analog IOs, Fieldbuses and Ethernet based protocols		
Tool flange	Standard ISO 9409-1-50		
Ambient Temperature	5°C to 40°C	5°C to 40°C	5°C to 45°C
Humidity	<75% relative humidity For limited period (<1 month): <95% relative humidity	<75% relative humidity For limited period (<1 month): <95% relative humidity	<75% relative humidity For limited period (<1 month): <95% relative humidity
Average Power Consumption	250W	250W	250W
Additional Options	Force control, integrated vision, conveyor tracking	Force control, integrated vision, conveyor tracking	Force control, integrated vision, conveyor tracking
Functional safety	SafeMove Collaborative included all safety functions certified to Category 3, PL d. It includes upto 16 safety zones		
Certifications			
SGS Functional safety	ISO 10218-1:2011 and the applicable portions of ISO/TS 15066, ISO 13849-1:2015, IEC 60204-1:2016 The product is compliant with ISO 10218-1:2011		
Additional Certifications (Standards)	UL1740 (for USA), CSA Z434 (for Canada)		

* wrist down configuration

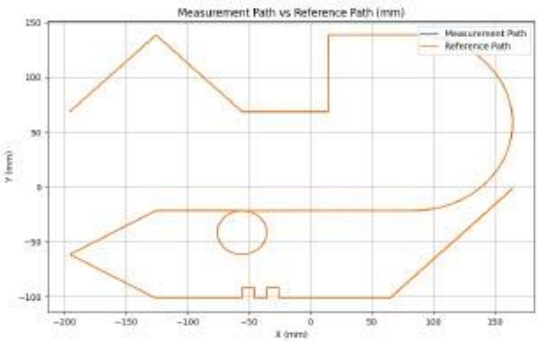
OmniCore ™			
	GoFa 5	GoFa 12	GoFa 10
Physical Controller Dimensions	C30 I 449x443x170 (WxDxH) mm I Weight 24kg		
Available Connections	Expandable Digital I/Os, Analog I/Os, Safety I/Os		
Power requirements	100 - 230 VAC 50 - 60 Hz single phase		
Available Communication Protocol	TCP/UDP IP, RTU, Fieldbuses: PROFINET Controller, PROFINET Device, PROFIenergy, PROFIsafe Controller PROFIsafe Device, EtherNet/IP Scanner, EtherNet/IP Adapter, CC-Link IE FB Master, CC-Link IE FB Device DeviceNet c/d		
Mounting Options	Standing, Rack mount, Vertical mount, Desktop Design		
IP Level	IP20		

FlexPendant			
	GoFa 5	GoFa 12	GoFa 10
Screen	8" color touch screen		
Resolution	1024x768		
Protection	IP54		
Available Cable Length	3m, 10m + extensions		
Additional Features	3D Joystick Adaptable for left-handed users		

Performance			
	GoFa 5	GoFa 12	GoFa 10
Max TCP Velocity	2,2 m/s	2 m/s	2 m/s
Max TCP acceleration (Controlled motion for nominal load)	36,9 m/s²	27 m/s²	28 m/s²
Max TCP acceleration (e-stop for nominal load)	61,6 m/s²	79 m/s²	94 m/s²
Pose repeatability	0.02 mm	0.02 mm	0.02 mm

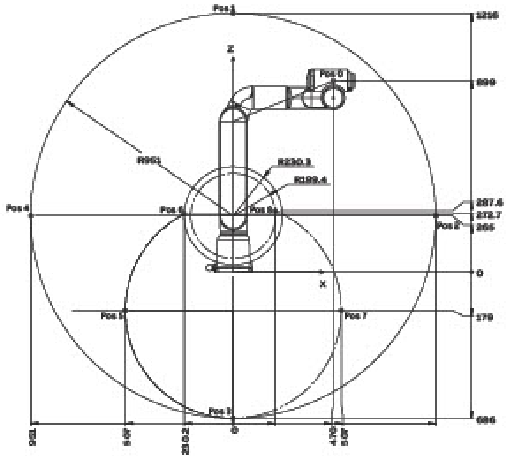
Ultra Accuracy (Feature)			
	GoFa 5	GoFa 12	GoFa 10
Absolute Position Accuracy	0.1mm	0.1mm	0.1mm
Path Accuracy	Down to 0.03mm	Down to 0.03mm	Down to 0.03mm

