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Prospects of Robot Laser Cutting in the Era of Industry 4.0

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Abstract

Laser cutting is a non-contact thermal cutting process and an integral part of manufacturing. In metal processing, laser cutting is at the forefront of the manufacturing chain followed by joining and manufacturing processes like welding. The future of metal manufacturing processes like laser cutting shall rely on intelligent systems such as automation and robotics based on the advancement of technology and digital transformation spearheaded by Industry 4.0. Moreover, the digital transition where robots and automated systems are key drivers creates a broader platform to utilize energy-efficiency materials. Such energy-efficient materials include high-strength steels (HSS) for structural applications (e.g. bio-energy structures, wind turbines, ice-going vessels) onshore, offshore and in the Arctic region. The aim of this paper is to elucidate the prospects of robot laser cutting systems in the framework of integrated metal manufacturing in future factories. Previous studies on laser cutting technologies are examined based on scientific and industrial perspectives. Robot laser cutting system is compared with the well-known flat-bed laser cutting CNC machine in several aspects including flexibility in manufacturing, ease for digitalization, off-line capabilities and investment analysis. The findings shall help to determine the competitiveness of robot laser cutting systems with flat-bed laser cutting CNC machines, especially when considering metal manufacturing in small and medium-sized enterprises (SMEs). The outcome of this study is to stir up experimental and computational research on robot laser cutting systems of metals, and help companies in their decision-making process when deciding which laser cutting system will best suit their manufacturing operations in the future.

Keywords

Laser Cutting, Robots, Automation, Integrated Manufacturing, Digitalization, Metals

1. Introduction

Cutting of sheet metal parts with laser was developed in the 1960s and the technology is currently available with different power sources like CO_2 laser, fibre laser and diode lasers. The laser cutting process requires precision, accuracy, speed and stability. As an example, in the automotive industry, laser cutting is done by sophisticated automated robots for cutting a variety of materials, mostly stamped metal parts, formed metal parts, sheet metal blanks, etc. Although it is prominent in the automotive industry, yet the robot laser cutting system is not often utilized in most industries. The reasons are that ordinary robots tend to focus on applications that require low precision. Also, ordinary robots are less efficient due to poor axes control capabilities or overloaded axes which are not suitable for fast-moving targets. In addition, ordinary robots are considered as lightweight with insufficient rigidity, thus resulting in instability and trembling problems [1]. For these reasons linear axis flat-bed laser cutting CNC machines have been accepted and are well known for cutting sheet metals, tubes and metal plates. It can be estimated that about 90% - 95% of laser cutting operations are performed with flat-bed laser cutting CNC machine, which seldomly employs 3-dimensional laser cutting heads for cutting 3D shapes and patterns.

Nevertheless, the current industrial revolution driven by Industry 4.0 promotes the integration of manufacturing systems with smart technologies pivoted on automation and robotics. This means that future factories will incorporate more automation and robotic systems, thus industries utilizing laser cutting processes will not be an exception. Therefore, industries other than the automotive may have robot laser cutting systems integrated into their manufacturing processes. It has been estimated by the International Federation of Robotics that by 2020 the worldwide stock of operational industrial robots will amount to over 3 million units [2], and the key industries to install robots include metal manufacturing. Based on these facts, the need to investigate the prospects of robot laser cutting in integrated metal manufacturing factories is imperative. **Figure 1** shows the various aspects investigated in this paper. Firstly, the various laser types and their deployment, especially in integrated metal manufacturing factories were studied. Secondly, equipment setup which in this case involves flat-bed laser cutting CNC machine and robot laser cutting systems was considered for comparisons. Exploring robot laser cutting systems in the age of Industry 4.0, several factors including flexibility and versatility, ease for digitalization, and offline cutting capabilities were examined. Finally, investment approaches for the two set of machines and equipment was considered necessary for discussion.

2. Laser Cutting in Integrated Manufacturing

In terms of market share, laser cutting is nowadays the most significant application in materials processing [3]. In the metal industry, laser cutting is at the forefront of the production chain where pieces of parts and patterns are cut from sheet metals, metal plates or metal tubes for manufacturing of large volumes or

