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Integrated Robot Motion and Process control for manufacturing reshaping

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***Abstract*—The future of metal manufacturing processes like laser cutting, welding, and additive manufacturing shall rely on intelligent systems spearheaded by Industry 4.0. Such a digital innovation is indeed driving machinery builders to a profound transformation. From custom machines designed and optimized for a specific process, the ambition is to exploit the openness and the large availability of industrial robots to increase flexibility and reconfigurability of multi processes implementations. The challenge is that machinery builders transform themselves into high-knowledge specialized process-driven robot integrators, able to optimize the robot motion with the process controller leveraging on intelligent sensing and cognition. The work describes the multi-annual collaboration of the BLM group and Politecnico di Milano, with the support of CNR, focused on the deployment of a complete working robotic workstation characterized by the full integration of the robot control and motion planning with manufacturing processes.**

***Index Terms*—Directed energy deposition, Laser Metal Deposition, Design for additive manufacturing, CAD/CAM**

I. Context

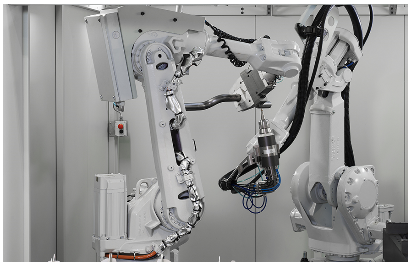
During the last decade, an enormous leap in development has happened in laser material processing. New and further developments in compact systems, sensorization, engineering, laser beam sources, and lighter and smaller laser tool heads have enlarged the field of laser material processing and brought along the possibility of using robots for laser processes. The adoption of robots displays many benefits in terms of workspace flexibility and reconfigurability compared to dedicated machine tools. Robots have workspaces easily extendable during the configuration and set-up process by adding auxiliary axes or mobile platforms. This also increases the reachability and so more complex parts can be machined. Regarding process flexibility and reconfigurability, robotized cells are easily customizable for various machining processes by changing the end-effectors or tools attached to the manipulator. Robots can also be integrated with other robots - even for handling purposes - or machine tools, creating more complex and evolving work cells. Furthermore, robots reduce the installation costs dramatically compared to 5-axes machines. This reduction is mandatory for many companies to allow them to move from traditional technologies to laser operations. Wearing the robot with a laser tool head, however, shows such machines' limits. The requirements of laser processes are, indeed, remarkable. First, they need both high static and dynamic accuracy. Second, the pathways must be carefully optimized to ensure dynamic accuracy, dexterity, and reachability. They are often very complex and generated by commercial CAM tools. Third cell configuration is challenging since the robotic systems may be composed of different robots plus external axes or even dedicated machines. Fourth, the sensors used for tracking and online processes and trajectory adjustments are often generators of a large amount of data (e.g., cameras) at high frequency. Fifth, the synchronization of the robot motion and the process control is demanding (e.g., power ramp and speed ramp synchronization). As an example, optimization needs an integrated controller for process and robot motion. Furthermore, industries are experts in the process but often do not have robotic competencies. Vice versa, process competencies are not always available for robot integrators. In such a context, the BLM group invested in collaboration with academia to tackle the challenges related to three different processes: 3D laser cutting, laser welding, and additive manufacturing with laser metal deposition (LMD). In each different project, the R&D division of the BLM group jointly worked with the expert in laser processes of the SITEC Laboratory of Politecnico di Milano. In addition, CNR-STIIMA supported BLM and Politecnico di Milano in the development of the robotic cell for laser cutting, and the LMD cell using a powder deposition head. For each of the three processes mentioned above, the paper describes some of the results shortly: (i) BLM is on the market with LT360, a flexible, dual-arm, robotic cell for laser cutting. (ii) a prototype for laser welding is in the beta version; (iii) two Robotic Additive Manufacturing prototypes are fully working at the SITEC Lab (One cell with a powder deposition head, a second cell with a wire deposition head).

II. BLM's reshaping of laser process through robots

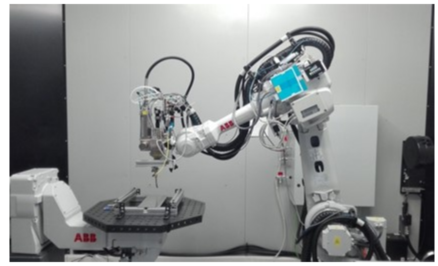
The BLM's reshaping of laser processes passes through the concept of fully integrating the robot platform with the process instead of developing a dedicated machine.

