THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Monitoring and Control of Robotized Laser Metal-Wire Deposition

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to Belma with love

Abstract

The thesis gives a number of solutions towards full automation of the promising manufacturing technology Robotized Laser Metal-wire Deposition (RLMwD). RLMwD offers great cost and weight saving potentials in the manufacturing industry. By metal deposition is here meant a layered manufacturing technique that builds fully-dense structures by melting metal wire into solidifying beads, which are deposited side by side and layer upon layer. A major challenge for this technique to be industrially implemented is to ensure process stability and repeatability. The deposition process has shown to be extremely sensitive to the wire position and orientation relative to the melt pool and the deposition direction. Careful tuning of the deposition tool and process parameters are therefore important in order to obtain a stable process and defect-free deposits.

Due to its recent development, the technique is still manually controlled in industry, and hence the quality of the produced parts relies mainly on the skills of the operator. The scientific challenge is therefore to develop the wire based deposition process to a level where material integrity and good geometrical fit can be guaranteed in an automated and repeatable fashion.

This thesis presents the development of a system for on-line monitoring and control of the deposition process. A complete deposition cell consisting of an industrial robot arm, a novel deposition tool, a data acquisition system, and an operator interface has been developed within the scope of this work. A system for visual feedback from the melt pool allows an operator to control the process from outside the welding room. A novel approach for automatic deposition of the process based on Iterative Learning Control is implemented. The controller has been evaluated through deposition experiments, resembling real industrial applications. The results show that the automatic controller increases the stability of the deposition process and also outperforms a manual operator.

The results obtained in this work give novel solutions to the important puzzle towards full automation of the RLMwD process, and full exploitation of its potentials.

Keywords: Laser Metal Wire Deposition, Additive Layer Manufacturing, Robotic Weld Equipment, Optical Sensors, Process Control, Process Development, Process Stability, Iterative Learning Control

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An important issue in metal deposition is constant monitoring and control in order for the process to be repeatable. If the process is not strictly controlled, it might create new exciting and original shapes. Bengt Lennartson and Anna-Karin Christiansson, thank you for applying just enough *control action* to give me the freedom to evolve new ideas, but enough *control action* to keep me close to the desired *trajectory*. Also thank you for being *robust* in handling my *unmodeled dynamics*. Your efforts are much appreciated!

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Abbreviations

ALM	Additive Layer Manufacturing
CAD	Computer Aided Design
CPU	Central Processing Unit
DAQ	Data Acquisition
DOF	Degrees Of Freedom
EB	Electron Beam
FEM	Finite Element Modeling
GMAW	Gas Metal Arc Welding
ILC	Iterative Learning Control
LMD	Laser Metal Deposition
LOF	Lack-Of-Fusion
MAG	Metal Active Gas
MD	Metal Deposition
MIG	Metal Inert Gas
MIMO	Multiple-Input Multiple-Output
Nd:Yag	Neodymium:Yttrium aluminum garnet
ODBC	Open Database Connectivity
OLP	Off-Line Programme
PI	Proportional-plus-Integral
PLC	Programmable Logic Controller
PTA	Plasma Transferred Arc
RLMwD	Robotized Laser Metal-wire Deposition
SISO	Single-Input Single-Output
TCP	Tool Center Point
TIG	Tungsten Inert Gas

Contents

I Introductory Chapters

II Included Papers

Part I

Introductory Chapters

Chapter 1

Introduction

1.1 Background

Traditional manufacturing methods of large and complex metal structures often require the use of one piece precision castings or oversized forgings. For structures made of high-cost materials, such as aerospace components, these methods generate significant production costs and long lead times. Naturally, there is a desire for new manufacturing techniques that are better suited for these types of structures. In the aerospace industry, there is further a desire to meet the high market requirements, with regard to minimal fuel consumption and high cargo capacities, which also creates a need for manufacturing techniques that can deliver structures that are both light and high-strength at the same time. During the past few years, the aerospace industry has therefore been investigating means toreplace the traditional one piece castings and towards more lightweight *fabricated* structures. A fabricated structure is built by joining smaller sub-components, preferably by welding, with a possibility to combine several material forms and alloys. The weight reduction potential arrives from an efficient use of different mechanical properties and achievable geometrical tolerances for castings, forgings and sheet material, [1, 2]. Using the fabrication concept, the subcomponent sizes can be reduced and design features simplified. This increases the supplier variety and thereby reduces the production cost due to increased competition. However, a drawback with fabrication, compared to one piece castings, is that the use of the stronger material forms, such as sheet material and forgings, is typically limited to geometrically simpler shapes. In order for the fabrication concept to be competitive, several challenges need to be overcome regarding both design and manufacture. One such challenge considers the ability to add features such as bosses or flanges on subcomponents of fabricated structures.

The aim of this thesis is to address the problem of adding metal features on to existing metal structures. The goal is to use a rapid manufacturing technique based on additive layer manufacturing (ALM), that produces metal parts directly from a CAD (Computer Aided Design) drawing, in a near net shape fashion. The ALM approach is attractive since it also offers a flexible way to component repair or modification, e.g. in die repair or die changes. Other applications include rapid prototyping and low volume production.

Since their first introduction three decades ago, ALM techniques for metals have been developed and commercialized in the industry under names such as Direct Metal Deposition [3], Laser Engineered Net Shaping [4], Shaped Metal Deposition [5], Selective Laser Melting [6], and Electron Beam Freeform Fabrication [7, 8]. In all of these techniques a heat source is used to create a melt pool into which a wire- or powderized feedstock is fed, or the heat source is applied to a powder bed, in order to create beads upon solidification. The beads are created by means of relative motion of the melt pool and the substrate, e.g. using an industrial robot arm or an XY-table. A part is then built by depositing the beads side by side and layer upon layer. The most popular approach has up to today been to combine a high power laser heat source with metal powder as the additive material, see e.g. [4]. Other traditional welding techniques have also been introduced, such as Tungsten Inert Gas (TIG) welding [9], Gas Metal Arc Welding (GMAW) [10, 11, 12], Plasma Transferred Arc (PTA) welding [13, 14], and Electron Beam (EB) welding [7, 8].

The high power laser based approach remains however the most successful due to several benefits, such as the relatively low heat input into the base material and good shape accuracy of the produced geometries. Metal powder has been the main choice of the additive material since it gives a flexible and robust process. However, the powder based processes have been developed towards the manufacture of small and complex geometries, with less focus on the deposition speed. The deposition efficiency varies depending on the system setup, and post handling of the scattered powder is needed. For larger features with moderate complexity, such as flanges or bosses, it is more rewarding to use wire based techniques, since these could lead to higher deposition rates, better material quality and better surface finish [15, 16]. While the use of powder requires specially designed feeding nozzles and sometimes special chambers (for powder bed processes), the wire based solutions require much simpler equipment resembling standard welding equipment.

There is however a major challenge when using wire as the additive material, namely to ensure process stability and repeatability. The deposition process has shown to be extremely sensitive to the wire position and orientation relative to the melt pool and the deposition direction. Careful tuning of the deposition tool and parameters, such as the wire feed rate, the energy input, and the traverse speed are therefore important in order to obtain beads, which are free from defects such as lack-of-fusion (LOF) or cracks. Droplet forming, i.e. globular transfer of the molten metal, is also a common disturbance that affects the geometrical profile of the deposited beads and stability of the subsequent layers. Because of its recent realization, current implementations of metal wire deposition in industry are still open-loop processes, and hence the quality of the produced parts relies highly on the skills of the operator. Many questions are still unsolved relating to different mechanisms in the deposition process that govern the stability of the deposition, the resulting metallurgical and material properties, and the geometrical fit of the deposited parts.

The scientific challenge is therefore to develop the wire based deposition process to a level where material integrity and good geometrical fit can be guaranteed, in an automated and repeatable fashion. The problem is multidisciplinary and involves several areas such as:

- Process development - understanding the correlations between a set of process parameters and resulting material and geometrical properties of the deposit.
- Virtual tools - automatic process planning of the deposition.
- On-line process monitoring and control - compensation of disturbances during deposition.
- Post-treatment - obtaining final properties through e.g. post heat-treatment and machining.

Solving these challenges would enable full automation of the deposition process, and thereby create a competitive manufacturing technology, suitable for a variety of applications. Full automation could mean the steps from a CAD drawing $\rightarrow$ automatically generated deposition paths and process parameters, based on a process knowledge database $\rightarrow$ on-line disturbance control based on feedback $\rightarrow$ post-treatment $\rightarrow$ final net shape geometry with correct material- and geometrical properties. This thesis gives solutions to some important steps on this manufacturing route.