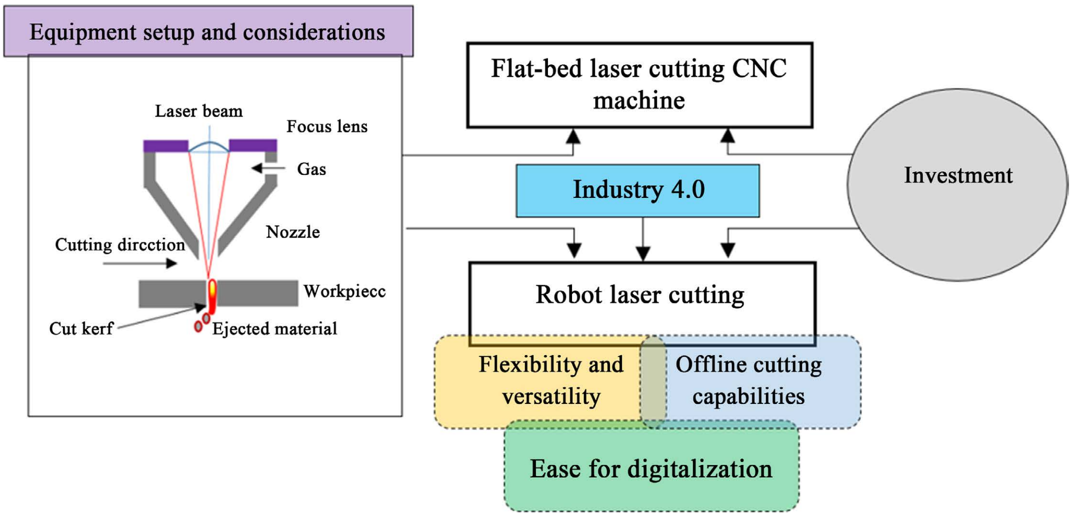

Figure 1. Schematic framework indicating key variables in laser cutting, especially when exploring robot laser cutting in the age of Industry 4.0.

low volumes of products to serve diverse industries. Laser cutting is a high-speed computer numeric control (CNC) process with cutting precision and accuracy of approximately 0, 05 mm, and it delivers very low heat effects to the cut parts. Common metals which are laser cut include mild steel, stainless steel and aluminum. In laser cutting, the physical properties of metals, especially thickness and surface reflectiveness and chemical composition, and mechanical properties are significant characteristics that need to be considered. For mild steel and stainless steel, the thickness range suitable for laser cutting is between 0, 5 - 20 mm while aluminum is between 0, 5 - 8 mm [3] [4].

Considering either flat-bed laser cutting CNC machine or robot laser cutting system, several parameters related to the laser system, materials and the process need to be examined. For the laser system, parameters such as the wavelength of the laser radiation, maximum output laser power, and laser beam quality are essential although they cannot be modified by an operator. Materials and processing parameters are those that can be adjusted by an operator. The material parameters include thickness and type of the material, while the processing parameters constitute the laser power, cutting speed, focal length of the focusing lens, focal point position relative to workpiece top surface, type and pressure of assist gas, gas nozzle diameter, and gas nozzle stand-off distance. However, as the laser system is delicate in materials processing, the different laser types are worth mentioning. The various laser types commonly deployed in the processing of metals include CO_2 laser, Fibre laser, disc laser and the diode laser. The types of lasers and their operational distinctiveness and similarities are explained.

2.1. Laser Types

CO_2 Laser: The carbon dioxide laser (CO_2 laser) is the most commonly used laser type. In a CO_2 laser, laser light is formed due to gas mixture with a composition of 78% helium, 12% nitrogen and 10% carbon dioxide. The wavelength of the CO_2 laser is typically 10.6 μm and requires moderate power levels to about 100 kW [4]. The CO_2 laser is suitable for cutting steels due to the high absorption rate of the laser beam [5] and good beam quality at high output powers sufficient for cutting thick-metal sections. Nowadays, CO_2 laser is particularly used in cutting steel plates > 5 mm thickness. The cutting quality of CO_2 is better than fibre laser and operationally faster when cutting thicker plates. Although it is deployed for cutting steels, stainless steel or aluminum, the CO_2 laser is well suitable for cutting non-metallic materials such as multiple plastics, glass, fabric, paper and wood [6] [7] [8]. CO_2 lasers cannot use optical fibres because the wavelength is absorbed by the fiber, so it is not possible to transfer the laser beam by fibre technology.

Fiber Laser: The laser beam is formed directly into the optical fiber and transmitted via the same medium to the machine cutting head. Diode laser is used as a light source while the fibre itself acts as a resonator and the medium. The fiber laser consists of several smaller modules and high power is achieved by combining the laser beam produced within the fibre. Fiber lasers are significantly smaller than CO_2 lasers and generate twice as much power. The efficiency difference between CO_2 and fiber laser is up to 6 - 7-fold. The wavelength of the fiber laser is typically 1070 nm and is suitable for cutting reflective materials such as aluminum or copper. The absolute advantage of a fiber laser is its good beam quality, since the beam itself is produced in a fiber resonator and need not to be separately transmitted to the fiber [6].

Diode Laser: Diode laser is not very common in laser cutting applications of metals, especially due to its lower laser beam quality compared to fiber and CO_2 lasers. The diode laser beam is formed as a result of a low-power diode laser that is bundled together. The wavelength of the diode laser is approximately 970 nm, which is also shorter than that of the fiber laser. Moreover, the laser beam is delivered to the target using optical fiber like the fiber laser. The diode laser is better absorbed by reflective materials such as aluminum as compared to a fiber laser, however, its usage is rare in the metal industry [6] [9]. The most significant weakness of the diode laser is the beam quality due to the challenges of combining several laser beams produced by low-power diode modules. In order to combine the beams, they must have different wavelengths. The diode laser has potential, and, in the future, it is believed to be a fully comparable alternative to fibre and CO_2 lasers.

