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Technical Communication

Towards the Application of Low-Cost Collaborative Robots in Laser Materials Processing

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The integration of low-cost collaborative robots (cobots) into laser materials processing (LMP) holds significant promise, especially for small and medium-sized enterprises (SMEs). Technological advancements have reduced costs and increased laser system flexibility, broadening their application. Additionally, demographic changes and labor shortages highlight the need for adaptable robotic solutions. Cobots, with intuitive programming, built-in safety, and low costs, suit SMEs performing small batch, varied production. However, their limited rigidity compared to industrial robots challenges precision and repeatability, demanding specialized path planning, calibration, and sensor fusion to ensure sub millimeter-level accuracy. This paper presents recent research on cobot-assisted LMP through laser cutting, welding, marking, and cleaning case studies. It discusses how optimized path planning, offline trajectory simulations, adaptive corrections, and hand-guided programming can overcome cobot limitations. The insights support broader adoption of cobots in laser materials processing and guide future research toward enhanced accuracy and effective human-robot-collaboration.
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1. Introduction

Laser materials processing (LMP) has undergone major changes in recent years. Among these, two developments are especially relevant to this study: the declining cost of high-quality laser sources [1] and the miniaturization of processing equipment, such as lightweight optics [2] and scanner heads [3] or multi-purpose equipment [4]. These advances have enabled flexible systems like handheld laser materials processing devices [5], lowering the entry barrier for small and medium-sized enterprises (SMEs).

Simultaneously, demographic shifts in high-wage countries, including Germany [6], Japan [7] and the US [8], are intensifying the need for automation. The welding profession, for instance, faces a shortage of skilled labor as experienced workers retire and fewer young professionals enter the field [9]. For SMEs involved in small series production or product ramp-up—such as electric vehicle chassis manufacturing [10]—this creates a critical bottleneck for scaling and maintaining quality.

Technological progress in LMP has made affordable, compact, and user-friendly tools more accessible to SMEs [11]. Solutions like handheld materials processing devices [5] and low-cost engraving systems [12] exemplify this trend. These tools support process automation and modular manufacturing, particularly suited for operations with frequent part changes. Emerging use cases—such as descaling, cleaning, and surface modification—further drive adoption in SMEs, benefiting from the flexibility and compactness of modern laser devices [13,14].

Collaborative robots (cobots) are another technology adding further value by addressing workforce shortages [15–17] and enhancing production flexibility. In 2023, cobots represented 10.5% of new robot installation [18], with the market surpassing $1 billion and projected to grow over 20% annually through 2028 [19]. Their intuitive interfaces, easy programming, and integrated safety features make them attractive to SMEs, especially given the comparably little capital investment required for adoption.

We advocate for the integration of these two technologies to create new value propositions for SMEs based on LMP. Integrating cobots with LMP offers a cost-effective, flexible automation solution. Tasks can be programmed or taught before the laser processes are executed autonomously once the operator has left the laser cell or other safety precautions are taken. Such semi-automated solutions are particularly relevant for tasks requiring intuitive interfaces, precision and adaptability, such as laser cutting, welding, cleaning, and marking—processes explored in this work—in small batch production. These process applications were chosen, as they highlight the challenges and opportunities of using low-cost cobots with limited rigidity and low payload capabilities in demanding manufacturing environments.

This paper investigates how cobots can enhance LMP for SMEs and current limitations of cobot-based LMP. We present a review of relevant trends, case studies, and research directions emphasizing how cobot-enabled LMP can address labor shortages, support small batch production, and maintain competitiveness. The study evaluates the system technology and current readiness of a cobot-based laser workstation across four representative applications. The objective is to document integration, architecture, control modes, safety, and practical feasibility on an SME-appropriate platform. We do not conduct process-parameter optimization or benchmarking of "improvements". Reference process parameter sets are used only to exercise the system under representative conditions.

2. Background and Related Work

2.1 Developments in Laser Materials Processing

The LMP market is experiencing rapid growth, valued at $26.5 billion in 2024 and projected to surpass $48 billion by 2031, driven by an 8% compound annual growth rate [20]. Technological advancements have significantly reduced the cost of fiber beam sources to around $1 per watt, making LMP more accessible [1]. Revenue generation in high-income countries is shifting either to high-end applications or to new and emerging markets such as SMEs and crafts.

Emerging segments in LMP include handheld welding systems and laser cleaning tools [5,21], now used even in cultural heritage preservation [22]. Laser marking and sublimation cutting enable product personalization and part traceability [23]. These compact, affordable solutions support flexible deployment, based on manual labor in diverse small-scale applications.

In parallel with these market dynamics, significant progress has been made in the design and functionality of key LMP components. Advances in miniaturization have resulted in lighter and smaller laser processing heads [2,3]. Moreover, the development of multi-purpose processing heads, capable of handling both welding and cutting tasks has improved operational flexibility [4]. These component trends not only reduce the physical footprint of LMP systems but also enhance their integrability with low-cost, intuitive cobot-based platforms, thereby expanding the accessibility and efficiency of laser processing for a wider range of applications.

2.2 Robots in Laser Materials Processing

Six-axis industrial robotic arms are commonly employed in LMP, as they bring flexibility and multi-axis motion to processes like laser cutting [24], welding [25], cladding [26,27] and more recently surface texturing [28]. In contrast to conventional CNC or gantry systems, a robotic arm can orient a laser beam along complex 3D paths, making it ideal for processing parts with curved or difficult geometries. Industries such as automotive and aerospace leverage robotic LMP in manufacturing and repair operations.

In applications requiring increased reach and autonomy, mobile robotic systems have been developed to perform laser processing on large-scale structures such as ship hulls or sheet metal components [29–31]. For extraterrestrial environments, mobile cobot platforms have been tested for in-situ laser sintering of regolith, paving the way for additive manufacturing in future space missions [32,33]. Additionally, specialized solutions such as the "Laser Snake" enable laser welding inside confined or hazardous spaces, including fusion facilities [34]. These developments reflect a broader trend toward employing non-conventional kinematic architectures in LMP, aiming to enhance process accessibility, flexibility, and automation potential across a growing range of industrial and research domains [35].