1.2 Objective

The objective of this research is to develop basic understanding for process characteristics of robotized laser metal-wire deposition (RLMwD), regarding deposition stability and formation of defects, through an experimental study using the titanium alloy Ti-6Al-4V. The choice of material is based on the fact that it is the most common material in aerospace applications, [17]. Based on the acquired knowledge, control strategies should be developed, such that they enable automatic control of the deposition process, with the aim to ensure process stability and good geometrical fit of the produced parts. The aims of this work are to:

- Develop an understanding of the novel laser metal-wire deposition process.
- Develop an understanding of the process window for deposition of the titanium alloy Ti-6Al-4V.
- Develop a method for manual remote control of a robotized deposition process.
- Develop a method for automatic height/width control of the deposited beads.

1.3 Research questions

Based on the objective presented above, a number of research questions have been formulated which are investigated in this thesis.

1. What features are important to monitor in order to ensure stable deposition, free from defects?

Process monitoring is the key factor in order to enable manual remote- and automatic control of the deposition process. When controlling the process manually, it has to be done remotely due to the safety reasons related to the high power laser used.

2. What parameters need to be tuned/controlled for a stable deposition process?

Many process parameters are important to tune carefully before deposition. Some still need adjustments during the deposition process. However, it is not feasible for an operator to handle more than a few parameters while running the process. The most important parameters should therefore be identified.

3. How can the bead width and height be measured in a reliable way?

Maintaining a flat surface for each layer, and making a good estimation of the layer height, has shown to be important for the stability of the process. The question is then how to measure, primarily the bead height, but also the bead width in a reliable way? This question is important to solve in order to enable automatic control of the process.

4. How to control bead width and height during straight bead deposition?

The first attempt towards automatic process control is made on multi-layered straight bead deposition. Issues such as measurement accuracy and reliability need to be investigated.

5. **How does the deposition system differ between single-bead and multi-bead deposition?**

In order to develop a process controller for arbitrary deposition patterns, the difference between the single-bead multi-layered deposition and multi-bead multi-layered deposition needs to be investigated.

6. **Can height and width control be generalized to arbitrary deposition patterns?**

For arbitrary deposition patterns the relation between the tool orientation and the deposition path direction varies continuously. Obtaining on-line height and width measurements is then not a straightforward task. Hence, the means to obtain feedback needs to be solved first. Further, the process behaves differently for different deposition patterns. Fundamental understanding of what is assumed to be the energy residuals' effect on the solidifying process of the deposited beads, in a multi-bead multi-layered deposition, puts certain requirements on the controller structure.

7. **What stability issues are associated with high-speed deposition, and how can these be overcome?**

In order to minimize the heat input into the substrate, it can be favorable to increase the deposition speed. What stability issues are related to higher deposition speeds? Can the developed process controller be adopted for this situation?

1.4 Research approach

The work reported in this thesis was organized in the following way: Since the laser deposition process using wire as the additive material is relatively new, the first step was to develop a basic understanding of the process characteristics (Paper 1) and thus answer to research questions 1 and 2. Once basic knowledge of the process was at hand, the fist attempt towards automatic control could be made. Research questions 3 and 4 were thus addressed (Paper 2). In order to find appropriate sensors for the harsh deposition environment, with heat radiation and high-power laser reflections, a number of experiments needed to be carried out in connection to Paper 2. The development of the process controller was therefore delimited to straight single-bead multi-layered deposition in order to ease on the workload in this first attempt. Subsequently, the control concept was developed towards arbitrary deposition patterns, addressing questions 5 and 6 (Paper 3). Once a generalized process controller was developed, the possibility

	What features are important to monitor in order to ensure stable deposition, free from defects?	What parameters need to be tuned/controlled for a stable deposition process?	How can the bead width and height be measured in a reliable way?	How to control bead width and height during straight bead deposition?	How does the deposition system differ between single-bead and multi-bead deposition?	Can height and width control be generalized to arbitrary deposition patterns?	What stability issues are associated with high-speed deposition, and how can these be overcome?
Paper 1	●	●					
Paper 2	●	●	●	●			
Paper 3	●	●	●		●	●	
Paper 4	●	●			●		●
Paper 5	●	●			●	●	●

Figure 1.1: Illustration on which research questions are addressed in the different appended papers.

of controlling the wire based deposition at high traverse speeds was investigated, addressing the last research question (Paper 4-5). This is an important issue to address in order to minimize the heat input into the substrate, and allow the use of different deposition speeds in order to control the temperature distribution in the deposited part. Figure 1.1 shows in which of the appended papers the different research questions are addressed. Note that the first two questions are central for this work and are therefore addressed in all of the appended papers.

1.5 Delimitations

The author has, based upon the overall aims, made the following delimitations of the research accounted for in this thesis:

- This research does not intend to produce an instruction book on how to precisely tune the deposition process for optimal stability and defect-free deposition. The problem areas are however highlighted and appropriate actions proposed.

- No modeling of the thermal behavior nor the fluid-flow of the melt pool is performed.

- System identification is performed using step response experiments on single beads.

- A fiber laser heat source is used within the scope of this work.

- The main material considered is the titanium alloy Ti-6Al-4V since it is commonly used in aerospace applications.

- During automatic control of the multi-layered deposition, only process stability and lack-of-fusion defects are considered. Other metallurgical properties, such as microstructure, stresses and deformations of the substrate are only briefly touched in one of the papers by other authors.

- The work is conducted in close cooperation with Swedish industry, why some process specific details are their proprietary and are therefore omitted in the thesis. Nevertheless, the research discussed here aims to present general methodologies in monitoring and control of RLMwD, why actual process parameters are of less interest.

1.6 Related works

To the author's knowledge, there are no similar works aiming at automatic online control of laser metal *wire* deposition, although several results have been published on this subject for *powder* feeding systems. On the other hand, many researches have been studying basic process characteristics of wire-based additive manufacturing and material properties of deposited beads and 3D parts, see e.g. [18], [19], [20], [21], [22], [23], [24], and [25]. Experimental results indicate that the direction and position of the wire relative the melt pool have strong influence on the stability of the process. Careful tuning of the wire feed rate, the heat input, and the traverse speed are also important in order to obtain defect-free beads. The results presented in [22] show that the tensile properties of the deposited Ti-6Al-4V parts match the properties of casted Ti-6Al-4V. More recent tensile tests and microstructural analysis for metal wire deposition can be found in e.g. [26], [27], [5], [28], [29], [30], [31] and [32]. Tensile tests described in [31] were performed on Ti-6Al-4V parts deposited by Volvo Aero at University West in Trollhättan, Sweden, using the deposition equipment described in this thesis. The results indicate that the interface between the substrate and the deposited material is stronger than the deposited material itself. This is derived from the tensile tests and low cycle fatigue tests, which all fractured in the deposited material, and not on the interface. The results further confirm earlier findings that the strength and fatigue properties of the deposited material are equal to or better than those for cast Ti-6Al-4V.

In [15] the material properties of parts deposited using either metal wire or metal powder as the filler material has been investigated. The comparison indicates that the microstructure of samples from both methods is similar, however with some porosity found in the powder-fed deposited parts. The surface finish and the material usage efficiency was however better for the wire-fed samples. In [33] a combination of both wire feeding and powder feeding of same steel material was tested indicating that the deposition efficiency can be increased if these two feeding techniques are combined. The level of porosity was approximately 20-30% lower than for samples made with powder feeding only. Other publications on combining powder and wire are e.g. [34] and [35]. In [35] it was investigated whether it is possible to find good process parameters and combine Ti-6Al-4V wire feeding with TiC powder feeding, in order to obtain well-bounded Ti-6Al-4V/TiC composites. It was found that, up to certain rates of TiC, it is possible to obtain a uniform distribution of the TiC particles in the new composite material. Laser wire deposition of Waspaloy was reported in [26]. Multi-bead walls were successfully deposited free from pores and cracks. The microhardness of the walls were investigated and discussed in relation to the number of layers and cooling/heating cycles during deposition.

Various deposition systems have been reported in the literature. For example, in [36] a combination of laser wire deposition and milling was used. After each deposited layer, milling was applied in order to provide a flat and stable surface for the subsequent layer. This way the stability of the process was ensured, however at the cost of manufacturing time. Similar approach was also reported in [14] where a plasma transferred arc heat source was used, and in [12] and [37] where metal arc welding were used instead. Metal deposition with arc welding was also reported in e.g. [11] and [10]. Use of TIG welding has also been reported in the literature, e.g. in [9] and [5]. In [9], a *3D micro welding* system was developed using metal wire with a diameter of 0.2 mm, while in [5] a system called Shaped Metal Deposition, originally developed by Rolls-Royce plc, is described. Other recent contribution to this variety of processes is metal wire deposition using an electron beam as a heat source, [38],[8]. Such heat sources offer further possibilities to reduce the heat input into the workpiece, compared to laser- or arc heat sources. However, a major drawback with this approach is the need for a vacuum chamber in order to use the electron beam.