Other laser types like the solid-state neodymium-doped yttrium aluminum garnet (Nd: YAG) laser with a wavelength around 1000 nm is less reflective and its absorption is high in most materials [10]. Nd:YAG laser delivers laser light through a fiber-optic cable, and the technology is prominent in thin-section high precision metal cutting [11]. A schematic diagram of a laser cutting front and possible effects are shown in **Figure 2**. The dynamic behavior of the laser cutting process affects the shape of the cutting front and the melt flow mechanism resulting in cut edge surface roughness observed as striations on the cut edge [12] (see **Figure 2(b)**). Another occurrence is the dross attachment (see **Figure 2(c)**)

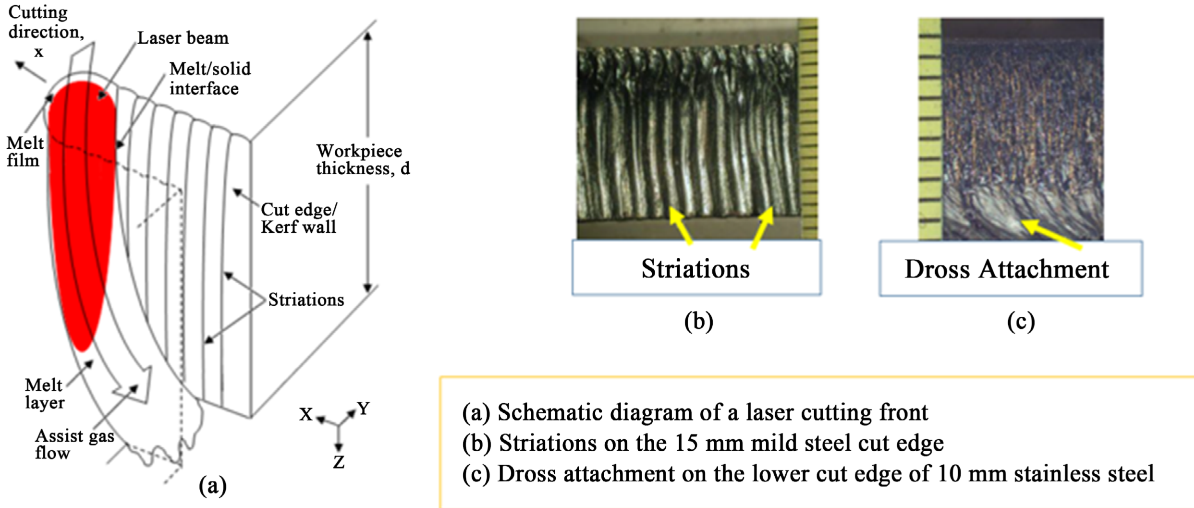

Figure 2. Illustrations of: (a) laser cutting front; (b) striations on mild steel cut edge; (c) dross attachment. Modified figures [3].

which describes the phenomenon where part of the molten metal which is not completely blown-off from the laser cut kerf re-solidifies and adheres firmly to the lower cut edge [13]. Metals with high surface tension and viscosity values are more prone to dross attachment.

2.2. Integrated Manufacturing

Laser cutting can be done in-house or as a sub-contracted service. Some large companies and SMEs manufacture their own parts using their own cutting systems in-house. Others also prefer to focus on their core manufacturing competence, for example, welding, and rather sub-contract the laser cutting as a service to SMEs who are specialized in such field. Those SME's that provide only laser cutting as a sub-contracted service do encounter high-mix low-volume laser cutting production because of the diverse customer segment they serve. Similarly, some SMEs that manufacture their own products and do laser cutting by themselves are exposed to high-mix low-volume production. These situations depict the concept of integrated manufacturing.

The concept of integrated manufacturing in this context represents a situation where several manufacturing processes are carried out in sequence and at different times in small batches in a factory. As illustrated in **Figure 3**, the sequence in manufacturing starts with materials handling. Materials to be cut are conveyed for laser cutting and either handled for bending and rolling or for welding, whichever comes first. The parts or components are afterwards handled for sandblasting where the cut components are cleaned. The sandblasted components proceed to be painted and conveyed for handling at the section for the finished product. The solid line means a direct sequence of operation from one manufacturing process to another. The broken line means an indirect sequence of operation. So, when a part is laser cut and it is moved to sand blasting and afterwards moved to bending and rolling, the part can either be moved for polishing

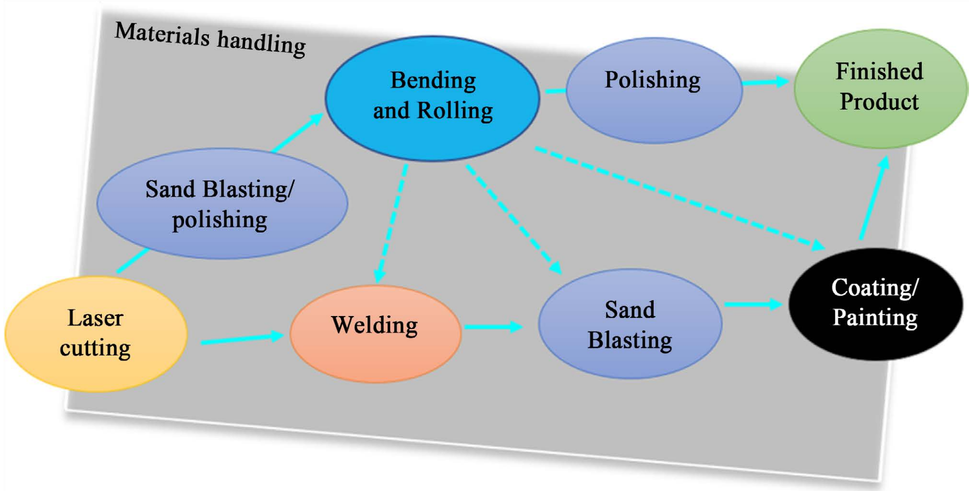

Figure 3. An illustration of integrated manufacturing in a factory which produces metal products.

and as a final product or moved from bending and rolling to be welded, sand blasted or coated before the finishing phase.