2.3 Collaborative Robots in Manufacturing

Collaborative robots have rapidly become essential enablers in modern manufacturing environments, particularly for small and medium-sized enterprises (SMEs). Unlike conventional industrial robots—which often require complex integration and specialized programming skills—cobots are designed for flexibility, ease of deployment, and intuitive operation. Their value lies not in high speed or large payloads, but in their ability to adapt quickly to changing production needs, without demanding extensive automation expertise [36–41].

Today, cobots are used across a wide range of manufacturing tasks, starting from pick-and-place and machine tending to quality control and assembly [39,40]. More recently, their application has expanded into joining processes, including arc welding—a domain historically dominated by conventional industrial robots [42–44]. The human-centric design of cobots makes them ideal for environments that demand frequent changeovers, short production cycles, close human-robot collaboration or experience labor shortages—like the European welding market [45].

Research prototypes like *MyWelder* presented by Ferraguti et al. in 2023 [44] illustrate this trend by enabling intuitive, cobot-assisted MIG/MAG welding through easy programming and interaction. The system allows efficient welding even in small batch production and has shown strong performance and usability in trials with professional welders [44]. Other academic approaches include manually teachable welding cobots or systems that generate weld paths automatically from 3D models [43].

In parallel, industry has begun to offer turnkey cobot welding systems. One example is the *TruArc Weld 1000* by Trumpf SE + Co. KG [46], which combines a Universal Robot UR10e cobot with an arc welding package. Programming is performed via hand-guiding and simple menu navigation, allowing quick setup and redeployment without robotic expertise. The system is optimized for low-volume, high-mix production where traditional automation would be inefficient or uneconomical. A comparable solution is offered by Lorch Schweißtechnik GmbH [47].

Recent research has further enhanced the applicability of collaborative robots in arc welding through the integration of sensor-based modules. One such system combines a cobot with a line scanner and a user-friendly interface to enable automatic seam detection and online path generation. This allows the robot to dynamically adapt to part tolerances and geometric deviations without requiring advanced programming skills or robotic expertise. The user's role is limited to selecting a start point or adjusting a few basic parameters, while both motion control and process configuration are handled autonomously by the system [48].

While collaborative robots have seen widespread adoption in arc welding now, their application in laser-based manufacturing has been more limited. A notable advancement in this domain is the introduction of the first commercial cobot system specifically designed for laser processes by IPG Photonics [49]. The system, known as *LightWELD*, combines a compact, high-performance fiber laser with a collaborative robotic arm and an intuitive user interface. It integrates process-specific presets and guidance tools that allow non-expert users to perform high-quality laser welds with minimal setup effort. This platform exemplifies the shift toward accessible, reconfigurable laser manufacturing solutions.

Despite cheaper fiber sources, lighter processing heads, and the first commercial cobot welder, laser-materials processing still lacks a truly plug-and-play collaborative platform that combines (i) the dexterity and sensing-driven path autonomy now routine in conventional welding with (ii) the safety, real-time process control, and compact form factor demanded by SMEs and mobile applications. As a result, users today must choose between manually operated handheld tools or rigid industrial-robot cells, leaving a gap for an intuitive, redeployable cobot systems that can execute multi-mode laser tasks—welding, cutting, marking and cleaning—without specialized programming or extensive safeguarding.

3. Methodology

Based on preliminary analyses and previous practical experiences, several critical challenges have been identified regarding cobot integration in LMP. These challenges include, among others, limitations in pose—position and orientation—accuracy due to reduced cobot stiffness, difficulties in ensuring consistent pose repeatability across tasks, inefficiencies or complexities in path planning and execution, i.e. resulting low path accuracy and, user interface complexity impacting operational usability, the constraints on achieving satisfactory processing feed rates without sacrificing process quality.

3.1 Process Selection

We consider *laser cutting*, *welding, marking*, and *cleaning* highly relevant processes for cobot-based systems in the field of LMP due to their wide range of applications and their suitability for automation with robotic systems. These processes utilize the precision and versatility of lasers to perform tasks that would otherwise be difficult or time-consuming with traditional methods. *Laser welding* and *cutting* are particularly beneficial for their ability to create strong, clean joints or precise cuts in a variety of materials, offering high feed rate, minimal heat input, and reduced material distortion. *Laser marking* provides the advantage of high-quality, permanent marks on a variety of surfaces, making it ideal for industrial labeling and traceability. *Laser cleaning*, on the other hand, offers an efficient, environmentally friendly method for removing contaminants, rust, or old coatings without the need for harsh chemicals or mechanical abrasion.

While all these processes share the use of laser technology, each has different demands and objectives when it comes to robotic integration. For example, laser welding and cutting require both high trajectory tracking precision and accuracy, synchronization between the robot and the laser, whereas laser marking demands fine control over feed rate and power, to achieve clear, durable marks. Additionally, laser cleaning and marking both require system integration with galvanometer scanners, that can either mean stitched processing (static, compare section 3.2, paragraph Laser Cleaning and Marking) or synchronized motion of the scanner mirrors and the cobot. Together, these processes form a versatile and complementary suite of case studies we present that align well with the capabilities of cobots and with the requirements of SMEs, allowing for precision, flexibility, and cost-effective automation in modern manufacturing environments.

3.2 Demonstrator Design

To evaluate the performance of cobot-based LMP, different demonstrators were developed and assessed across different processes.

Robot Platform

The demonstrators are built around a six-axis UR5e collaborative robot from Universal Robots (UR), which has a maximum payload capacity of 5 kg, maximum reach of 850 mm and pose repeatability of ± 0.03 mm. For details on the difference of pose accuracy, pose repeatability and path accuracy we refer the reader to [50]. Custom-designed mountings are used to integrate various processing heads with their laser optics onto the robot's tool flange. The tool center point (TCP) is set to the laser's focal point, and the processing head assemblies including mounts are configured in the robot's control system as an end-effector, with specified mass, inertia and center of gravity. The control system is UR OEM controller running PolyScope 5. The robot is programmed using URScript.

Laser Cutting and Welding

For case studies on laser cutting and welding, the setup utilizes a SPI redPower CW laser with a maximum power of 1 kW at 1080 nm, delivering a beam via fiber optics to a dual process LaserMech FiberMini II processing head (see Fig. 1). Beam waist diameter is approximately 60 µm and the Rayleigh length is 2 mm. Gas hoses are routed to the processing head to provide necessary shielding or assist gas during operation.