Laser metal *powder* deposition has however been the most dominating approach and hence resulted in a variety of systems, developed by different research groups, such as Direct Metal Deposition [3], Direct Light Fabrication [39], Laser Engineered Net Shaping [4], Laser Based Flexible Fabrication [40], Blown Powder Process [41] and Direct Laser Metal Sintering [6]. On-line control of metal *powder* deposition has been reported in several papers. In [42], a closed loop controller of the bead height was developed. The height of the beads was correlated to phototransistor measurements, and the laser was turned off whenever excessive height was measured. During the time the laser is turned off the powders are scattered and not deposited. In [43], a powder flow control system was developed based on the motion system speed profile. The controller contributed to avoid problems such as excessive built-up due to motion system's acceleration/retardation, e.g. in sharp corners. In [44], [45] and [46] the temperature signal from the melt pool was studied through a photodiode and the signal was used to control the laser power in order to maintain a stable weld pool temperature. As a result, improved homogeneity of the microstructure and better dimensional accuracy of the deposited samples were achieved. In [47] and [48] a path independent height measurement system was described based on images from three cameras symmetrically placed around the melt pool. In [49] the melt pool size was measured with a camera mounted in the laser optics. The signal was used for controlling the laser power in order to maintain stable melt pool size, which resulted in better geometrical precision of the deposited geometries. Similar approaches were undertaken in [50] and [51], where instead a pyrometer was utilized to measure the real temperature of the melt pool. In [50], the obtained temperature signal was used to control the scanning velocity of the laser processing head, in order to maintain a stable melt pool temperature, while in [51] the laser power was controlled instead. In [52] similar work was done for a powder based system, here also including a CCD camera for particles-in-flight monitoring of powder stream.

The majority of the aforementioned references utilize a process specific feature, namely the fact that the catchment efficiency (i.e. the ratio between melted and scattered powders) depends partly on the melt pool temperature. This basically enables height control through melt pool temperature control, and thereby also easy accessible real-time feedback. The concept cannot be transferred to metal *wire* deposition in a straightforward manned, because all wire that is fed into the process is deposited, i.e. the volume of added material per unit length of deposit is always constant for constant wire feed rate. Nonetheless, height deviations as a function of temperature do occur in metal wire deposition, as a result of displacement of the molten metal, due to e.g. surface tension forces. However, the relations are often noncausal (e.g. a wide melt pool that affects previously deposited adjacent beads), and thus much harder to model and relate to real-time temperature measurements.

The work done in [43] differs from the other references because it addresses the shortcomings of the utilized motion system, rather than focusing on real-time process measurements. Based on the speed profile of the motion system, the powder flow rate is controlled in order to minimize height variations of the deposit. This approach might not reduce the disturbances associated with e.g. temperature accumulation, but it will reduce height deviations caused by acceleration/retardation of the motion system. The idea is therefore transferable to a wire based system, and should be investigated for deposition of complex structures or deposition at high speeds, i.e. situations where possible shortcomings of the motion system might influence on the process.

In order to assure desired quality of the deposited parts and to be able to optimize the manufacturing design, it is important that certain behaviors such as the thermal behavior, distortions, and residual stresses can be predicted in advance. Several publications have been reported on different numerical simulations of metal deposition, predicting e.g. the thermal cycles in multi-layered deposition [53], induced component microstructure [54],[55], stress [56], or deformations [57]. The ultimate goal is to use these tools for process development and automatic process planning. However, the huge computational complexity often associated with these numerical tools make their use in practice very challenging. The models are further often valid in a limited working space, which creates a need for comprehensive calibrations whenever new conditions are imposed. Such calibrations are both costly and time consuming. Papers related to automatic process planning of metal deposition have up to now mostly been focusing on the final step of the planning chain, i.e. the automatic generation of deposition-tool paths, see e.g. [58],[59],[60],[61]. In these references process parameters and corresponding bead dimensions were decided in advance, i.e. not proposed by the process planner. Path generation was thus only designed to fill the volume of the intended part without any regards to e.g. thermal history, residual stress or deformation.

It is therefore important to continue the work of process understanding, modeling, and simulation, in order to develop advanced process planning tools. Parallel to that, it is also important to develop monitoring equipment and control strategies which are adapted to industrial environment. This will ensure robustness and repeatability, minimize the need for manual handling, and also enable efficient use of process planning tools.

1.7 Main contributions

The novel contributions of this thesis are:

- **Development of a stable robotized laser metal-wire deposition process for the titanium alloy Ti-6Al-4V.** Understanding the process behavior is fundamental for future deduction of the process envelope for this novel technology, in order to fully exploit its capabilities. This includes practical solutions for non-contact measurement of vital parameters.

- **A height control method, based on Iterative Learning Control, for automatic deposition of arbitrary shapes and deposition patterns.** Minimizing the need for manual interventions is an important step towards ensuring a robust and repeatable process suitable for industrial use.
- **A robot height controller for increased process stability and thereby minimized risk for lack-of-fusion defects.** Ensuring defect-free deposits is essential if additive manufacturing is to be successful in demanding applications such as the manufacture of aerospace components, where this technique has one of its highest cost-saving potentials and environmental benefits.

1.8 Publications

The thesis is based on the following appended papers. Papers 1-3 have been peer reviewed. The thesis author provided the main ideas and conducted all experiments by himself, except the deposition of multi-layered wall in Paper 1, and had the main responsibility for the manuscript preparation of the publications.

Paper 1

A. Heralić, M. Ottosson, K. Hurtig and A.-K. Christiansson, Visual feedback for operator interaction in robotized laser metal deposition, *Proceedings of the* 22^{nd} *Conference on Surface Modification Technologies*, 2008,Trollhättan, Sweden

Paper 2

A. Heralić, A.-K. Christiansson, M. Ottosson, and B. Lennartson, Increased stability in laser metal wire deposition through feedback from optical measurements, *Optics and Lasers in Engineering, 48(4), pp 478-485*, 2010

Paper 3

A. Heralić, A.-K. Christiansson, and B. Lennartson, Height control of laser metal-wire deposition based on iterative learning control and 3D scanning, *Accepted for publications in Optics and Lasers in Engineering*

Paper 4

A. Heralić, C. Charles Murgau, Dž. Imamović, A.-K. Christiansson, and B. Lennartson, Towards stable high-speed metal-wire deposition, Part I: Parameter study, *Submitted to Journal of Laser Applications*

Paper 5

A. Heralić, A.-K. Christiansson, and B. Lennartson, Towards stable high-speed metal-wire deposition, Part II: Automatic deposition using feedback control, *Invited submission to Journal of Laser Applications*

Chapter 2

Process description

The central part in RLMwD is the generation of beads using a high power laser source and additive material in the form of metal wire. The laser generates a melt pool on the substrate material, into which the metal wire is fed and melted, forming a metallurgical bound with the substrate. By moving the laser processing head and the wire feeder, i.e. the welding tool, relative the substrate a bead is formed during solidification. The relative motion of the welding tool and the substrate is in this work made using a 6-axis industrial robot arm. The formation of a bead is illustrated in Figure 2.1 along with images from the real process.

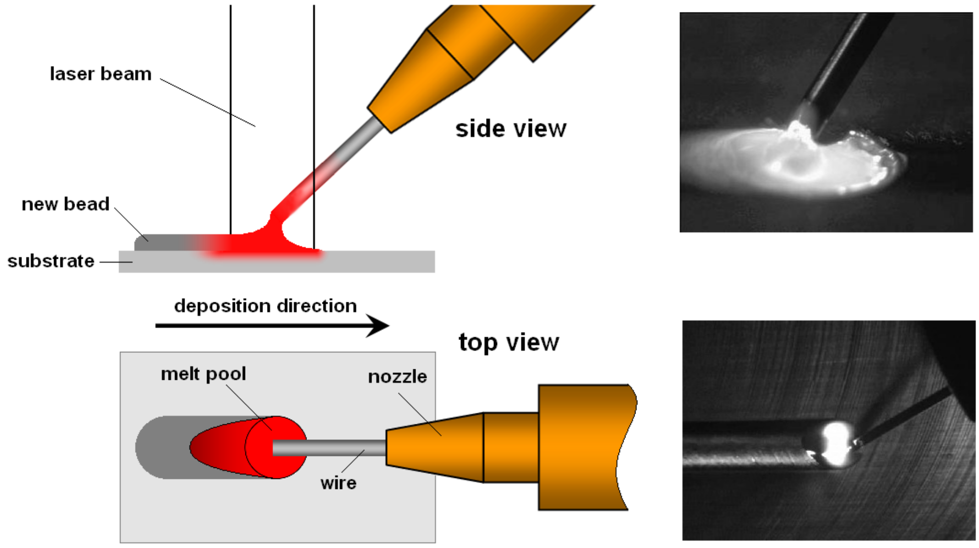


Figure 2.1: Left: Illustration of the laser-wire interaction. The molten metal solidifies into a bead by relative motion of the welding tool and the substrate. Right: Top- and side view images of the real process.