By considering the various manufacturing processes, not less than ten machines and equipment are required to perform such tasks with some level of assistance from humans. Time spent in materials handling may affect efficiency and productivity taking into consideration the manufacturing cycle in the factory. However, by deploying automation, few robots could be installed to perform such fragmented manufacturing processes with little human collaboration to drive efficiency, productivity and consistent material flow in the factory, hence reducing the number of machines in the factory to create more working space ergonomically.

The adoption of robot laser cutting and automated systems may be cost-effective in an integrated manufacturing factory thereby augmenting the high cost in purchasing flat-bed laser cutting CNC machines. Also, benefiting from digitalization in the age of internet of things (IoT) and devising new business models which are economically viable and befitting by laser cutting companies are profound. Investment strategies need to be examined in both scenarios. Nevertheless, selecting laser equipment, either flat-bed laser cutting CNC machine or robot laser cutting for cutting of wide range of materials must be carefully evaluated, taking into consideration the laser types, assist gases, day-to-day manufacturing processes in the factory, business model and investment.

3. Equipment Set-Up

3.1. Flat-Bed Laser Cutting CNC Machine

A typical flat-bed laser cutting CNC machine is illustrated in Figure 4. Due to its bulky nature, these types of laser machines occupy a large workspace. The dimensions of the entire machine considering the length, width and height could be in the range of 13,050 × 7050 × 2450 mm. The cutting area for nominal sheet sizes of 4000 × 2000 mm is typically 4064 × 2032 × 70 mm. The CNC mechanism of the machine allows positioning accuracy of ±0.1 mm, repeatability of ±0.05 mm and high precision due to its rigidity and X, Y, Z coordinates. There are possibilities to adopt 3D laser cutting heads to such machines to aid in the cutting of sophisticated patterns and parts. Normally, the laser power of such machines range between 4.4 - 10.0 kW and the laser technology is normally CO_2 or fibre laser [14]. The flat-bed laser cutting CNC machine seems to be the market choice and holds about 90% - 95% presence in large companies and SME's workshops globally. The common laser cutting machine manufacturers in the global market include Trumpf, Bystronic, Amada, Prima Power, Mazak, Bodor, Salvagnini, Han's laser, Tanaka, Koike, etc.

3.2. Robot Laser Cutting Systems

A robot laser cutting system is simply an automated laser technology with a cutting head that relies on the kinematics of the robot manipulator and dexterity of the robot end effector. A robot laser cutting system comprises a servo-controlled mechanism, a multi-axis mechanical manipulator that has a laser cutting head mounted to the robot's end effector. **Table 1** shows a summary of the characteristics of robot manipulators [15]. The cutting head has focusing optics for the

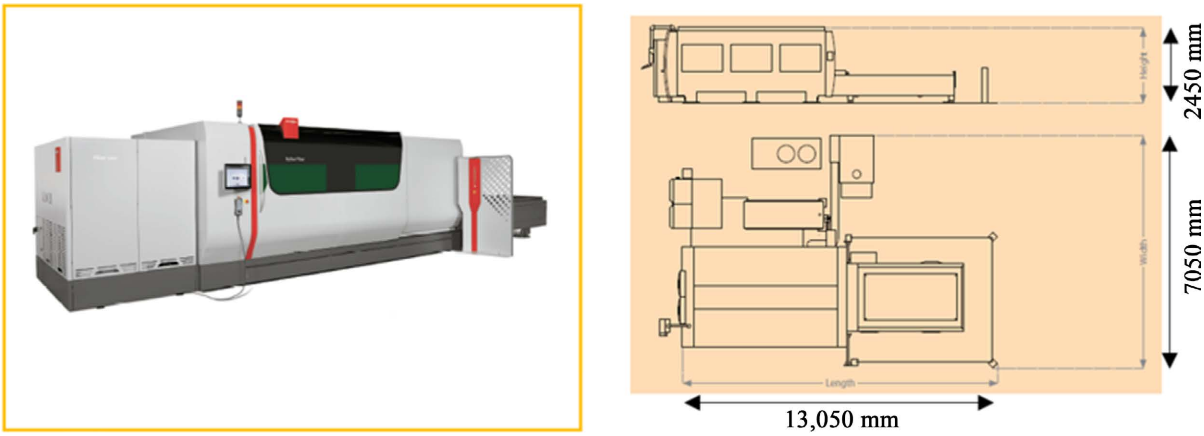

Figure 4. Pictorial and dimensional illustration of a flat-bed laser cutting CNC machine (BySprint Pro 4020) [14].