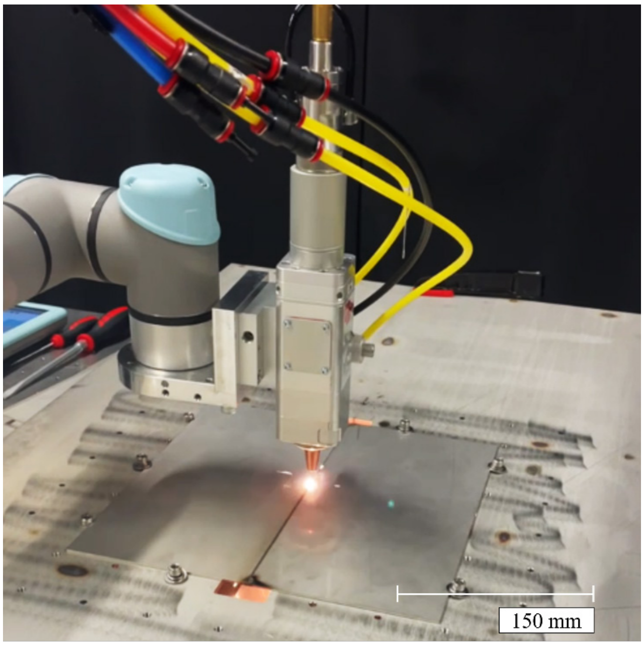

Fig. 1 Universal Robots UR5e with LaserMech FiberMini II during seam butt joint laser welding of AISI 304 (EN 1.4301) stainless steel

Laser cutting and welding are dynamic mode, as no active beam deflection system is employed. Thus, the robot system moves the processing head and thereby the laser focal point along the intended laser-material-interaction path. In these cases, one must differentiate between three types of paths (compare also [50]): the intended path, the command path and the attained path. Fig. 2 visualizes the different types of paths schematically. The intended path (red) represents the geometry of a part to be produced, the command path (green) which represents a computed path the robot can follow given its kinodynamic constraints and that is sent to the robot controller for execution, and an attained path (blue points), which is the path that results from the measurement of motion that occurs when the command path is executed by the controller. These paths are highly dependent on the way the robot is programmed.

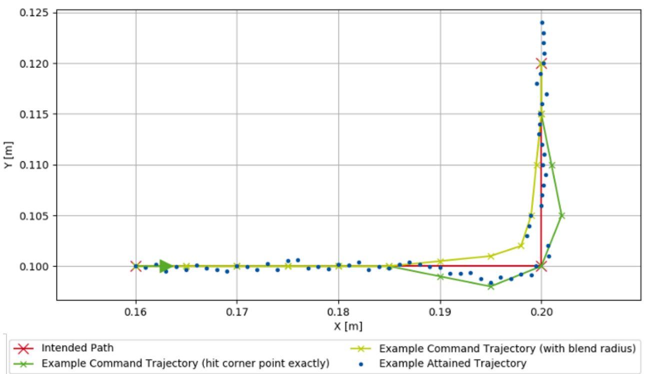

Fig. 2 Visualization of different path types in robot-based laser cutting and welding

Laser Marking and Cleaning

The case studies on laser marking and cleaning utilize a SPI redEnergy G4 nano pulsed fiber laser. This laser has a maximum power of 100 W at 1060 nm and can achieve a maximum pulse repetition frequency of 4000 kHz. The fiber and cables are directed to a Scanlab ScanCube7 galvanometer scanner, which is controlled by the Scanlab RTC6 control card (see Fig. 3 for the demonstrator). The focusing lens (Thorlabs LB1779-A-ML) in the galvanometer scanner has a focal length of 300 mm, the beam waist diameter is approximately 210 µm, and the Rayleigh length is 32 mm.

In the context of laser marking and cleaning with robotic systems and galvanometer scanners, two distinct operational modes can be defined: Static Mode and Dynamic Mode. Static Mode—also referred to as stitched processing—corresponds to processes where the surface area to be cleaned or marked lies entirely within the deflection range of the galvanometer scanner. In this mode, the robot's role is limited to initial positioning, ensuring the scanner is placed correctly before the process begins. Once positioned, the scanner operates independently, and no synchronization with the robot's motion is required.

In contrast, dynamic mode addresses processes where the surface area exceeds the scanner's deflection range. Here, a combined motion of the robot and scanner is necessary to cover the entire target area effectively. This mode requires precise synchronization between the robot's movement and the scanner's deflection, particularly in marking applications where pattern accuracy and process continuity are critical.

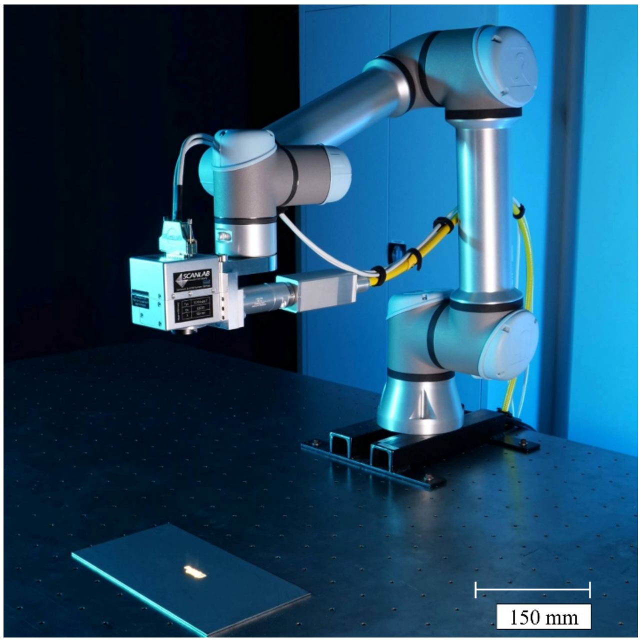

Fig. 3 Universal Robots UR5e with Scanlab ScanCube 7 during laser marking of AISI 304 (EN 1.4301) stainless steel

3.3 Evaluation Framework

To assess the performance of cobot-based LMP, our evaluation framework employs five main criteria: *pose accuracy*, *pose repeatability*, *path planning and accuracy*, *user interaction simplicity* and *processing feed rate*.