2.1 Process parameters

Prior deposition, a set of process parameters need to be chosen and the equipment needs to be tuned accordingly. The main process parameters are the laser power, the wire feed rate and the traverse speed. These control the energy input, the deposition rate and the cross-section profile of the beads, i.e. the width and the height. The energy input is determined by the chosen traverse speed and the laser power, which also controls the width of the resulting beads. The height of the beads is determined by the amount of wire that is fed into the melt pool in relation to the traverse speed and the laser power.

Given the nominal laser power, traverse speed and the wire feed rate, there are additional parameters regarding the relation between the wire feeder orientation to the laser beam, traverse speed, and the substrate, that need to be decided. Careful tuning of these parameters is necessary in order to enable stable deposition on a flat surface. For deposition of straight beads on a flat surface, the following parameters need to be considered:

Laser power - one of the main parameters, decides the maximum energy input. Depending on the laser beam size and the traverse speed, laser power also controls the melt pool size and consequently the width of the beads.

Laser power distribution - affects the melt pool dynamics. Examples on different distributions are top-hat and Gaussian distributions.

Laser/wire or laser/substrate angle - affect the process window and the true energy input. The angle between the laser beam and the wire influence on the sensitivity to changes in wire feed rate and variations in distance between the wire nozzle and the substrate. The angle between the laser beam and the substrate influence on the reflection of the laser beam, and hence the absorbed energy.

Laser beam size and shape - control the size and the shape of the melt pool (together with the laser power and the traverse speed). A common choice is a circular beam shape, although rectangular shapes are being used as well (e.g. with diode lasers). The size is chosen to reflect the desired bead width.

Laser beam focal length - controls how collimated the laser beam is at the substrate surface. Consequently, it decides the sensitivity to distance variations from the focus lens to the substrate.

Laser wavelength - controls the absorption of the laser beam, i.e. in metals the absorbtion of laser light is not equal for all wavelengths (or materials).

Wire feed rate - one of the main parameters, decides the added mass per time unit. Affects mainly the bead height and needs to be chosen in relation to the laser power and the traverse speed.

Wire diameter - should be chosen in relation to the laser beam size to ensure proper melting and a flexible process.

Wire/substrate angle - affects the melting of the wire and thereby also the stability of the process. Properly chosen, the metal transfer between the wire and the melt pool is smooth and continuous. Wrongly chosen and the transfer might become either globular, i.e. droplets, or the wire will enter the melt pool still solid. A higher angle gives less sensitivity to deposition direction, but at the same time a smaller process window of allowable wire feed rates.

Wire tip position relative to the melt pool - also affects the melting of the wire and thereby the stability of the process.

Wire stick-out - not as critical as the wire angle or the wire tip position, but the stick-out might need tuning depending on the expected deposition conditions. It affects primarily the flexibility of the process to variations in height between the wire nozzle and the substrate.

Feeding direction - decides from which direction the wire enters the melt pool, and thereby affects the melting of the wire, and thus the metal transfer. Different choices of feeding direction change the range of allowed wire feed rates. In some cases it can also affect the shape of the bead.

Traverse speed - one of the main parameters, decides the added mass per unit length and input energy per unit length. At lower traverse speeds the deposition process is easier to maintain stable, unless the temperature of the deposit becomes too high. At high traverse speeds lower energy inputs can be obtained for same mass added material per unit length. However, motion system's acceleration and path accuracy must be more carefully considered.

2.2 Laser-wire interaction and process stability

Tuning the parameters described in Section 2.1 influences on the metal transfer between the solid wire and the melt pool, which is important for stability of

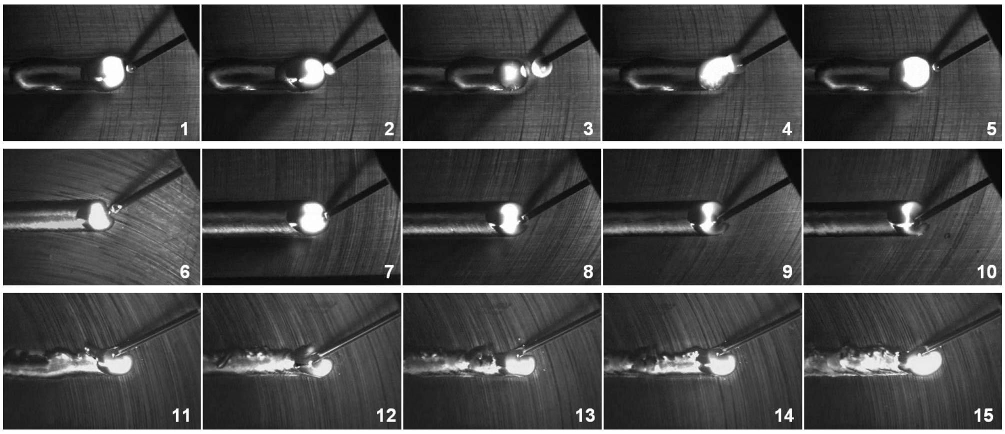


Figure 2.2: Different transfer modes between the solid wire and the molten metal (see text for details).

the deposition process. There are in general three ways the metal wire can be deposited: by globular (droplet-like) transfer, smooth transfer, or by plunging. Only smooth transfer gives a sound process, but it requires careful tuning of the aforementioned parameters.

If the equipment is set-up so that the wire tip spends too much time in the laser beam (e.g. by choosing a too high feeding angle in relation to the other parameters), it will reach the melting temperature somewhere above the melt pool. The metal transfer between the solid wire and the melt pool might then be stretched to a point where the surface tension can no longer bind it to the melt pool/wire tip. Consequently, the wire and the melt pool will separate and the surface tension will form the molten wire tip into a sphere, in order to minimize the surface energy. Because the wire is constantly fed and heated up by the laser, the droplet will grow until the gravitational forces exceed the surface tension holding the droplet together, at which point the droplet will detach. A new droplet will directly start to form on the wire tip, and the process is repeated, see images 1-5 in Figure 2.2. This type of deposition gives highly irregular bead shapes, which makes 3D deposition not feasible.

Moreover, once globular transfer starts, it is hard to abort. What is basically required is that the physical contact between the molten wire tip and the melt pool is reestablished. At the same time the process parameters must be changed to appropriate values. Note however that, once the globular transfer has started, it is often not enough to just change the process parameters to appropriate values, i.e. the contact between the wire and the melt pool must be reestablished as well. This might e.g. required a temporary increase in wire feed rate above the desired value, until the smooth metal transfer is obtained. The timing is however crucial in order not to exaggerate the amount of wire fed into the melt pool and thereby risking insufficient melting, see plunging below.

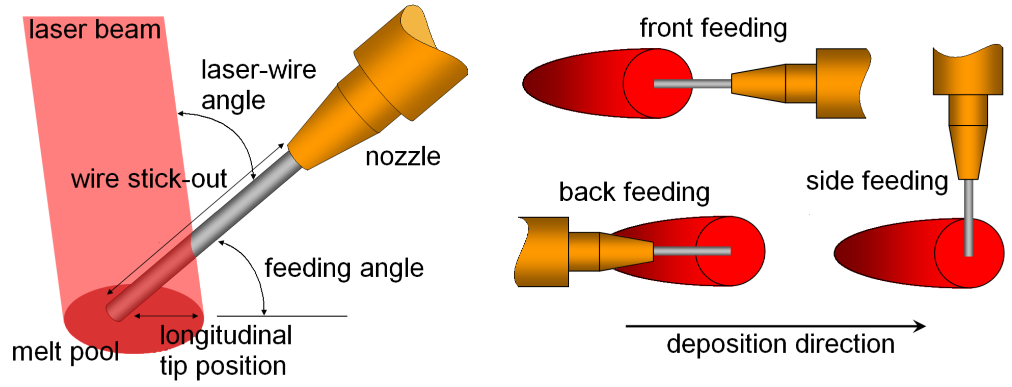


Figure 2.3: Left: Setup parameters regarding the wire tip in relation to the weld pool and the nozzle. Right: Example on different feeding directions.

If the wire feeder on the contrary is carefully tuned so that the wire is melted close to the intersection with the melt pool, there will be a smooth metal transfer from the solid wire to the liquid metal, see the right part of Figure 2.1 and images 6-8 in Figure 2.2. The resulting beads will have a smooth surface shape and a sound metallurgical bounding to the substrate. Hence, this is the desired deposition condition.

The third way to melt the wire is mainly by heat conduction from the melt pool, i.e. by plunging the wire into the melt pool, see images 9-10 in Figure 2.2. However, precautions must be taken not to have too high wire feed rate relative the heat energy in the melt pool, otherwise the wire might not be properly melted. This can result in defects such as lack of fusion (LOF). Images 11-15 in Figure 2.2 show a deposition sequence where the wire feed rate is too high relative e.g. the energy input, resulting in a damaged bead. Note, however, that LOF defects start to occur at much lower wire feed rates for which the resulting beads are more or less indistinguishable from the normal beads.