Table 1. Robot manipulator characteristics.

Characteristics	Description
Repeatability	Up to 0.03 mm (0.1 mm is common)
Velocity	Up to 5 m/s
Acceleration	Up to 25 m/s
Payload	From around 2 - 3 kg up to ≈750 kg
Weight/Payload	Around 30 - 40
Axis	6 degree of freedom (3 translational and 3 rotational)
Communication	Profibus, Canbus, Devicent, Ethernet and serial channels (RS232 and RS485)

laser beam and is often an integral height control mechanism. Depending on the laser technology deployed, an assist gas delivery package distributes a cutting gas, either oxygen or nitrogen, to the cutting head cable [16].

Robot manipulators used for laser cutting operations can be mounted in different forms. For example, the robot manipulator can be mounted on the factory floor, on the wall or in a gantry position. Figure 5(a) shows a typical example of a robot laser cutting system mounted on the factory floor. With this type of set-up, the robot laser cutting system can be stationary or movable on tracks. When stationary, a movable cutting bed with an automated mechanism may be deployed. On the other hand, when the robot laser cutting system is movable on tracks, a stationary or movable cutting bed with an automated machine could be deployed. The other forms are the gantry or overhead positions where the robot manipulator is mounted on crane-like structures above the factory floor as shown in Figures 5(b)-(d). Gantry robot systems operate like Cartesian or linear robots where movement occurs in the horizontal plane (*i.e.* from left to right or front and back) and in the Y and Z plane due to the reachability of the manipulator and rotary motion of the end effector. These features of the gantry robot enhance the maneuverability of the laser cutting head for complex tasks in terms of reach, speed and accuracy.

In this modern era of industry 4.0, the advantages of applying robots in laser

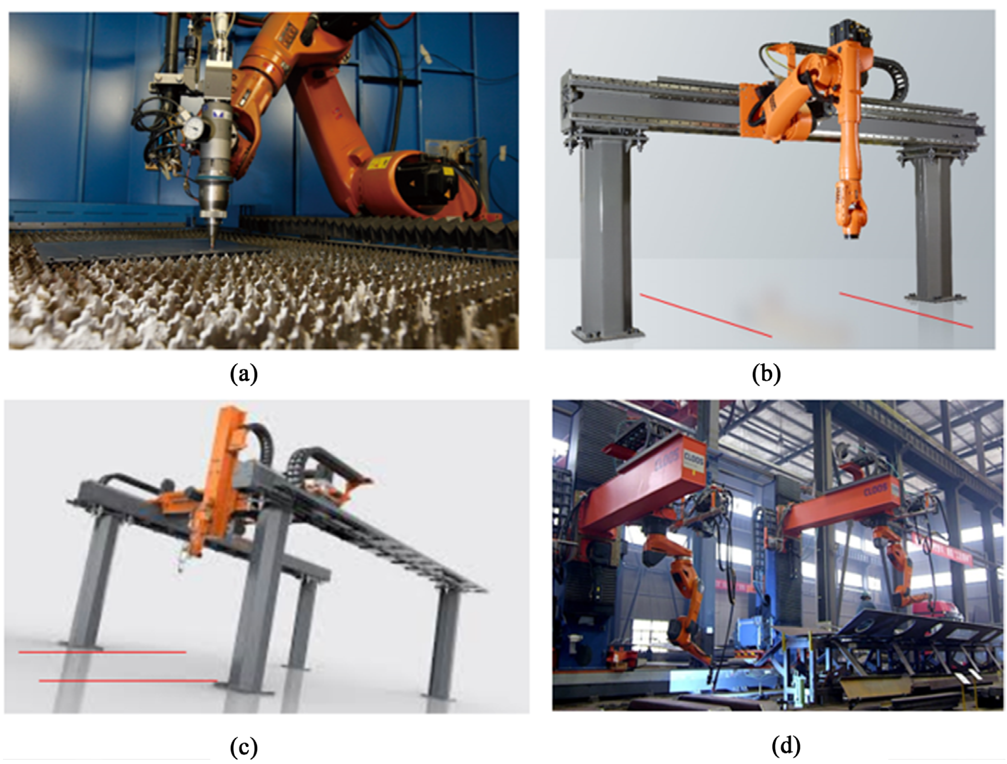

Figure 5. Different robot set ups for laser cutting operations: (a) A floor mounted robot laser cutting system; (b) A gantry mounted robot laser cutting system which operates in the X-Y-Z plane; (c) A gantry mounted Cartesian robot laser cutting system which operates in the X-Y-Z plane; (d) A gantry mounted linear robot laser cutting system which operates in the X-Y-Z plane.

cutting operations are convincing. Basically, Industry 4.0, with its focus on automation, robotics, big data acquisition, big data fusion and big data analytics, envisions the transformation of traditional industrial manufacturing into smart manufacturing where the manufacturing systems are able to: 1) digitally monitor physical processes and make adaptive intelligent decisions through real-time connectivity, collaboration and communication with humans, machines and sensors [17]; and 2) adjust their behavior in response to diverse situations and requirements based on past experience and learning capabilities [18]. Therefore, the use of robot automated systems complements the trends and direction forming the basis of the Industry 4.0 concept. Thus, robot laser cutting systems are worth exploring, especially as regards to flexibility and versatility, ease for digitalization, and off-line laser cutting operations.