Pose accuracy quantifies the robot's ability to position and orient its tool at the absolute command location. *Pose repeatability* complements this measure by evaluating the consistency of the attained poses across multiple cycles.

Path planning and accuracy is evaluated by examining whether the generated trajectories satisfy constraints (e.g. kinematic, dynamic such as velocity and acceleration profiles, but also computational resources) while minimizing deviations between the intended, command and resulting attained paths. This criterion addresses the inherent complexity of generating optimal trajectories for diverse geometries, which is critical for processes such as laser cutting and welding that demand high tracking precision.

User interaction simplicity considers the intuitiveness of the interface provided to operators. Given that these low-cost cobot-based solutions likely target SMEs with limited robotics expertise, assessing the ease of setup, programming, and maintenance is essential for rapid adoption.

Processing feed rate addresses the capability for high throughput applications by evaluating the cartesian speed that is required for processing. Processes such as laser welding are commonly processes with lower processing feed rate than, for example, laser cutting so that they are less demanding.

3.4 Case Studies

To illustrate the capabilities and boundary conditions of cobot-based LMP, we devised and experimentally evaluated four case studies—rectangular sheet-metal cutting, butt-joint welding, 3D CE-logo marking, and localized rust removal—that together span the key processing modes and accuracy challenges faced by SMEs.

Laser Cutting of Rectangular Sheet Metal

To assess cobot-based laser cutting of 2 mm thick sheet metal (stainless steel AISI 304 (EN 1.4301)) the task is to cut out a rectangle of size 49 x 50 mm. The resulting specimen is analyzed using optical microscopy (Keyence VHX 7000) and optical 3D scan based on structured light projection (GOM ATOS Q). This task represents a common use case we expect. Furthermore, corners provide different aspects of interest in robotics: in two of four corners the direction of motion changes sign. Additionally, a corner requires instantaneous stop of motion and start motion, i.e. mathematically an infinitive acceleration and deceleration is required. This is not physically possible for the robotic system. Either a command path must be an exact stop path, where at the corner the cartesian velocity is zero, or a corner must be rounded resulting in path inaccuracy. The case study uses constant feed rate of 3.5 m/min with 1 mm blend radius, i.e. corners are rounded. As a representative process parameter set laser power was 1 kW with 2 mm nozzle standoff distance and on-surface beam diameter of 88 µm. Argon was used as cutting gas at 10 bar based on previous studies for continuous cutting of 2 mm AISI 304. Additionally, non-process motion experiments were conducted at 1 m/min and 7 m/min cartesian speed measuring TCP position using 3D coordinate measurements from Leica AT 930 laser absolute tracker.

Laser Welding of a Butt Joint

To assess cobot-based laser welding, a seam butt joint laser welding of two pieces of sheet metal (stainless steel AISI 304 (EN 1.4301)) is performed. The processing head is positioned in a way that a 200 µm beam diameter results on surface. This case study represents one expected use case for cobot-based laser welding. Additionally, welding a butt joint requires high positioning accuracy and path accuracy. To ensure correct positioning at the beginning and end of the weld, the robot is positioned using the teach panel, to achieve sub millimeter positioning accuracy (± 0.1 mm). Motion between these points is programmed to be executed with constant cartesian velocity and linear cartesian interpolation. Thus, this case study does not put focus on the simplicity of user interaction. The weld is analyzed in accordance to [51] to assess the quality of cobot-based laser welding results. Process parameters were scaled from Walther et al. 2022 [52], who report butt welding of 1 mm AISI 304 at 4.98 m/min and 1 kW; assuming approximately constant linear energy input, we therefore used a feed rate of 2.54 m/min at 1 kW with a 200 µm on-surface beam diameter and argon shielding gas at 1 bar as a representative parameter set.

Laser Marking of Logos on 3D Surface

To evaluate static cobot-based laser marking, a CE logo is marked on a coated 3D surface as an illustrative example. The chosen 3D surface is a semi-spherical shape. The system is positioned by hand teaching to investigate the current state of user interaction simplicity. The scanner provided visual guidance for the user by showing the marking object using a pilot laser. Subsequently, the marking process is initiated with pre-defined parameters. Scan vectors are calculated using ScanLab LaserDesk software, where the user only provides a vector image in an appropriate format. Dynamic cobot-based marking is not part of the case studies. A marking speed of 1 m/s was used at an average laser power of 75 W. Pulse repetition rate was 100 kHz with a pulse duration at 10% of 261 ns. Parameter studies on nanosecond fiber-laser marking of metallic surfaces report that average powers between 60 and 100 W, repetition rates around 100 kHz, and pulse durations in the hundreds of nanoseconds yield stable marking performance with limited thermal side effects [53,54]. Although the current application involves a coated metallic surface, these studies define a relevant process window for nanosecond laser–material interaction. The chosen parameters were selected to remain within this known range and were subsequently visually adjusted to achieve complete coating removal and sufficient marking contrast without visible substrate damage.

Laser Cleaning of Patch Oxidized Sheet Metal

To assess static cobot-based laser cleaning, a partially oxidized piece of sheet metal is used as an illustrative example. The current status of simplicity of user interaction is the focus of the investigation. A camera (Allied Vision Mako G040 B POE) and the galvanometer scanner are both mounted to the robot flange, allowing detection of oxidized areas within the working area. The scanner provided visual guidance for the user within the camera's field of view using a pilot laser. The camera captures an image, which is then processed to calculate scan vectors for rust removal. The image processing involves creating a binary mask of the oxidized areas using thresholding, followed by morphological operations to clean the mask. Connected components are identified. Lines are generated within these components. Their coordinates are transformed into scanner coordinates and subsequently, after determining appropriate scan vectors for rust removal, the laser cleaning process is performed. The marking speed used was 2.404 m/s at an average laser power of 100 W. An ellipse-shaped wobble movement was added with an amplitude of 1 mm and 6000 Hz. A pulse repetition rate of 100 kHz and a pulse duration at 10% of 261 ns was set. Experimental studies on nanosecond laser cleaning of oxidized metals report effective oxide removal for fluences between 3 and 6 J/cm² and high pulse overlap, enabling efficient cleaning without substrate damage [55,56]. While these references address similar but not identical materials, they provide a valid process framework for nanosecond laser cleaning. The selected parameters in this study were chosen to remain within this literature-defined range and were then empirically refined through visual evaluation to ensure reliable oxide removal. Dynamic cobot-based cleaning is not part of the case studies.