2.3 Tuning the process parameters

The parameters described in Section 2.1 are decided depending on the chosen material, desired deposition rate, and the maximum accepted heat input. Note that, this thesis does not intend to give a precise guideline on how these parameters should be tuned, but instead give a general explanation to how they affect the process. In this section some of the parameters are further discussed. Figure 2.3 shows some of the tunable parameters regarding the wire setup.

A central part in deciding the process parameters is the required energy input, which is decided based on the desired deposition rate, deformation restrictions, the material's viscosity, and available laser power and beam spot sizes. This puts

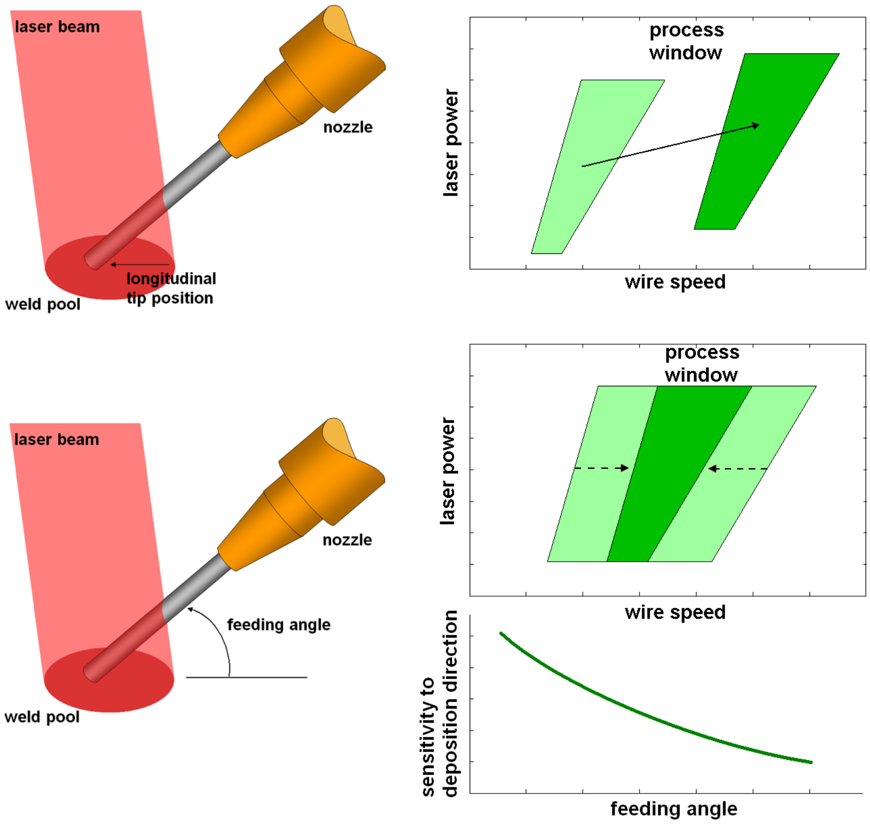


Figure 2.4: Change of process window due to change in wire setup. Top: The wire tip position is changed so that the heat input is increased, which shifts the process window and redefines the maximum and minimum wire feed rates. Bottom: The wire feed angle is increased, which changes the "width" of the process window and the sensitivity to deposition direction.

a requirement on the laser power, the traverse speed, and the wire feed rate. The laser beam should preferably be as orthogonal to the melt pool as possible for minimal reflections, however, without the risk of getting a reflection back into the optics. The wire tip position relative to the melt pool should be adjusted with regards to the chosen mass per time unit. If front feeding is used (see Figure 2.3), and the mass per time unit is low, the wire should enter the melt pool closer to the leading edge. Changing this parameter mainly affects the maximum and minimum wire feed rate for the chosen laser power and traverse speed, see the top part of Figure 2.4. A closely related parameter to the wire tip position is the wire/substrate angle. If the angle is low, high wire feed rates might be possible since plunging can be exploited in a better way. However, for extreme wire feed rates, only front feeding is feasible. This then limits the choice of complex deposition paths, such as zig-zag or spiral patterns. To decrease the sensitivity to feeding direction and thereby allow for arbitrary deposition patterns, the

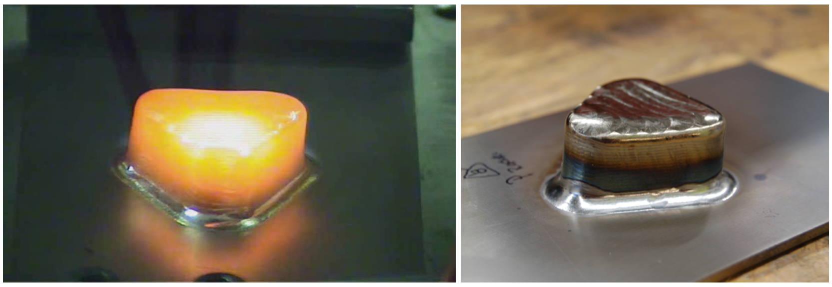


Figure 2.5: Left: Heat accumulation due to short pauses between layers, the picture is taken 10 s after the last layer was finished. Right: The final geometry.

angle between the wire and the substrate should be increased. However, the flexibility to deposition pattern comes at the price of smaller process window, see Figure 2.4. Consequently, a compromise is needed.

2.4 Multi-layered deposition

Obtaining stable single bead deposition onto a flat substrate requires careful tuning of the process parameters, as discussed in the previous sections. Ultimately however, the goal is to deposit 3D parts, i.e. deposit several adjacent beads in a layer, and repeat the deposition for a number of layers. The step from a single bead to a 3D part is however not straightforward. The precise shape of the layers are influenced by several additional sources such as e.g. the deposition pattern, the distance between the adjacent beads, and the motion system's speed and path accuracy. The relations are complex and hard to predict, which complicates the planning of the deposition, e.g. estimation of the layer height. One such example is the temperature due to heat accumulation, which needs to be considered during multi-layered deposition, see e.g. Figure 2.5 that shows an example on how the heat is accumulated in the deposited part due to short pauses between the layers.

The additional uncertainties in 3D deposition impose a problem from a stability point of view. If e.g. the layer height is wrongly estimated, the relation between the wire and the substrate will be changed from what is expected (i.e. the relation for which the process parameters are originally tuned). As a result, the deposition process might go from a smooth transfer of the molten wire to either globular phase or plunging. Consequently, as long as the process is not fully understood, and the shape of the layers and deterministic disturbances cannot be predicted with a sufficient accuracy, 3D deposition will require constant on-line monitoring and parameter adjustments. In this thesis, mainly two parameters are controlled, wire feed rate and the robot's tool center point in the z-direction.

Chapter 3

The RLMwD equipment

During the work reported in this thesis, two RLMwD cells have been developed and built-up at the Production Technology Center, University West, in Trollhättan, Sweden. Details regarding the cell structure, the deposition tools used in the experiments, and the monitoring system are given in this section. The basic idea is to use industrial standard equipment in order to show the usefulness for a number of welding industries. This in turn has resulted in necessary modifications and developments described in this chapter.

3.1 Automatic generation of robot programs

The starting point is a desire to manufacture a component according to a CAD drawing. The CAD drawing is imported to an OLP (Off-Line Programming) tool where the desired geometry according to the CAD-specification is sliced into layers of uniform height. For each layer the OLP tool generates the paths along

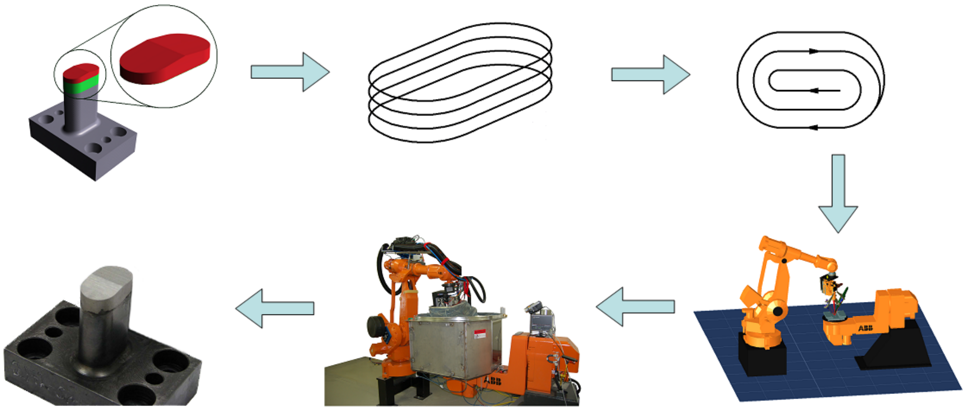


Figure 3.1: The RLMwD concept. The figure illustrates a case where abrasion resistant metal is added on the surface of softer material to obtain a punching die.