Ultra Accuracy Test Performance (Error measurement)			
	GoFa 5	GoFa 12	GoFa 10
Average Error	0.04mm	0.04mm	0.04mm
Max Error	0.16mm	0.15mm	0.18mm

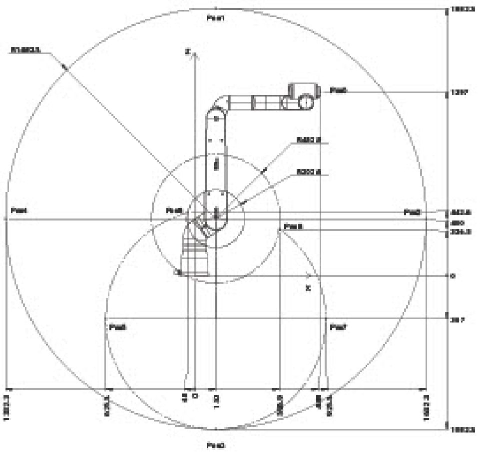


GoFa Ultra Accuracy Test: Reference Path vs. Measured Path

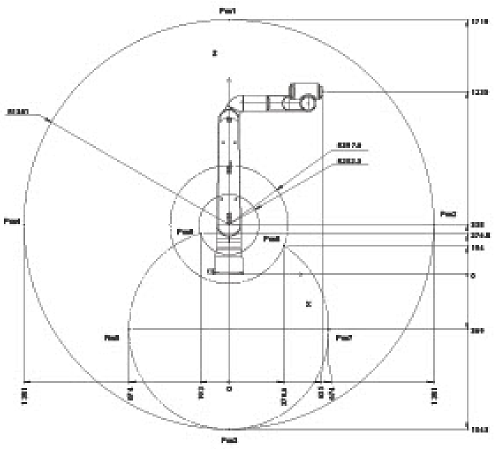
Physical						
	GoFa 5		GoFa 12		GoFa 10	
Dimensions robot base	165 x 165 mm		200 x 200 mm		200 x 200 mm	
Weight	28 kg		48 kg		51 kg	
Movement						
	GoFa 5		GoFa 12		GoFa 10	
Axis movement	Working range	Axis max. speed	Working range	Axis max. speed	Working range	Axis max. speed
Axis 1 rotation	-180° to 180°	125 °/s	-270° to 270°	120 °/s	-270° to 270°	120 °/s
Axis 2 arm	-180° to 180°	125 °/s	-180° to 180°	120 °/s	-180° to 180°	120 °/s
Axis 3 arm	-225° to 85°	140 °/s	-225° to 85°	125 °/s	-225° to 85°	125 °/s
Axis 4 wrist	-180° to 180°	200 °/s	-180° to 180°	200 °/s	-180° to 180°	200 °/s
Axis 5 bend	-180° to 180°	200 °/s	-180° to 180°	200 °/s	-180° to 180°	200 °/s
Axis 6 turn	-270° to 270°	200 °/s	-270° to 270°	200 °/s	-270° to 270°	200 °/s



01 GoFa 5 Working range, Side view



02 GoFa 10 Working range, Side view



03 GoFa 12 Working range, Side view

abb.com/robotics

B.2. Schectl UK 100 S

The following technical sheet provides the key specifications and operational parameters of the Schechtl UK 100 S bending machine used within the mini factory. This information is essential for understanding the mechanical constraints, bending capacities, and safety requirements that shaped the fabrication workflow described in the thesis. The machine's geometry, clamping behaviour, interchangeable bending blocks, and maximum bending angles directly influence the design of the sheet-metal pieces and the sequencing of the bending operations.

The technical sheet serves as a reference for the calibration of the digital workflow, ensuring that the bending angles computed in Grasshopper remain compatible with the physical capabilities of the machine. It also supports the integration of the robot and the AR guidance system by providing accurate data on clearances, working envelopes, and mechanical tolerances. Including this document in Annex B allows readers to verify the machine parameters used throughout the research and to reproduce the experimental setup with full technical fidelity.