4. Results

In the following subsections, major qualitative observations for each case study are presented.

4.1 Laser Cutting

The influence of path accuracy on the quality of laser-cut parts was examined (compare Fig. 4). Deviations between the actual and target contour were primarily observed at sharp corners, with maximum deviations reaching up to 0.89 mm at the first 90° corner, where the robot reverses its direction of motion, and this deviation decays gradually along the subsequent straight edge. Along linear segments, deviations remained significantly lower, typically ±0.1 mm. The overshoot at corner points was clearly reflected in the contour, indicating a strong influence of dynamic path deviations on the resulting part geometry.

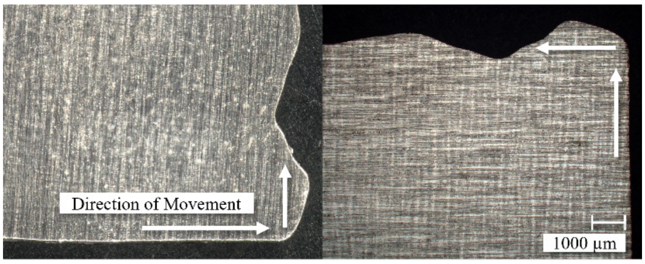

Fig. 4 AISI 304 (EN 1.4301) stainless steel rectangle laser cut from sheet metal using our cutting and welding demonstrator. The direction of movement of the cobot used for handling of the processing head is indicated with white arrows. Oscillation of up to 0.89 mm amplitude are observable after change of direction.

Internal robot state data reveals that this oscillation is not correctly measured by axis position encoders. Fig. 5 provides a visual comparison highlighting the mismatch between the internal robot state data and the reference measurements at 7 m/min.

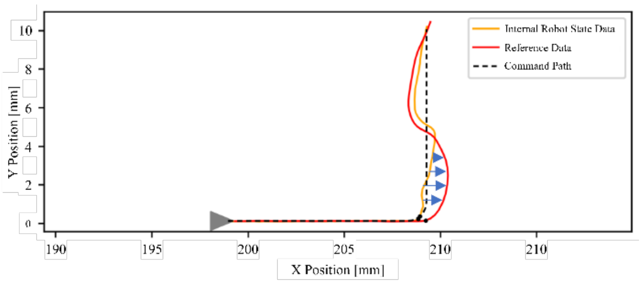

Fig. 5 Top-down (XY) view of the robot path at 7 m/min. The robot's internal state data are shown in orange, the reference data are shown in red, and the commanded path is shown as a black dashed line. Blue arrows indicate the deviation between the internal state and the reference data.

4.2 Laser Welding

The influence of path accuracy and robot motion characteristics on the quality of laser welds was examined. Experiments produced both acceptable (compare Fig. 6 a, displaying an etched cross-section of a weld with no defects according to visual inspection) and non-acceptable welds. Visual inspection in accordance with [51] found defects of types 402 (incomplete penetration), 504 (excessive penetration), 511 (incompletely filled grove), 515 (root concavity) and 5011 (continuous undercut, compare Fig. 6 c), as defined in [57]. Additionally, etched cross-sections of welds showed defect type 2011 (pores) where defects were observed in visual inspection (compare Fig. 6 b). Defects were mostly found at the beginning and end of a weld.

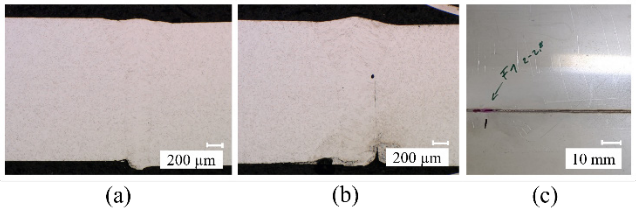

Fig. 6 Butt seam laser welding process results. (a) shows the etched cross-section where no defect was found in visual inspection of an acceptable welding result. (b) shows the etched cross-section of a non-acceptable welding result, with pore (type 2011 according to [57]) visible within the weld cross-section. (c) shows a detail of a welding result; incompletely filled grove (type 5011 according to [57]), as defined by visual inspection, is visible at the beginning of the weld seam.

4.3 Laser Marking and Cleaning

The results of the static cobot-based laser marking and cleaning experiments were analyzed with a focus on user interaction simplicity. Both the semi-automated laser marking and laser cleaning processes demonstrated a high level of usability for operators, facilitating straightforward and rapid programming and setup. Visual guidance using a pilot laser simplified positioning for operators; however, orientation and focal length adjustments required careful consideration and needs prior process knowledge.

The marking process yielded precise and consistent engravings of the CE logo on the coated 3D surface, demonstrating the system's capability to achieve markings even on complex geometries (see Fig. 7). Although the variations in the 3D surface affected laser focal length changes, the process still resulted in acceptable marking quality.

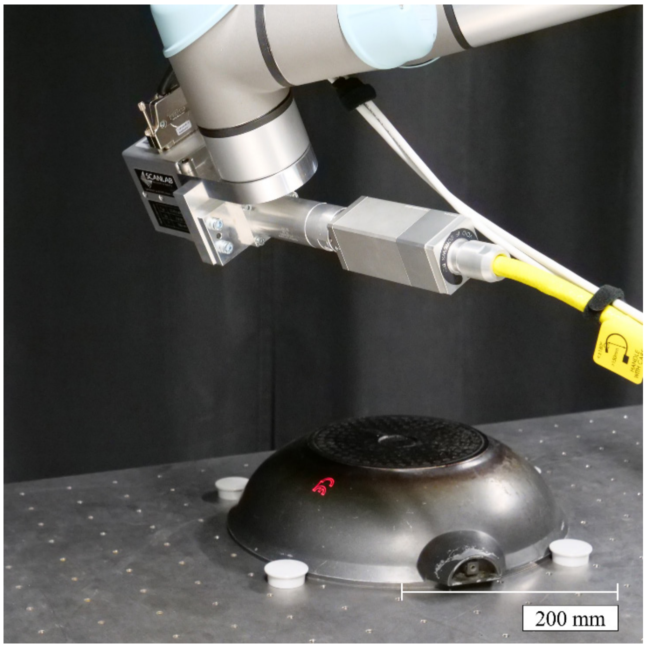

Fig. 7 Laser marking of a CE logo on a coated semi-spherical 3D surface using a static cobot-based system. The system is manually positioned.