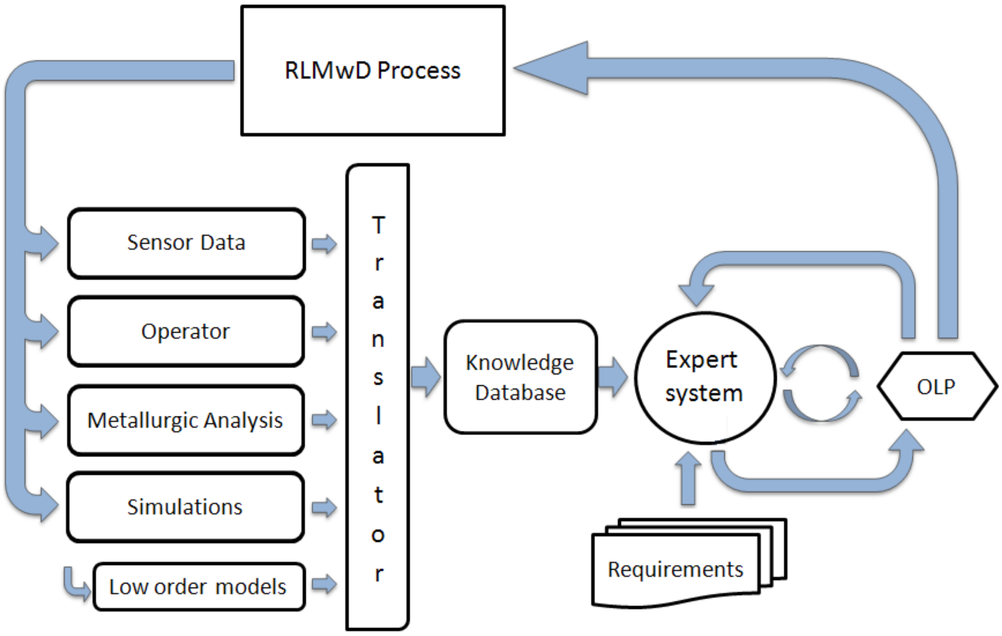


Figure 3.2: Desired process planning tool based on the results obtained in this work. Process parameters are automatically derived by an expert system based on requirements and a knowledge database with inputs from both the real process and simulations.

which the beads should be deposited to fill the layer. The pattern algorithm needs to know some basic data before the automatic path generation can start such as:

- Estimated layer height, which determines the number of slices.
- Bead width and desired offset between two adjacent beads, which determine the number of paths in one layer.
- Type of pattern, i.e. the robot path for each layer, e.g. straight line, zig-zag, spiral or other.
- Geometric constraints due to the equipment used.

Before the generated program is downloaded into a real robot, the deposition paths are tested in a robot simulator to assure that the motions are allowed by the equipment. After approval, the program is run in the physical cell and the geometry is deposited. An operator or a control system monitors the deposition and adjusts process parameters if necessary. Some post-machining of the deposited part might be needed depending on the application. The development of the OLP tools is outside the scope of this thesis. However, the OLP related research conducted by our group is reported in [62] and [63].

During experimental work conducted in this thesis, the assumption that the layer height is constant has been proven wrong, see e.g. Paper 2 and 3. Thus, in

Papers 3-5 the OLP was not utilized. Instead, the developed measurement system was used to decide the offset of the robot in the vertical direction, based on the real layer height. The total number of layers is then unknown. The deposition is therefore repeated until the desired component height is reached. It was further discovered that the choice of deposition pattern highly affects the temperature distribution and accumulation in the deposited part. Current development of the OLP tools, conducted by our research group, aims therefore to include process knowledge, based on real measurements and simulation of e.g. residual stresses and temperature, in the automatic process planning, see Figure 3.2. The goal is to better predict the layer heights, the temperature distribution, mechanical and metallurgical properties, and the geometrical profiles, and through an iteration loop derive proper process parameters based on different requirements.

3.2 RLMwD cell

One of the objectives in this work is to strive towards developing an RLMwD equipment that is based on off-the-shelf components. The deposition cell developed in this work is therefore based on a standard laser welding cell. It consists of the following components:

- A 6 kW fiber laser from IPG Photonics. Fiber lasers offer good beam quality and higher energy efficiency than the more common lamp or diode pumped Nd:YAG lasers. The fiber laser operates at 1070 nm.

- A 6-axis industrial IRB 4400 robot arm from ABB. The use of an industrial robot instead of an XY-table enables high flexibility in terms of feasible geometries that can be built, and parts that can be modified or repaired. The high quality of modern industrial robots offers sufficient accuracy and good repeatability for the intended application.

- A deposition tool consisting of both a laser processing head and the developed measurement system, which is described further in this chapter.

- A Fronius wire feeder with controlled wire feed rate. In order to ensure as stable wire feed rate as possible, a push-pull wire feeding system with closed-loop control from Fronius is installed. The push-pull system means that there are two wire feeding units, one close to the wire spool and one attached on the laser processing head. Internal communication between the units ensure good tracking of the requested feed rate at the nozzle.

- A MIG/MAG power source from Fronius to enable hot wire deposition, i.e. additional heat input by letting electrical current flow through the wire.

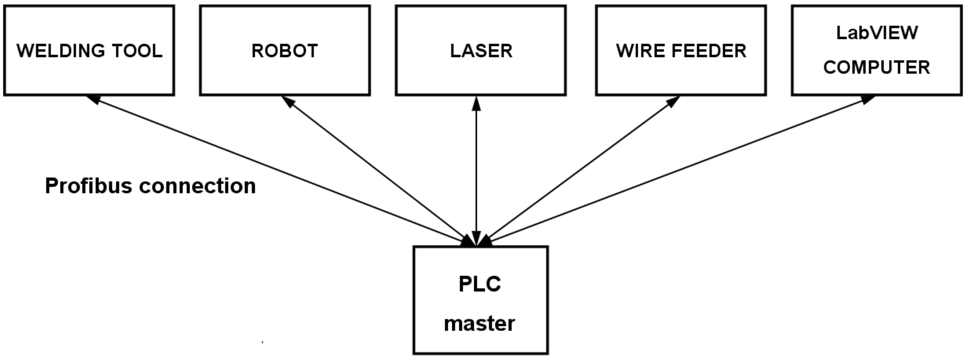


Figure 3.3: Communication architecture between the RLMwD system parts and the LabVIEW data acquisition and control unit.

The power source can also be used for hybrid welding applications. However, hot wire deposition is outside the scope of this thesis.

- An inert gas tent made of transparent plastic, with argon gas and oxygen sensor to ensure oxygen "free" atmosphere.
- An industrial fieldbus (Profibus) for signal exchange between system parts.
- A database (MySQL) for storing all data measured during deposition. Due to a high amount of information that is stored during deposition a database is necessary in order to enable easy access to selected information.
- An RLMwD-control system implemented in LabVIEW and Matlab. The RLMwD-control system is run either in automatic or manual mode. In both modes, the laser power, the wire feed rate, and the robot's vertical offset and speed can be adjusted.

3.3 Data acquisition and process control system

The RLMwD data acquisition (DAQ) and control system is an in-house development aimed at providing the ability to monitor and control RLMwD process parameters in real time. The control is made at a safe distance from the laser beam and in a comfortable way. The system is implemented in LabVIEW using standard PCs with Windows XP. The data acquisition system supports standard analog signal levels such as 0-10 V and 4-20 mA, and communication standards such as RS232, RS485, Firewire and Profibus.