3.2.1. Flexibility and Versatility

Robot laser cutting systems possess enough flexibility and versatility when compared to flat-bed laser cutting CNC machines. Test results about robot laser cutting as reported corroborates with the aspect of flexibility and versatility, especially as a technology that could potentially revolutionize the laser cutting industry [19]. On the positioning, robot laser cutting system could be installed in a gantry position or on the factory floor for an exceptionally large working space. Due to its flexibility, robot laser cutting is increasingly popular in the automotive industry. However, robot laser cutting systems could be harnessed in other applications such as in the manufacturing of pressure vessels. Cutting circular shapes and patterns on sheet metals for the manufacturing of pressure vessels can be made by first bending the metal and afterward cutting the patterns or circles from the top, or bottom or from the sides. The usual norm in the manufacturing of pressure vessels is that circular shapes are cut on sheet metals and afterward bent. The challenge here is that the circular shapes become elliptical after bending, which then require further manual cutting and grinding processes, thus affecting the accuracy of the shapes, productivity of the work and economy of scale.

Additionally, the ability to cut 3D shapes and complex geometries from sheet metals and stamped-metal blanks, formed metal parts, tubes and metal plates are attributes of the robot laser cutting system. Robot laser cutting system can adapt to variations and changes in manufacturing requirements and can handle customized products in either high-mix low-volume or low-mix high-volume manufacturing settings. Based on its versatility and integratability, robot laser cutting system can perform other manufacturing tasks when the laser system is de-coupled. A typical illustration is the framework of integrated manufacturing (**Figure 3**), where at least one robot can be reused interchangeably to perform most of the manufacturing processing. The low cost of robot laser cutting systems as creating new businesses in the automotive industry has been reported. The report states that 3D laser-cutting robotic solutions are emerging as the most preferred choice for many laser-cutting applications such as for automotive spare parts, engineering machinery industry, passenger car bodies, farm vehicles, and electric cars [1]. In the same vein, it has been reported that the return on investment of robot laser cutting is less than 2 years, and when a robot laser cutting system is implemented, the possibility of eliminating multiple workstation machines and equipment is feasible, thus creating avenues for the same robot to be used in other manufacturing tasks [16]. Some success stories have been told about robot laser cutting, especially from robot manufacturers including KUKA, ABB, FANUC, YASKAWA, STÄUBLI, and KAWASAKI. These success stories define robot laser cutting systems as having these advantages: less energy consumption, lower maintenance demand, small batch processing, fast cutting speeds, shortened production cycle, small kerf, smooth cutting edge at 3D surface, less pollution in production, enhanced human collaboration, no tool wearing, long service life, high reliability and stability for mass production and processing requirements.

3.2.2. Ease for Digitalization

Robot laser cutting systems provide enough flexibility for devices to be attached to the robot manipulator, end effector or the laser cutting head for sensing and monitoring purposes. Laser cutting operations could be monitored and predicted through on-line process monitoring techniques (pre-process, In Situ, and post-process monitoring) and furthermore by modelling and control through artificial intelligence (AI) methods. Among the AI methods: artificial neural networks (ANN), fuzzy logic, neural-fuzzy networks, adaptive neuro-fuzzy inference systems (ANFIS), genetic algorithm (GA), and particle swarm optimization (PSO) algorithm, the ANN is often deployed for modeling and control of rare events in the field of robotic welding and could be applied in the field of robot laser cutting. Detailed scientific information about the introduction to neural networks methods for modeling and control of rear events is given by [20].

Practically, the ANN relies on input and output information such as experimental data and this information provides the basis on which the structure and parameters of the model is identified. Retrieving and gathering data for modeling and simulation purposes is assured when ANN is deployed. Considering laser cutting and the parameters involved, a simple ANN architecture to model and control the input and output data can be developed as represented in **Figure 6**. The ANN architectural configuration is to assist in decision-making, optimize prediction and control of the robot laser cutting operation where quality, accuracy and precision cuts are required. The ANN architecture relies on learning algorithms such as the back propagation (BP), resilient propagation (RPROP), Levenberg-Marquardt, genetic algorithm (GA) and particle swarm optimization (PSO) algorithm [20]. Generally, input data are weighted through sum biasing and are then processed through an activation function to produce the output. After each process, the output is matched to the output that is desired, and the difference between them gives an error signal. The weight is adjusted by presenting