The Schechtl UK handles the production of special shapes, box and cassette forms and adjustment tasks. It can bend up to 1.50 mm steel and is available in working lengths 1 m and 1.25 m. The comprehensive range of standard equipment and many extension options make the UK a real multi-tool.

BENEFITS

- Segments with the original Schechtl **quick clamping system**
- **Tool-free adjustment** of all segments supplied in the 3 areas lower, bending and clamping beam (Standard height of all segments 100 mm)
- **Bending angle limitation** for uniform, recurring bending operations
- Quick, tool-free adjustment of the **clamping beam clamping pressure**
- Tool-free adjustment of the **bending beam lowering**
- Foot pedal for **free-hand clamping** of the workpiece
- **Practical**: storage tray for the segments
- **Storage box** for accessories and tools that also serves as a sheet support
- 4 swivel castors with locking brake for **mobile use** in the workshop

TECHNICAL DATA

Subject to change

MODEL	UK		125	100
WORKING LENGTH		mm	1250	1000
OUTPUT	Steel (400N/mm²)	mm	1,25	1,50
	Stainless steel (600N/mr	mm	0,80	1,00
	Cooper (300N/mm²)	mm	1,50	2,00
	Aluminium (250N/mm²)	mm	2,00	2,25
	Zinc (150N/mm²)	mm	2,00	2,00
DIMENSIONS	Length	mm	1730	1480
	Depth	mm	740	740
	Overall height	mm	1180	1180
WEIGHT		kg	290	260
CLAMPING BEAMS	Opening height	mm	96	96

SERIES EQUIPMENT

The following series equipment is possible depending on the version (working length/control):

- ✓ Segments with quick clamping system
- ✓ Clamping beam pressure setting
- ✓ Bending beam lowering
- ✓ Bending beam stop
- ✓ Storage box
- ✓ Foot pedal
- ✓ Castors

ADD-ONS - OPTIMISE YOUR UK

The following add-ons are possible depending on the version (working length/control):

- ✓ Clamping beam segments in R 2 mm
- ✓ Clamping beam segments in R 3 mm
- ✓ Clamping beam segments 140 mm high
- ✓ Clamping beam segments 160 mm high
- ✓ Back gauge 1000 mm
- ✓ Universal backgauge table UA125
- ✓ Windowsill insert, standard
- ✓ Windowsill insert, variable (6-part)

All details onUK

Schechtl Maschinenbau GmbH
Viehhauser Str. 4
D-83533 Edling
(Zentrale) +49 8071 / 5995-0
(Sales) +49 8071 5995-111

B.3. Schmalz Compact Ejector

The following technical sheet provides the key specifications of the Schmalz compact ejector integrated into the custom end effector of the mini factory. This pneumatic component is responsible for generating the vacuum required to grip and manipulate aluminium sheets during robotic handling and tending operations. Its performance characteristics, including suction capacity, response time, air consumption, and mounting geometry, directly influence the reliability and speed of the pick-and-place workflow.

The compact ejector plays a central role in ensuring stable adhesion between the suction cup and the sheet surface; its lightweight design and integrated valve system make it suitable for collaborative robotic applications where precision, safety, and rapid switching are essential. The technical sheet included in this annex provides detailed information on operating pressures, flow rates, nozzle configurations, and installation requirements, all of which informed the design of the end effector and the calibration of the robotic movements.

Including this document in Annex B ensures full transparency regarding the pneumatic hardware used in the project and supports the reproducibility of the experimental setup.

Eiettore compatto

SCPi 15 NC VD M12-5

Art.-Nr.: 10.02.02.03343

SCPi 15 NC VD M12-5

Dati tecnici

Attributo	Valore
Diametro dell'ugello	1,5 mm
Collegamento elettrico	Connectore M12, 5 pol
Tipo di protezione IP	IP 65
Vuoto max.	-850 mbar
Consumo d'aria in aspirazione	115,0 l/min
Capacità di aspirazione (max.)	75,0 l/min
Campo di pressione (pressione di esercizio) [bar]	4,0 ... 7,0 bar
Valvola di controllo	Chiuso senza corrente
Funzione dell'eiettore	vacuostato digitale

L'eiettore compatto SCPi / SMPi viene fornito come prodotto finito per connessione (senza cavo di connessione).