The signal exchange between the RLMwD system parts is made using Profibus. The communication architecture is illustrated in Figure 3.3. The Profibus master is a PLC (Programmable logic controller) unit that handles the safe operation of

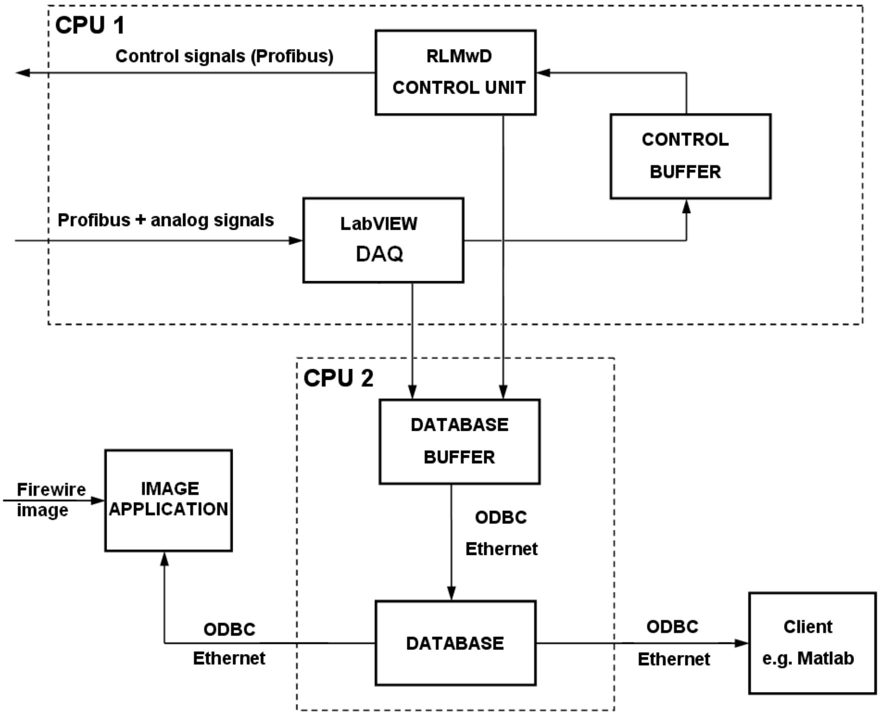


Figure 3.4: The information flow of the measured data, see text for details.

the entire RLMwD system. It also bridges over all communication activity that occurs between the RLMwD system parts and the control unit. This way the main process parameters, i.e. the laser power, the wire feed rate and the speed of the robot, can be monitored, recorded and controlled if necessary. Using the Profibus connection, the control unit also receives, and records, information regarding the robot position, equipment status, nominal process parameters, current time, real width and height obtained through the measurement system, i.e. the welding tool described in Section 3.4 and forward. The particular structure of the Profibus connection shown in Figure 3.3 is chosen to allow the LabVIEW unit to be switched off whenever the RLMwD equipment is to be used for other applications than metal deposition, e.g. laser welding.

The data acquisition system also enables monitoring of analog signals such as the oxygen level in the deposition environment, temperature signals through pyrometers or thermocouples, and melt pool images and additional surveillance images. The fieldbus data is sampled at a rate of up to 50 Hz in the current implementation. All data that is collected by the data acquisition system is saved in an information database, except the video clips, which are saved in separate files with overlayed time stamp and other process parameters on top of the video. The reason for choosing the database approach is the high amount of information that is collected during a deposition experiment, and the need for fast access to time synchronized selected data, both on-line and off-line.

The information flow of the measured data is shown in Figure 3.4. The process is divided into two main loops distributed on two parallel CPUs. The main loop in CPU1 collects the data from the fieldbus and the analog acquisition board, and sends it to a *control buffer* and a *database buffer*. The *control buffer* holds measured data from the last few seconds in order to enable the RLMwD controller to perform on-line signal processing if necessary. All control signals that are generated by the RLMwD control unit (run either in automatic or manual mode) are sent to the database buffer and merged with the other data at the corresponding time stamp.

The second loop in CPU2 empties the database buffer on a frequent basis and stores the information in a database. Distribution of this operation on a parallel process ensures that the loop time of the main process, i.e. data acquisition and control, is not affected by the heavy load caused by information transfer to/from the database. The communication with the database is done over Ethernet using ODBC (Open Database Connectivity) and the saved data can be extracted using any software supporting ODBC, e.g. Matlab. All data is saved with a corresponding time stamp to enable full tracing of the recorded events and also full synchronization between the data.

The use of a database for information handling has enabled flexible measurement analysis both on-line during experiments and off-line. This has been a useful tool for development and understanding of the RLMwD process.

3.4 RLMwD tool, first generation

The first tool used in this work is based on an off-the-shelf seam tracker manufactured by Permanova Lasersystems in Sweden, [64], as shown in Figure 3.5. The main reason for utilizing this tool was its ability to provide images of the melt pool through the focusing optics, see Figure 3.6. The tool consists of an optical system for laser beam focusing, a wire feeder, melt pool cameras, and low-power laser diodes that project thin lines on the substrate. The optical part consists of a collimating lens, a $45°$ mirror and a focusing lens. The mirror is dichroic, i.e. it reflects certain wavelengths such as the fiber laser wavelength (1070 nm), but transmits the visible wavelengths. Hence, unique top view images of the melt pool can be acquired. Two melt pool cameras were installed, one with a close-up of the melt pool for measurements, and the other with a wider field of view for general overview. The included laser diodes, which are normally used for finding the seam during welding, were here intended for height feedback, both in front and behind the melt pool, see Figure 3.6.

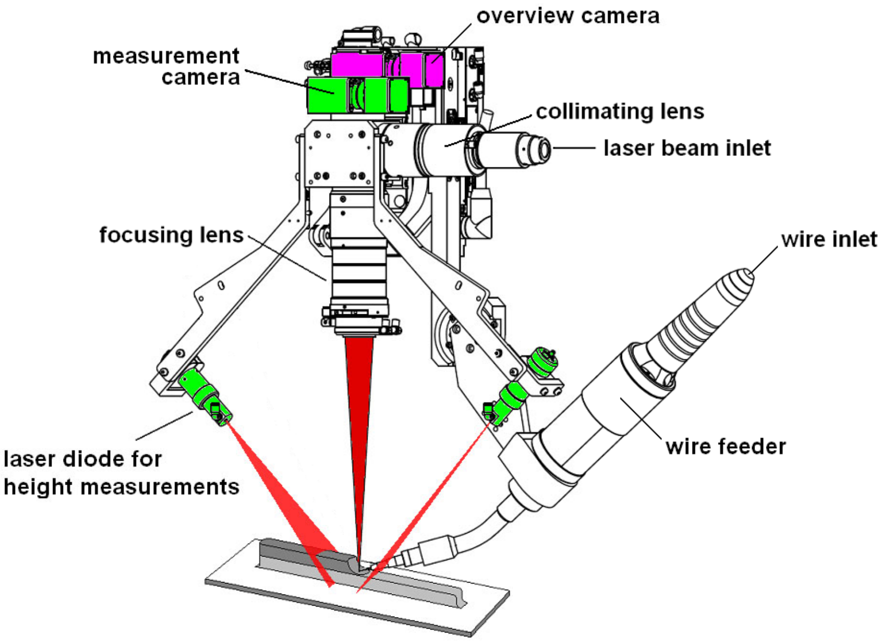


Figure 3.5: First generation RLMwD tool used in this work.

3.4.1 Bead height measurements

By height measurements is here meant the deviation from a reference height defined at the robot's tool center point (TCP). The robot's TCP is defined at the wire tip for a chosen wire stick-out. The heights are obtained by measuring the offset of the laser lines in pixels (ĥ in Figure 3.6), which are due to an angle between the laser lines and the measured surface, and relating it to the real height (h). This of course needs careful calibration of the setup. An edge searching algorithm scans the image and looks for sharp gradient changes, i.e. the laser lines shown in the right part of Figure 3.6). An edge is found when the gradient between two adjacent scanned lines is larger than a predefined threshold.

For small deviations around the nominal height the relationship between the real height h and the relative line position in pixels $\hat{h}$ can be approximated by a constant value

$$h = \hat{h} c_h$$

In order to calibrate the height measurements, i.e. to find c_h, a set of precision gauge blocks can be measured with the focus point placed on a planar surface. The c_h is then obtained by averaging the results, i.e.

$$c_h = \frac{1}{n} \sum_{i=1}^{n} \frac{h_i}{\hat{h}_i}$$

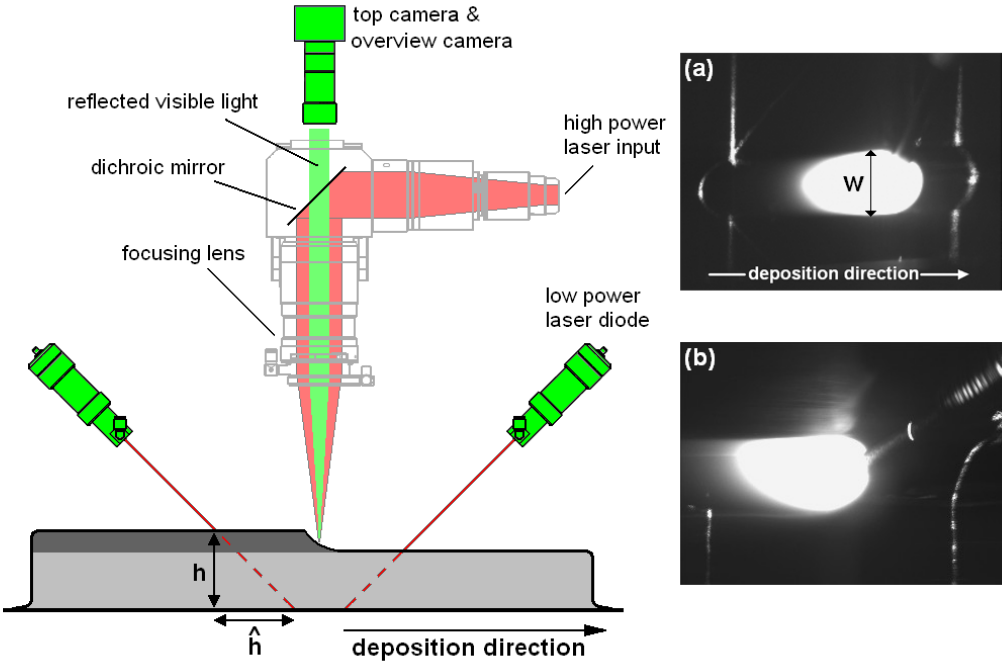


Figure 3.6: Schematics of the first generation RLMwD tool, with the high power laser light transmission in the optics indicated. Images to the right show how the process is observed by the top-view camera. Image (a) shows a case when both laser lines are visible. Image (b) shows when the rear laser line is no longer visible due to a higher surface temperature.