The cleaning process yielded satisfactory results for applications such as preparing surfaces for welding, ensuring optimal conditions prior to subsequent manufacturing steps. Effective rust removal not only enhances adhesion during welding but also contributes to improved overall quality in final products. The analysis was conducted primarily through visual assessment of images captured during the cleaning process, as illustrated in Fig. 8. This visual evaluation allowed for an effective determination of cleaning quality and uniformity across treated surfaces.

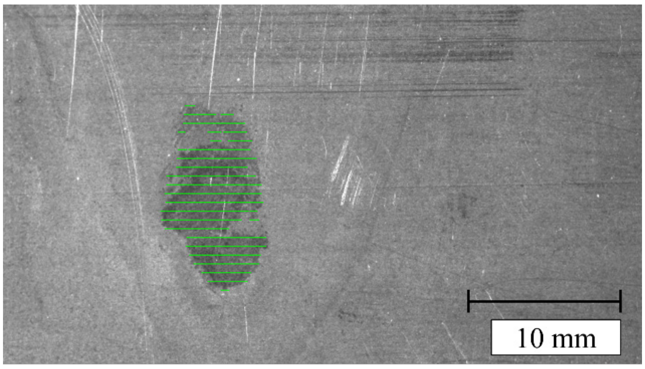

Fig. 8 Camera based detected oxidized parts of metal sheet with calculated scan vectors for laser cleaning vectors marked in green. An ellipse-shaped wobble movement is added by Scanlab RTC6 control card.

5. Discussion

While LMP holds immense potential for increasing productivity and reducing labor-intensive tasks, the integration of low-cost cobots into these processes presents unique hurdles. This section outlines the main challenges facing small and medium-sized enterprises (SMEs) when automating LMP with collaborative robotics.

5.1 Discussion by Case Study

The case studies presented in section 4 highlight both the capabilities and limitations of low-cost cobots in LMP. In the following, key observations for each process—laser cutting, welding, marking, and cleaning—are discussed in detail, with a focus on the critical challenges identified.

Laser Cutting

In the context of laser cutting, a major holdback for path planning arises from the challenge of maintaining consistent motion dynamics at abrupt changes in direction. The case study revealed that maintaining constant cartesian velocity at positions of direction change, particularly at sharp corners, is problematic. The limited dynamic performance of the cobot prevents instantaneous changes in motion direction without introducing oscillations, leading to deviations in the resulting part geometry. Overall, these findings emphasize the need for integrated path and process planning advancements to enable high-quality laser cutting with low-cost collaborative robots.

Laser Welding

In the context of laser welding, a major holdback for user simplicity is the insufficient coupling between path and process planning, which increases setup complexity and contributes to welding defects. This lack of integration was reflected in the occurrence of welding defects, particularly at regions associated with acceleration and deceleration phases, as illustrated in Fig. 6 (c). Laser welding remains a highly promising application for cobot-based systems, especially given the availability of commercial solutions [58], that emphasize user interaction simplicity through preset libraries. These libraries link material type and thickness to recommended process parameter settings, substantially reducing the setup complexity for non-expert operators. However, despite these advances, further improvements in user interface design are necessary to enhance system intuitiveness and to broaden accessibility for SMEs.

Laser Marking

In the context of laser marking, a major holdback for user simplicity lies in the limitations of current user interfaces, which complicate tasks such as focal adjustment, image import, and alignment—despite the system's generally intuitive operation and basic automation capabilities, as highlighted in the case study. Specifically, the orientation and positioning of the Z-height, and consequently the correct focal length, were found to be challenging for operators.

The case study demonstrated effective marking of CE logos and similar designs; however, it underscored the importance of ensuring proper rotational alignment during marking tasks.

Overall, these findings emphasize the necessity for ongoing development in user interface design and automated processes to optimize laser marking capabilities with collaborative robots.

Laser Cleaning

In the context of laser cleaning, a major holdback for user simplicity remains, although the system is closer to practical use compared to other processes. The case study showed that a 'human-in-the-loop' approach improves cleaning effectiveness by allowing users to make real-time adjustments based on surface condition and cleaning results. For example, if insufficient material was removed, operators initiated additional cleaning passes; excessive removal (visual inspection) was not observed to be detrimental in out setup but required monitoring.

5.2 Discussion by Category

Pose Accuracy and Repeatability

Across our case studies, accuracy and repeatability constrain outcomes primarily when the robot moves the focal point (cutting, welding), whereas scanner-executed tasks (marking, cleaning, static mode) largely decouple end-result precision from the cobot's absolute placement. In cutting, straight segments stayed close to target (typically ±0.1 mm), but direction changes produced repeatable overshoot/oscillation up to 0.89 mm, which dominated the geometric error budget at corners. Internal encoders under-reported these transients compared with the laser-tracker reference at 7 m/min, indicating that dynamic error is not fully observable from axis states alone. In welding, sub-millimeter positioning at start/stop was sufficient for acceptable seams; observed defects clustered at the beginning/end of the trajectory, pointing to local motion transients rather than broad drift across repeats. For marking and cleaning in static mode, the robot provided coarse placement while scanner precision and vision targeting determined final accuracy and consistency; pilot-laser visualization and camera-derived masks were decisive, and the operation was typically single-pass per part, reducing the practical importance of cycle-to-cycle repeatability on the arm.

Overall, the impact of pose accuracy and repeatability is process-dependent: critical for reliable initiation and dynamic segments in cutting and welding, and secondary for scanner-based static tasks where calibration and image-to-scan mapping dominate.