A. Reshaping the Robotized Laser Cutting

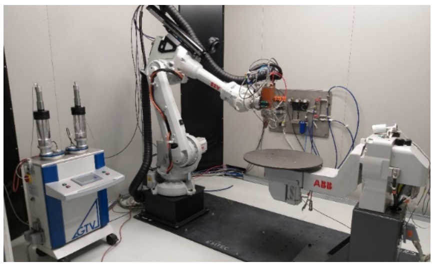
The first cell described here is the LT360, a flexible robotic 3D laser cutting system offered by BLM GROUP. This com-



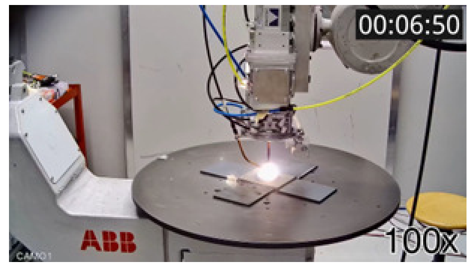
(a) BLM LT360 - Laser Cutting.



(b) Robotized Laser Cutting LW R&D Prototype at SITEC Lab of the Politecnico di Milano.



(c) Robotized Direct metal Deposition Additive Cell at SITEC Lab the Politecnico di Milano.



(d) Robotized Wire Additive Cell at SITEC Lab the Politecnico di Milano.

Fig. 1: The four robotic cells developed by BLM. (a,b,c,d) have been developed in collaboration with Politecnico di Milano. (a,c) have been developed in collaboration with CNR.

mercial robotic system is re-engineered product of an output of an R&D project, co-funded by Regione Lombardia and developed at SITEC Lab, supported by CNR. Laser cutting is the more flexible and effective way to cut 3D components, making cutting even tiny batches of parts possible. The cell is characterized by a dual-arm design to optimize flexibility. The cutting robot (ABB IRB 2400/16) can be completed with a handling robot (ABB IRB 2600/20) to quickly process 3D complex components such as bent pipes or hydroformed components. The LT360 provides the "BLM GROUP laser technology": the laser source (IPG or nLight up to 3 kW, 50μm) is connected to a cutting head with a local axis and a Precitec capacitive sensor, and the LT360 offers advanced laser options as Active Focus, Active Piercing, and Active Speed. The HMI and the CAM benefit from decades of experience in laser cutting, enabling the LT360 the cutting complex 3D components and manage small batches and frequent changeover.

B. *Maximizing the adaptability of Robotized Laser Welding*

Laser welding provides several advantages compared to conventional arc-based welding processes such as MIG/MAG or TIG welding. The highly focused energy source allows high levels of power can be focused on a small laser beam (100-500μm) and employed flexibly in different configurations such as butt-, lap-, and edge joints. However, the use of the small beam sizes renders the process prone to defects in the presence of gap formation. To maximize the adaptability of the process toward 3D parts with non-stringent dimensional tolerances concerning joint fitting, BLM Group, jointly with SITEC, has developed the LW R&D Alpha Prototype.

The cell is a flexible robotic laser welding cell, provided by a 6kW active fiber laser (IPG YLS 6000 CT) coupled with a wobbling head (IPG D50 Wobble). The system can operate with a lateral cold wire unit (Abicor Binzel MFS v3.1). The laser source can be configured with different processing fibers according to the application's needs[1]. The wobbling head allows for oscillating the beam in programmed forms (e.g., circular, linear, infinity, 8-shape). It can be employed to execute pre-programmed scan trajectories. The processing head is manipulated with a 6-axis anthropomorphic robot (ABB IRB 4600/45 2.05) and a two-axis tiling rotating table (ABB IRBP A-250) able to fit flexibly medium to large-sized components used in automotive, aerospace, energy, e-mobility sectors as well as consumer products. The system operates with several material types such as stainless steels, high strength steels, Al-, Ni-, and Cu-alloys in autogenous welding or using a filler wire.

C. *Laser Metal Deposition Additive Manufacturing*

On the one hand, similarly to the previous cell, the most critical target for the cell is flexibility. On the other hand, laser metal deposition requires several sensors eventually integrated with the robot motion control. Furthermore, the prototype hosted at the SITEC Lab can be equipped with two different deposition heads: i) a deposition head (Kuka Industries MWO-I-Powder) for the deposition of metallic powders, ii) a coaxial wire deposition head (CoaxPrinter, Precitec) for the deposition of metallic wires. Both deposition heads can be mounted on

[1]Employing 100μm processing fiber together with the 200mm collimating and 300mm focusing units, the waist beam diameter is 150μm.