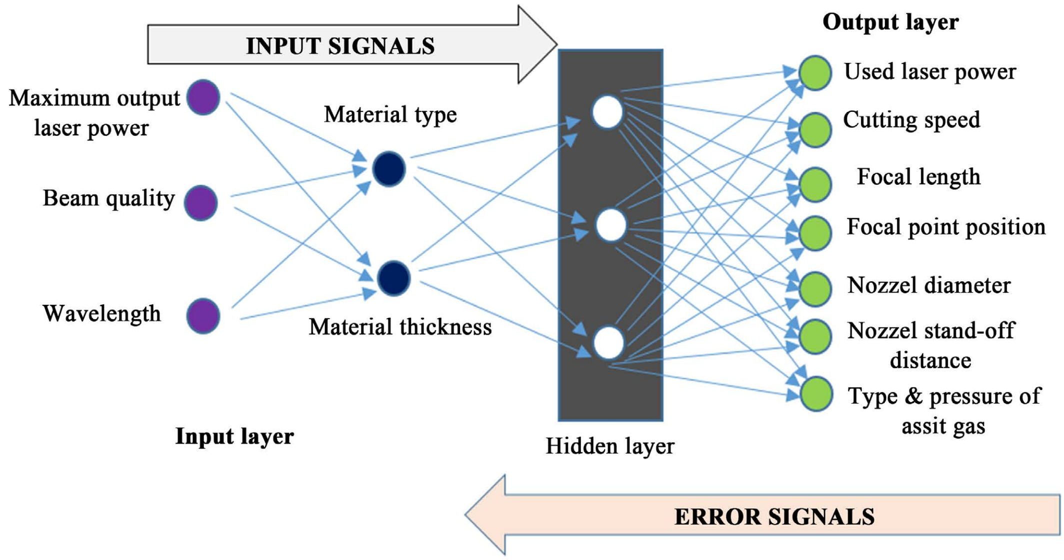

Figure 6. An illustration of a possible ANN architecture for modelling and control of parameters in robot laser cutting.

the error back to the neural network system in a manner that will decrease the error for every iteration. This process aims to reduce the error value and makes the neural network system model approach the desired target. The adopted learning algorithm adjusts the weights as the iteration increases, thereby reducing the error and getting closer to the desired target [20] [21] [22].

The possibilities of digitally monitoring the physical process in real-time are advantages that could be achieved using robot laser cutting systems. In addition, nesting and predicting optimal cutting sequences to avoid distortion of the material, visualizing the entire process and eliminating severe heat-affected zones (HAZ) that could affect material's properties before and after cutting can be merited to robot laser cutting systems.

3.2.3. Off-line Robot Laser Cutting

3D simulation software has been developed to augment robot laser cutting of sheet metals, tubes, stamped-metal plates, etc. This development adds significant value to metal cutting in the sphere of digitally transforming the laser cutting industry towards Industry 4.0. Considering offline technology, a simulation model (virtual twin/digital twin) of the real robot laser cutting system is developed to facilitate operations both in virtual and real-time modes. Simulating the robot laser cutting process means that the effects of cutting do not always need to be experimented in real-time, thus resulting in productivity savings, economical use of materials and efficient use of energy, reducing online programming time while alleviating the risk of possible breakdowns or workplace accidents. Robot laser cutting programs are, therefore, made offline and ready for operations in real-time. The entire setup involves measurements, calibration, verification and validation of the cut points and targets. Research shows that off-line laser cutting software helps in simulating the impact and transfer of heat in metal cutting, which therefore reveals how the heat is distributed in the material and the possible effect of temperature on material properties. The software tools also allow to select optimal patterns and cutting order while anticipating and detecting potential unforeseen anomalies during the layout phase. Correcting the cutting path and trajectory of the laser cutting operation in order to maintain high quality, accuracy, consistency and precision is feasible [23]. Commercially available software solutions for robot laser cutting operations include ALMA CAM software, and BeroSIM offered by Vicomtech and Lantek.

4. Investment Analysis

In laser cutting, investing in smart technologies is crucial where automation and robots remain the leading key drivers of modern-day manufacturing and production. Providing enhanced technical solutions certainly require new investments. To invest in flat-bed laser cutting CNC machines with sophisticated features which mostly are costly (>500,000 €), or automated robot laser cutting systems with adaptive features which are comparatively less costly (<200,000 €) or a combination of both is a choice to make. Paying close attention to automation and robots, it is an arguable fact to provide response to a question like what is the profitability of the investment? From the financial viewpoint, several calculations are used for evaluating the profitability of investments when dealing with automation and robots. Holamo recommended utilizing net present value (NPV) formula, as expressed as follows [24]:

$$\text{NVP}(i) = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} + \frac{RV}{(1+i)^N} - C_0 \quad (1)$$

where NPV(i) is discounted value of the investment, t is time periods (years), N is total number of periods = depreciation time, i is company set target for internal rate of return, R_t is cash flow during period t, RV is residual value at the end of depreciation time, and C_0 is the total initial investment cost. If, with given restrictions for N and i, the output NPV (i) > 0 the investment is generally profitable, and NPV calculations are useful when comparing different kinds of investments with each other. The NPV will indicate which investment will be the most profitable, shown by the highest NPV value [24]. This formula could, however, be used to compare the profitability between procuring flat-bed laser cutting CNC machine and robot laser cutting systems for cutting variety of materials, shapes and thicknesses, especially when considering an SME factory with high-mix low-volume manufacturing. Investments in automation and robots should be considered from a strategic point of view, also when planning new business models, considering new target markets, and implementing other future factory concepts.