Path Planning and Accuracy

Geometry fidelity hinged on how the commanded trajectory and the robot's dynamics shaped the attained path. The intended–command–attained path triad clarifies this: the intended part geometry is converted to a command path that respects kinodynamic limits, yet the attained path can diverge around high curvature and transients. In cutting, fidelity was high on straights but degraded at corners when constant Cartesian speed was enforced; the corner overshoot visible on parts and in motion traces reflects limited dynamic authority at abrupt direction changes. In welding, linear interpolation at constant speed between accurately taught points produced acceptable seams, while quality loss aligned with acceleration and deceleration phases rather than with steady-state tracking on the straight. In static marking and cleaning, robot path planning was largely irrelevant; accuracy was governed by vector generation in the scanner software and the image-processing pipeline (masking, morphology, component extraction, coordinate transforms), which determined where and how energy was deposited.

Taken together, dynamic, robot-moved processes are constrained by curvature handling and transient response, while static scanner tasks are constrained by vector-generation quality and registration.

User Interaction Simplicity

The operator burden tracked the degree of motion/process coupling, but across all processes the dominant effort was laser process setup rather than robot motion programming—moving and teaching the robot were generally straightforward. Independent of process, operators had to establish focal position and orientation, select and verify process parameters (e.g., power, speed, wobble frequency), and check energy delivery on the workpiece.

For cutting, expert decisions with direct geometric consequences—e.g., choosing exact-stop vs. blended corners and aligning frames—coincided with parameter tuning that affected cut quality, despite otherwise straightforward workflows. Welding teaching was intuitive, but process-parameter selection (and balancing motion profiles with process stability) still relied on expertise. In marking and cleaning (static mode), robot programming was simplest (coarse positioning, pilot-laser visualization, and automatic vector generation from images), yet practical effort still concentrated on focus and orientation, confirming that chosen parameters produced the desired surface outcome, with more emphasis on basic camera usage than on robot programming.

Overall, interaction complexity was common to all processes because of laser process setup; differences between processes mainly reflected how strongly trajectory choices influenced quality—highest in cutting, moderate in welding—and how much the scanner and vision stack front-loads targeting in marking and cleaning.

Processing Feed Rate

Throughput interacted with quality via the robot's dynamic response for robot-moved processes but was chiefly a scanner setting for static tasks. In robot-moved processes such as cutting, maintaining constant speed through sharp corners triggered oscillations that grew with speed; non-process motion tests at 1 m/min and 7 m/min and cutting at 3.5 m/min illustrate how higher velocities amplify path instability at curvature. In welding, defects correlated with acceleration and deceleration phases rather than with the nominal steady-state feed, underlining sensitivity to local speed transients. By contrast, marking at ~1 m/s and cleaning at ~2.404 m/s (with wobble) were adequate for the demonstrated tasks; here, throughput was determined by changeover time, not by robot or scanner speed.

Consequently, usable feed rate is limited by curvature and transient handling for cutting and welding, and by scanner vectoring and stitching for marking and cleaning.

5.3 Key Barriers to Adoption and Complementary Organizational, Safety and Digitalization Aspects

Arising from our case studies, Table 1 summarizes our findings, consolidating the key points from the analysis and discussion presented above. A full circle indicates the most critical remaining challenge for the process; an empty circle indicates that the criterion is not considered a barrier to adoption. Note that columns do not sum to one circle, as multiple criteria may simultaneously require further research. We believe that the main areas for future research are on the criteria *path planning and accuracy* as well as *user interaction simplicity*.

Table 1 Importance of improvement across criteria for each laser process. *Pose Acc.* = pose accuracy and repeatability, *Path Plan.* = path planning and accuracy, *User Simp.* = user interaction simplicity, *Speed* = processing feed rate.

	Pose Acc.	Path Plan.	User Simp.	Speed
Laser Cutting	◑	●	◑	◑
Laser Welding	◑	◕	●	◔
Laser Marking	◑	◑	●	◔
Laser Cleaning	◔	◔	◕	◔

Beyond the technical challenges already analyzed, several complementary aspects deserve consideration to facilitate adoption of cobot-assisted LMP.

First, workforce upskilling and reskilling remains pivotal: empirical data on the time required to retrain a conventional shop-floor welder to a hybrid "laser-robot technician" role are still scarce, although such dual competences will be indispensable for SMEs.

Second, change-management in brown-field production environments must be planned so that mobile or table-top cobot cells can be integrated without disturbing ongoing production.

Third, the coexistence of collaborative manipulators with class-4 laser sources demands a harmonized safety framework; the current overlap between safety aspects of collaborative robots 59–61] and laser safety [62,63] leaves certification pathways ambiguous, and comprehensive risk-reduction chains—from guarding and feed rate-monitoring to fail-safe shutters—are missing.

6. Future Research Direction

Building on the case-study evidence, we outline a focused research agenda organized by the four evaluation criteria. The following items translate observed limitations into proposals and design targets for cobot-assisted LMP in SME contexts, where effort is most likely to yield impact.

6.1 Pose Accuracy & Repeatability

Future work should improve how we observe and control the TCP in dynamic segments. First, increase observability of transient TCP error beyond joint encoders—either by integrating external metrology (e.g., vision or laser tracker) or by adding model-based observers—so that curvature-induced deviations become measurable during execution. Second, identify and parameterize compliance and vibration modes in the arm–tool–work chain and apply targeted feedforward and filters to attenuate repeatable oscillations at direction changes. In static scanner tasks, the priority shifts to robust hand–eye and scanner extrinsic calibration; quantify how drift in these transforms maps to mark and clean error on 3D surfaces, and develop a consolidated one-click auto-calibration routine (TCP, scanner extrinsic, focal check, safety interlocks) to bound pose error before execution. Beyond initial setup, investigate online hand–eye and workspace re-registration (e.g., RGB-D cameras) to maintain TCP accuracy for slightly different setups. Finally, define process-aware acceptance bands (e.g., tighter tolerances at weld initiation and termination than in steady runs) so that compensation efforts focus where they most affect quality.