a 6-axis anthropomorphic robot (ABB IRB 4600-45). The flexibility of the cell is increased by 2 degrees of freedom positioner (ABB IRBP A-250). A 3 kW fiber laser source (IPG Photonics YLS 3000) with 1070 nm emission wavelength is adopted. The system is equipped with a 50 μm feeding fiber coupled with a fiber-to-fiber coupler with a 400 μm processing fiber to guarantee the beam delivery up to the deposition heads. The MWO-I-Powder permits different working conditions in terms of beam spot dimension. [2] The powder feeding system is a GTV TWIN PF 2/2-MF. Argon serves as a carrier and process shielding gas. Different metallic powders can be printed: steels, nickel-based super-alloys, cobalt-based alloys, copper alloys, titanium alloys, and aluminum alloys. Multi-material and functionally graded parts fabrication are possible.

A multi-sensor coaxial monitoring system is implemented in the MWO-I-Powder. The monitoring system comprises a two-color pyrometer (Dr. Mergenthaler Lascon LPC04), a coaxial CMOS camera in the near-infrared (NIR), and a triangulation system composed of a CMOS camera and an external green diode laser. The sensors permit the monitoring of melting pool temperature and geometry and the deposition height measurement through the triangulator. The CoaxPrinter from Precitec exploits beam shaping capabilities to insert the wire feedstock provided via an industrial wire feeding system (Abicor Binzel, [1]). The CoaxPrinter is equipped with an axicon lens to change the original Gaussian distribution of the incoming beam into a ring shape. Different metallic wires can be printed: steels, nickel-based super-alloys, titanium alloys, and aluminum alloys.

III. Challenges and Performances for Laser Robotized Processes

Remarkably, all three cells need auxiliary axes or even a second robot to perform the tasks properly. Improving the static machining accuracy of such robotic systems is a difficult task, even more, due to the closeness of the off-the-shelves industrial robots. Although geometrical errors do not affect the repeatability of a robot manipulator, as these kinematic parameters are used in robot controllers to generate reference trajectories and control the poses (position and orientation) of the robot end-effector in Cartesian space, discrepancies lead to deterioration in the path accuracy of the robot manipulators. These effects are essential in robotized processes, especially when the path is complex and requires many detachments, reorientations, and re-approaches. Therefore, the calibration of the cells has followed the most advanced procedures, using external dimes. Furthermore, large datasets have been gathered to identify the best calibration data set.

The robotic application needs integrated planning for the robot and the process. Indeed, this allows maintaining the robot far from a low-dexterity issue and, at the same time, provides an understanding of where and when to disconnect the path to enable the necessary robot reorientation as needed. Furthermore, particular attention must be devoted to integrating the robot cell models and motion planning strategies inside commercial tools, allowing the designer to interface straightforwardly with the robot as used with CNCs.

These requirements lead to two main actions: first, trying to exploit the redundancy of such robotic systems opens the possibility to optimize the motion; second, modeling the robot behavior to integrate it into the motion plan definition.

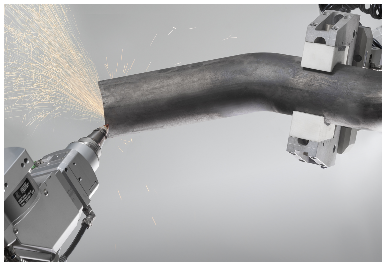
About the former, the exploitation of the redundancy is connected to optimizing the placement of the work-piece position. In most industrial cases, the human operators solve the redundancy by leveraging their own experience; even a feasible solution takes a considerable amount of trial to be found. Indeed, optimizing a generic performance index along a path is complex due to the dimension of the feasible-configuration space. In [6], it has been investigated the use of an iterative layered optimization method that integrates a Whale Optimization and an Ant Colony Optimization algorithm to achieve a quasi-optimal, collision-free solution in the feasible-configuration space.

About the latter, the robot's behavior changes according to the geometry and user settings. For example, the robot velocity cannot be considered constant along sharp vertex despite the wishes of the robot programmer. Dynamic scaling of the velocity and path modification are encoded in the motion planner because the robot control is designed to reduce dynamic tracking errors, differently from CNC machines. In such a case, the solution consists of modeling the robot and identifying the best motion plans minimizing the difference between the expected and actual behavior.