5. Discussion

Manufacturing has become highly integrated, especially in the metal industry where several processes need to be performed seamlessly to get the final product through. The need to consider machines and equipment which are flexible, versatile and easily adaptable with smart technologies in this era of intelligent manufacturing remain vital, especially when considering SMEs that operate on high-mix low-volume manufacturing. In laser cutting, the flat-bed CNC machine has had prominence till date. It can be estimated that about 90% - 95% of laser cutting operations on 2D sheet metal blanks are performed with the flat-bed laser cutting CNC machine. Occasionally, 3D laser cutting heads are fitted to flat-bed CNC machines for cutting parts that are three-dimensional. However, robot laser cutting has proven to be effective and efficient in cutting materials that are stamped, drawn or even flat shaped. For this reason, robot laser cutting is mostly utilized in the automotive industry without reservations. Some advantages of robot laser cutting systems over flat-bed CNC laser cutting machines include:

- Flexibility and versatility;
- Ease for digitalization;
- Offline laser cutting;
- Low investment cost;
- Highly suitable for integrated manufacturing;
- Workshop space utilization is very high;
- Easily deployable in emerging markets and operations can be monitored with AI and IoT capabilities.

From an industrial point of view, some companies in other industrial sectors still hold on to the old belief that robot laser cutting systems cannot function productively like that of the flat-bed laser cutting CNC machines. Some of the reasons why robot laser cutting systems have not been widely accepted dwells on the fact that ordinary robots tend to focus on applications that require low precision. Cutting a 5 mm diameter circle is complicated, and if cut the end shape looks elliptical. Secondly, such ordinary robots are less efficient due to poor axes control capabilities or overloaded axes which are not suitable for fast-moving targets. Also, ordinary robots are considered lightweight with insufficient rigidity, thus resulting in instability and trembling problems [1]. It is also identified that the limitation of ordinary robot regarding cutting speed is, however, not due to the intensity of the laser, but due the mechanical set-up deployed to move the workpiece and the laser [25]. Without holding any biases, such reasons are clearly things of the past. Although it could be considered that most robot laser cutting system integrators do not have sufficient experience with laser cutting process and have done little research in robot motion control, as pointed out by [1], it is still arguable that modern-day robots are equipped with efficient axes control systems for accurate, efficient and precise positioning and trajectory movement. Nevertheless, with modelling and simulation capabilities, robot laser cutting systems can be trained and controlled to overcome such limitations previously encountered with ordinary robots.

Robot laser cutting systems today, therefore, seem to be stable due to the wide range of deployable automated configurations, an example being the gantry position. Moreover, the usability of robots is gaining value in future factories where automation and digitalization remain global tools for manufacturing. Gerrit Gerritsen pointed out that automation has not yet progressed well in the sheet metal industry, with 20% automated systems as compared to the automotive industry with 90% record [26]. Gerritsen further emphasized that using robots was not worthwhile until now. This is because a sheet metal processing company using a robot may produce 1000 equipment brackets and other small series of products in different time schedules during the day and achieve productivity and efficiency. It is then possible to cater for high-mix low-volume production in the case of sheet metal processing as well as low-mix high-volume production in the case of a car manufacturer producing the same chassis one hundred thousand times.

The choice of equipment rely on investment, and investment analysis in every business is crucial, especially when planning to purchase new machines to replace old technology which has a track record in the industry. Nevertheless, evolving trends in industries must be adhered to and this comes with several considerations for new technology, expansion of factory operations to new or emerging markets like Africa, energy efficiency and sustainability factors, etc. Finally, on energy efficiency and sustainability factors, a clear comparison can be made between robot laser cutting systems and flat-bed laser cutting CNC machines. The act of changing power sources to match laser cutting systems in order to measure and monitor their environmental footprints and powering them by renewable energy sources (e.g. wind or solar power) are interesting prospects of robot laser cutting systems. Further investigations need to be carried out in this regard.

6. Conclusion

The prospects of a robot laser cutting system have been examined in this work. Comparisons and several considerations were made, not only on equipment set up with flat-bed laser cutting CNC machines but on factors relating to intelligent integrated manufacturing and investment. The main considerations which shift the focus from flat-bed laser cutting CNC machines to robot laser cutting systems for the sheet metal industry and other potential metal work industries where energy-efficient materials are used are the aspects of automation and digitalization. By far, it can be said that robot laser cutting systems seem to be more flexible and versatile in terms of operations, easily adaptable with intelligent sensing and monitoring devices for modelling and simulation, and thus can deliver offline laser cutting functionalities which brings leverage to productivity and profitability. Although the position of flat-bed laser cutting CNC machines in the global market remains strong, despite huge investments needed, its counterpart robot laser cutting system shows resilience in future factories. Also, system integration and operational outlook of robot laser cutting system seems to be cost-effective and provides sustainable solutions, especially for SMEs that are known to operate high-mix low-volume system of manufacturing and production. Finally, the robot laser cutting systems remain a potential source of equipment for future laser cutting operations in diverse industries, being the sheet metal industry, automotive industry and other sectors. Hence, its potential to spearhead digitalization and automation in laser operations cannot be underestimated. Experimental and computational research, as well as further literature works, need to be conducted to advance the research in robot laser cutting of metals.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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