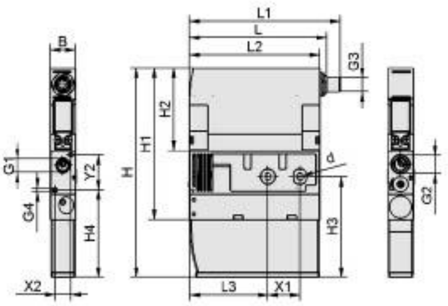
Accessori disponibli: cavo di connessione, distributore di collegamento, piastra di raccordo aria compressa, piastra ciece eiettore, attacco Quick Change (Adapter Quick Change), tester eiettore

Contattare Schmalz: Schmalz s.r.l. • Via Ticino 105 • 28066 Galliate (NO) • +39 0321 621 510 • schmalz@schmalz.it

Eiettore compatto

SCPi 15 NC VD M12-5

Art.-Nr.: 10.02.02.03343



Dati di costruzione SCPi 15 NC VD M12-5

Dati di costruzione

Attributo	Valore
Lunghezza L1	129,70 mm
Lunghezza L2	112,50 mm
Lunghezza L	118,50 mm
Larghezza B	22,00 mm
Altezza H1	131,50 mm
Altezza H2	71,50 mm
Altezza H	181,50 mm
Diametro interno d	6,60 mm
Filettatura G1	G1/4"-IG
Filettatura G2	G3/8"-IG
Lunghezza L3	67,50 mm
Altezza H3	87,50 mm
Altezza H4	76,00 mm
Griglia forata Y2	30,0 mm
Griglia forata X1	27,5 mm
Griglia forata X2	14,0 mm
Filettatura G4	M4-IG
Filettatura G3	M12x1-AG

Dati tecnici

Attributo	Valore
Diametro dell'ugello	1,5 mm
Diametro interno del tubo flessibile aria compressa raccomandato	6,0 mm
Diametro interno tubo flessibile raccomandato a vuoto	6,0 mm
Grado di evacuazione	85,0 %
Livello di pressione acustica libero	75,0 dB(A)
Peso	0,560 kg
Consumo d'aria massimo da soffiare	200,0 l/min
Consumo d'aria in aspirazione	4,061 cfm
Capacità di aspirazione (max.)	2,648 cfm
Campo di pressione (pressione di esercizio) [bar]	4,0 ... 7,0 bar
Temperatura d'intervento	0 ... 50 °C
Campo di pressione (pressione di esercizio) [psi]	58,0 ... 101,5
Vuoto max.	-25,100 inHg
Famiglia di prodotti	SCPi
Valvola di controllo	Chiuso senza corrente

Nota: La tensione di alimentazione per vacuostati ed elettrovalvole è di 24 V DC. Consumo d'aria: alla pressione di esercizio ottimale. Diametro tubo flessibile: per lunghezza max. 2 m

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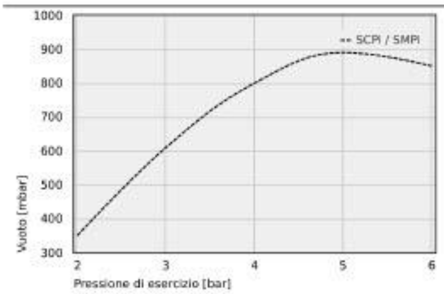
Eiettore compatto

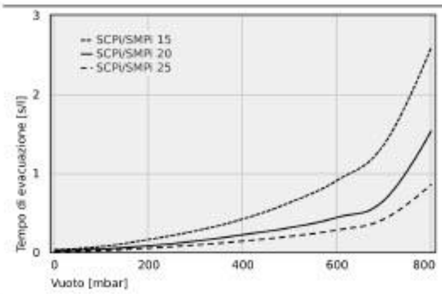
SCPi 15 NC VD M12-5

Art.-Nr.: 10.02.02.03343

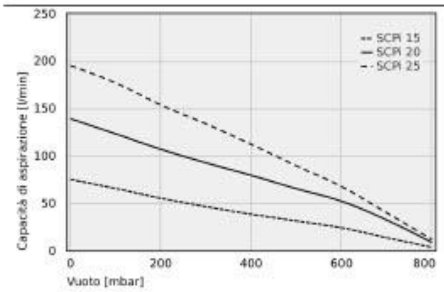
Dati sulle prestazioni



Vuoto eseguibile a varie pressioni di esercizio



Tempi di evacuazione per diversi intervalli di vuoto [s/l]