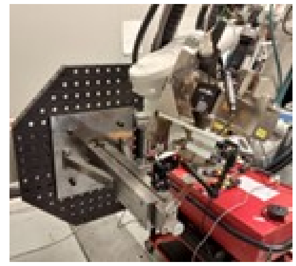
Considering the LT360, on the one hand, using a dual-arm solution make the LT360 a flexible solution with fast commissioning. Furthermore, the customer can easily configure it with different combinations of standard modules. On the other hand, the definition of the motion plan according to the relative poses and the robot models becomes fundamental. Furthermore, the motion plan must be optimized together with the laser process model. Indeed, operators difficulty define the laser parameters properly: they have to be optimized to the robot's relatively low speed, and the geometries could require some corrections. Thanks to the laser management functions by BLM GROUP, the LT360 "optimizes itself," adapting the laser parameters to the actual speed, managing the piercing phase, and automatically changing the focal distance. Moreover, motion planning is extremely demanding and fundamental for Laser Cutting processes, where the execution speed should be the highest as possible and pushes the limits of industrial robots

The technological issues with the laser welding process are similar to the ones with the laser cutting process. In laser welding, the first goal consists of minimizing the gap in a butt-joint weld. Furthermore, the motion plan must consider many constraints given by the geometry of the head and the process. Conventionally the maximum allowable gap in a butt-joint weld is approximately the size of the beam. Accordingly, the process requires accurate fixing strategies

[2]The deposition head can be equipped with two different powder nozzles from Fraunhofer ILT for powder delivery. A three-jet nozzle (Fraunhofer ILT 3- JET-SO16-S) is for productive deposition, and a coaxial nozzle Fraunhofer ILT COAX 40 F) is for more refined and more precise deposition.

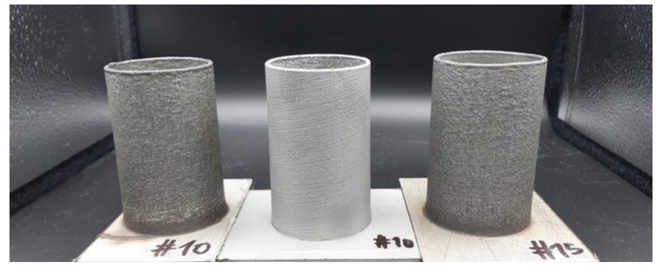


(a) BLM LT360. Laser cutting of a tube (dual-arm configuration)



(b) welding of complex structure, using LW R&D Alpha Prototype.

(c) Complex geometry, Robotized DMD Additive manufacturing



(d) thin-wall objects, Wired Additive Manufacturing.

Fig. 2: Robotized Additive Cell at SITEC Lab of the Politecnico di Milano.

and more stringent tolerances for manufacturing the welded components. For complex 3D geometries, small to medium-sized with lots with variable component types, the need for rigid and complex fixtures are limiting factors for using laser welding. These issues lead to the online modification of the path. Specifically, the LW R&D Alpha Prototype implements two different strategies. First, it uses a wobbling technique to ensure a wider weld seam resolving gap issues up to $1mm$ without compromising the quality. Second, a proprietary inline seam tracker corrects the robot trajectory and pose using a coaxial camera and external illumination. The ongoing research focuses on in-source dynamic beam shaping capabilities for improved weld quality and offline programming solutions for complex 3D parts.

Finally, consider the Additive processes. The accuracy problem is similar to the previous ones, while motion planning is much easier. Specifically, the LMD process aims at free-form large component production without the use of supports. The $6 + 2DoF$ of the robotic system increase the flexibility. Integrating the CAD/CAM system results in a 3D slicing strategy to fabricate multi-directional and complex components (e.g., the exhaust manifold produced for the Made4Lo project https://youtu.be/SN2oDExzX2o) [2]. This approach allows more straightforward planning and reduces fabrication time. The implementation of the sensor permits the control of process stability during productive and finer depositions, avoiding problems of overgrowth and undergrowth [3]. Moreover, the flexible orientation of the tool and positioner allows finishing treatments on the surfaces. One of the most critical aspects of 3D printing is the poor surface finishing, commonly characterized by high roughness values. The LMD cell uses the combination of the laser as a tool and robots for the surface finishing of complex components. The laser is used for the soft-remelting of printed surfaces to reduce the roughness [4]. In addition to accuracy issues, the further challenge in additive manufacturing is closing the loop with the monitoring systems. During the regional funded project MADE4LO, CNR and Politecnico started an investigation to deviate the robot path according to the melting pot tracking. This investigation, which is still undergoing, is a real challenge where robot and process control must be strongly integrated. Furthermore, Politecnico di Milano is exploiting the Robotized Additive Manufacturing Cell to research the optimization of powder catchment efficiency for stable deposition [5]. Similarly, substantial efforts are still being invested in WireLMD printing for significant free-form components and massive production.

IV. Conclusion

The paper presented the result of the collaboration of the BLM Group with Politecnico di Milano and the support of CNR.

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