6.2 Path Planning & Accuracy

The planning stack should explicitly account for curvature and the intended→command→attained gap. We propose curvature-aware, jerk-limited time-parameterization that predicts slow-downs through tight corners (rather than enforcing constant Cartesian speed), combined with corner pre-shaping and model-based feedforward to minimize overshoot. Where geometry or quality demands it, insert planned acceleration / deceleration segments with time-varying laser power to traverse transients cleanly. To give the planner more options at corners, expose additional process DOF (e.g., rotation about the optical axis, small surface-normal tilts) and solve redundancy resolution jointly with motion limits. During setup and teaching, evaluate Augmented Reality (AR) overlays that visualize intended/commanded paths and keep-out zones to reduce setup errors that propagate into geometric deviation. Across all processes, couple motion to process parameters so that power/energy per unit length remains consistent as the trajectory slows or blends.

For scanner-executed tasks, accuracy is governed by vector generation and registration rather than robot paths; future work should benchmark mask creation, morphology and fill strategies, and 2D→3D registration on curved parts, and treat vector quality as a first-class planning objective. Study human-augmented autonomy in which an operator demonstration seeds a planning model that generalizes and refines trajectories across similar parts, bridging planning and user interaction.

6.3 User Interaction Simplicity

To reduce expert dependence—especially in SMEs—we prioritize guided setup tools that define the workpiece coordinate system and reference point (datum), with live previews of how choices (exact stop vs. blend radius, frame alignment) alter the command path, supported by template libraries for common patterns (e.g., corners with validated blends; start/stop with tuned ramps) and context-aware GUIs that surface only the parameters relevant to the current task. These flows should be strengthened by automatic material and thickness validation to pre-select safe, process-consistent parameter sets, and by a one-click calibration workflow (TCP, focus, interlocks) that bounds setup effort before execution.

For marking and cleaning, vision-assisted setup remains central: pilot-laser overlays and cameras (or distance sensors) that auto-suggest focus and orientation, native image import with one-click alignment and registration to the part, and AR guidance to visualize intended or commanded paths and keep-out zones before execution. To further lower operator effort in these static scanner tasks, we propose "press-start" workflows in which the system automatically detects components and generates vectors for cleaning and marking with minimal input. Building on this, enable an autonomous multi-part workflow: after the operator configures the mark once on a reference part (e.g., positions the CE logo), the system processes that part and then executes an exploration pass (e.g., outward spiral) to detect, register, and mark the remaining identical parts in the workspace fully autonomously.

On the workflow side, teach-and-repeat can streamline operation by letting an operator demonstrate once while the system refines timing and parameters with curvature-aware profiles. Extending this idea, human-augmented autonomy (demonstrate→repeat) should be assessed as a UX pattern that abstracts operator skill into reusable task templates and bridges to planning generalization across similar parts.

As enabling conditions, we assume a two-step safety mode (collaborative setup, then autonomous laser operation in a safeguarded cell) and modular plug-and-produce cells suitable for brown-field sites. Finally, deployment and digitalization choices should be made explicit: edge- vs. cloud-based execution for perception and control (latency, cost, maintainability in SME settings), basic connectivity (OPC UA/MQTT/DDS) for traceability and supervision, and the cybersecurity implications of that connectivity as part of the practical usability envelope.

6.4 Processing Feed Rate

Feed rate should be treated as a coupled motion-and-process variable. In robot-moved processes, employ predictive corner slow-downs with synchronized power modulation to stabilize local fluence, and design transient-aware ramps at start/stop to reduce defect clustering without sacrificing throughput. For large areas, extend to dynamic robot-scanner mode and study scheduling between robot motion and scan deflection to preserve pattern fidelity while maximizing effective feed rate. Across processes, add affordable inline sensing (coaxial cameras, reflectance/height cues) and lightweight AI predictors to flag emerging defects and trigger closed-loop adjustments (power/feed rate or re-clean passes) when targets are not met.

7. Limitation

The study's generalizability is constrained by its reliance on a single UR5e cobot and controller generation, because different low-cost arms with other joint compliances, control bandwidths or firmware implementations could yield divergent accuracy and user-interaction outcomes. Moreover, the evaluation was restricted to planar laser welding and cutting, excluding complex three-dimensional operations such as tubular cutting or saddle-joint welding, and it addressed only static modes of laser marking and cleaning, leaving the behavior of scanner-synchronized, dynamic processing unexamined. Finally, the work is qualitative, drawing on illustrative case studies rather than statistically robust datasets, which limits the strength of performance extrapolations and cross-platform comparisons. The study does not report process-parameter sweeps, optimization ranges, or head-to-head comparisons of planning and compensation methods. Reported examples are representative demonstrations only. As such, the paper establishes the system's current readiness and integration pathway, not a performance benchmark.

8. Conclusion

This paper presents and evaluates multiple case studies—laser cutting, welding, marking, and cleaning—that leverage the benefits of low-cost collaborative robots for LMP. While each process reveals specific challenges—particularly regarding path accuracy, user interaction simplicity—the experiments demonstrate that cobots are indeed a flexible platform capable of handling diverse tasks in small series or custom-manufacturing settings.

However, cobot-based LMP is not always the best fit. Its suitability depends heavily on the specific application, the geometry of the part, and the nature of the process. The choice of kinematic concept must be guided by these factors.

In contrast, cobots show particular potential in environments characterized by mixed production and small batch sizes, where process and geometry flexibility are critical. In such cases, their ease of use, reconfigurability, and compactness can offer real advantages over conventional systems. Laser cleaning, for instance, can be relatively easy to automate with cobots, but its true value for SMEs depends more on how well the system is tailored to their specific use case than on the complexity of integrating the process itself. Not every SME will benefit equally, and in many cases, the effort required to adapt the system to individual workflows outweighs the simplicity of the robotic integration.

Nonetheless, several technical and organizational limitations remain. The dynamic inaccuracies observed, especially during rapid path changes or corner movements, highlight the influence of path-planning constraints on outcome quality. Moreover, user interaction interfaces were a recurring challenge, especially for SMEs with limited in-house robotics expertise. Finally, standardized safety architectures for combining cobots and laser equipment are missing for future pathways.

Overall, the findings suggest that cobot-assisted LMP holds considerable promise for SMEs, particularly those in high-wage regions seeking to automate repetitive or hazardous tasks with a cost-effective and versatile platform. By addressing the challenges in path accuracy, user interfaces, and integrated safety measures, cobot-based solutions for laser cutting, welding, marking, and cleaning can significantly expand their impact on modern manufacturing workflows.

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