Capacità di aspirazione a diversi gradi di evacuazione [l/min]

Vuoto eseguibile a varie pressioni di esercizio

	2	3	4	5	6
SCPi / SMPi	350	610	800	890	850

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SCPi 15 NC VD M12-5

Art.-Nr.: 10.02.02.03343

Tempi di evacuazione per diversi intervalli di vuoto [s/l]

	0	100	200	300	400	500	600	700	800
SCPi/SMPi 15	0.03	0.07	0.16	0.27	0.42	0.63	0.91	1.37	2.60
SCPi/SMPi 20	0.02	0.04	0.08	0.14	0.22	0.31	0.44	0.66	1.54
SCPi/SMPi 25	0.01	0.02	0.05	0.09	0.14	0.20	0.28	0.42	0.86

Capacità di aspirazione a diversi gradi di evacuazione [l/min]

	0	100	200	300	400	500	600	700	800
SCPi 15	75.0	65.4	55.2	46.3	38.3	31.2	23.9	13.5	3.4
SCPi 20	139.0	123.1	106.8	92.5	79.3	65.2	51.9	32.1	8.5
SCPi 25	195.0	176.8	153.6	133.6	112.0	89.3	67.4	39.7	11.7

Ulteriore documentazione

I dati CAD e altri documenti relativi all'articolo sono disponibili all'indirizzo: **www.schmalz.com/10.02.02.03343**

Dati di ordinazione accessori 10.02.02.03343

Typ		Numero articolo
Cavo di connessione	ASK B-M12-5 5000 K-5P	21.04.05.00080
Distributore di collegamento	ASV SM/CPi B-M12-5 3xS-M12-4	10.02.02.03372
Distributore di collegamento	ASV SM/CPi B-M12-5 2xS-M12-4	10.02.02.03490
Piastra di raccordo aria compressa	GP 2 SMP 15..30/SCP 20..30	10.02.02.00917
Piastra di raccordo aria compressa	GP 3 SMP 15..25/SCP 20..25	10.02.02.00918
Piastra di raccordo aria compressa	GP 4 SMP 15..20/SCP 20	10.02.02.00919
Piastra di raccordo aria compressa	GP 5 SMP 15	10.02.02.00920
Piastra di raccordo aria compressa	GP 6 SMP 15	10.02.02.00921
Piastra cieca eiettore	EJEK-PL SMP(i)15..30/SCP(i)20..30	10.02.02.00728
Adapter Quick Change	ADP-Q 90.5x22x29.7 SMPi/SCPi	10.02.02.03463
Tester eiettore	EJEK-TEST SMPi/SCPi	10.02.02.03588
Filtro tazze a vuoto	VFT G1/4-IG 80	10.07.01.00119

Dati di ordinazione pezzi di ricambio 10.02.02.03343

Typ		Numero articolo
Dispositivo silenziatore (quadr)	SD 111x21x45 SMPi/SCPi	10.02.02.03381

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Eiettore compatto

SCPi 15 NC VD M12-5

Art.-Nr.: 10.02.02.03343

Dati di ordinazione pezzi soggetti a usura 10.02.02.03343

Typ		Numero articolo
Set parti soggette ad us. eiettore	VST SMPI/SCPI	10.02.02.99965
Set parti soggette ad us. eiettore	VST SCPi-ERW	10.02.02.99963

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List of Figures

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My heartfelt thanks go to my family and to all the people who stood by me during these intense yet profoundly fulfilling years. Their patience, encouragement, and presence made everything possible.

Finally, I want to thank the people who never stopped believing in me, even in those moments when I was the first to doubt myself. This work exists because of that unwavering faith.