3.4.2 Bead width measurements

The bead width is assumed to equal the melt pool width, marked as w in Figure 3.6). To obtain correct width measurements the exposure time of the camera must be carefully adjusted in order for the measurement algorithm to properly detect the edges of the melt pool. For this, sufficient contrast between the melt pool contour and the surroundings is needed. However, the exposure time must not be too high in order to avoid blooming distortions of the melt pool in the image. In order to find the correct exposure time, beads were deposited with the desired nominal parameters (with the real width known in advance) while the exposure time was tuned until correct measured width was obtained. This procedure might need revising when process parameters with substantially different heat input than the ones used for calibration are used.

3.4.3 Evaluation results

The two laser diodes were originally red-color (off-the-shelf) diodes at 785 nm. Although the projected laser lines were focused and with relatively high power (80 mW), the wavelength is not optimized for hot process measurements. This

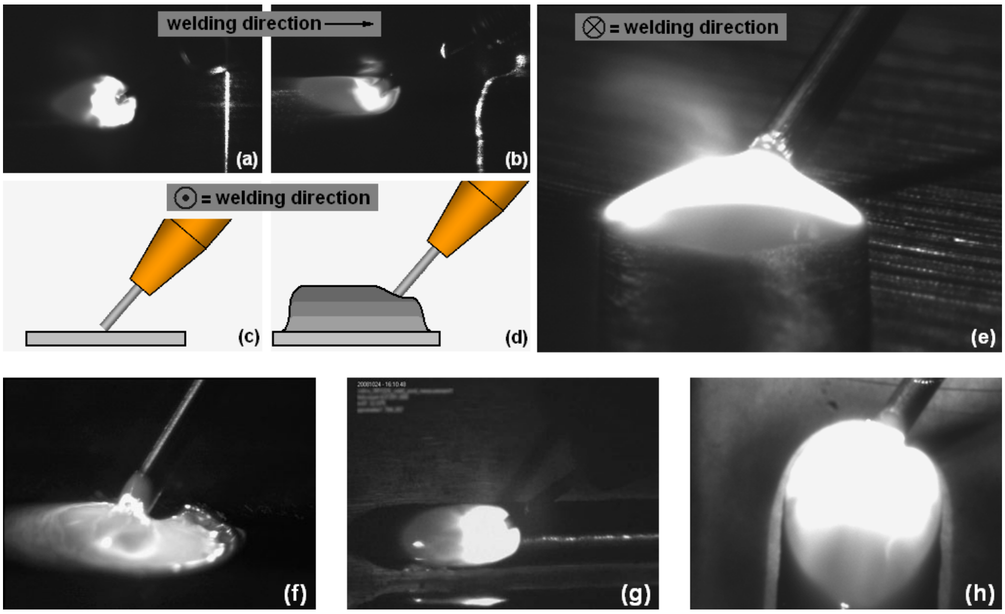


Figure 3.7: First generation tool setup. Images (a-d) show how the top layer height relative the welding tool is observed. Images (e-h) show close-up images captured by the melt pool camera from different angles, see the text for details (halogen illumination has been used in images e-h).

fact, together with the general difficulty of detecting laser lines on shiny surfaces, made the height measurements with this setup unreliable for automatic control. The rear height measurements were particularly affected because the temperature of the melt pool made the laser line hard to detect, unless pointed several cm behind the melt pool. This is illustrated in the right part of Figure 3.6.

Nevertheless, the tool setup could be utilized for manual control. The operators were able to use the melt pool images for making appropriate adjustments on the wire feed rate in order to maintain a stable and sound process. For straight bead deposition, the height feedback in front of the melt pool was also used to obtain a rough estimate of the height variations. Examples on visual feedback obtained during manual deposition is shown in Figure 3.7. Images (a-b) in Figure 3.7 show the top view of the melt pool and a projected laser line for two different situations, i.e. a bead on a planar surface (a), and an edge bead on top of few deposited layers (b). To clarify images (a-b) corresponding cross-sections are illustrated in images (c-d) in the same figure. In Figure 3.8 some of the parts deposited using this tool are shown.

During the deposition experiments, other placements of the melt pool camera were also investigated. Some of the resulting images are shown in Figure 3.7. Image (e) was obtained with a rear placement of the camera at 35 degrees from the substrate. Image (f) had the same angle relative to the substrate but was

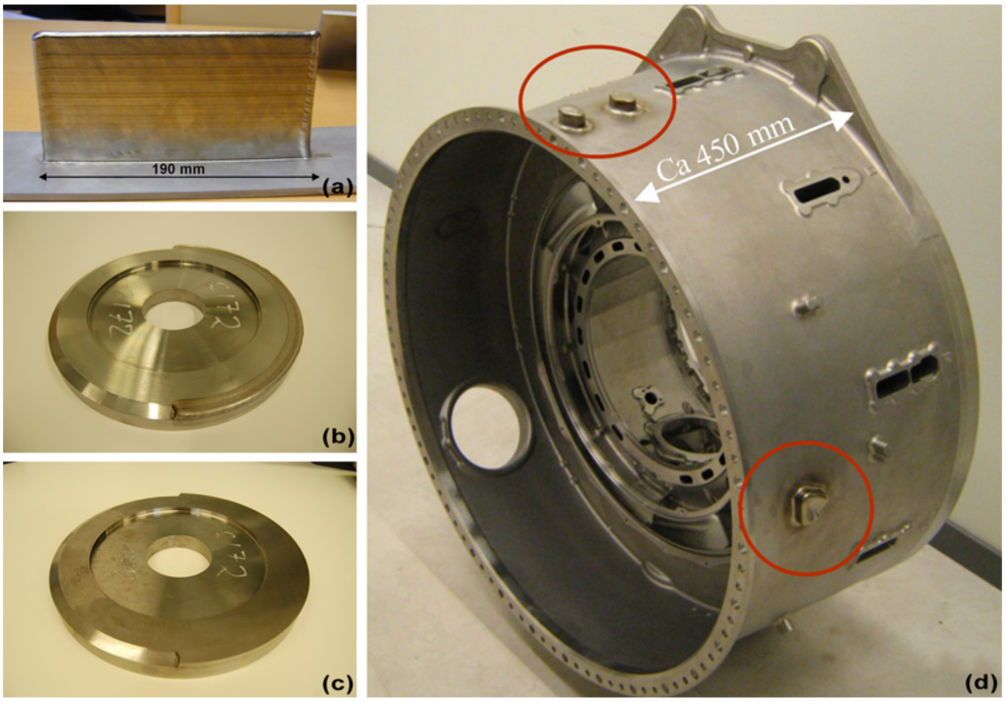


Figure 3.8: Geometries manufactured using manually controlled RLMwD (a and d deposited by Volvo Aero). (a): Multiple-bead wall. (b): Cutting edge deposited on a chamfered edge, (c): final shape is obtained after machining.(d): An aero engine casing with three different bosses deposited on the surface.

directed orthogonal to the deposition direction. Image (g) top view. Image (h) rear view with a 50 degrees angle from the substrate. In images (e-h) halogen illumination of 100 W was used in order to get a better image of the melt pool surrounding area .

The conclusion is that the desired way of monitoring the melt pool for manual control is mainly by placing the camera on the same vertical level as the melt pool, and orthogonal to the deposition direction. However, from a practical point of view, this placement is the most problematic due to reduced degree of freedom. Also, obtaining a side view of the melt pool, orthogonal to the deposition direction, is not feasible in practice for non-straight deposition patterns. More details regarding the manual control based on visual feedback is given in Paper 1.

3.5 RLMwD tool, second generation

In order to enable automatic control, the measurement accuracy needed to be improved. To start with, the red laser diodes were replaced by a single near-UV laser diode (409 nm), and the laser stripe was projected in front of the melt pool. During previous experiments, it was realized that a field of view covering both

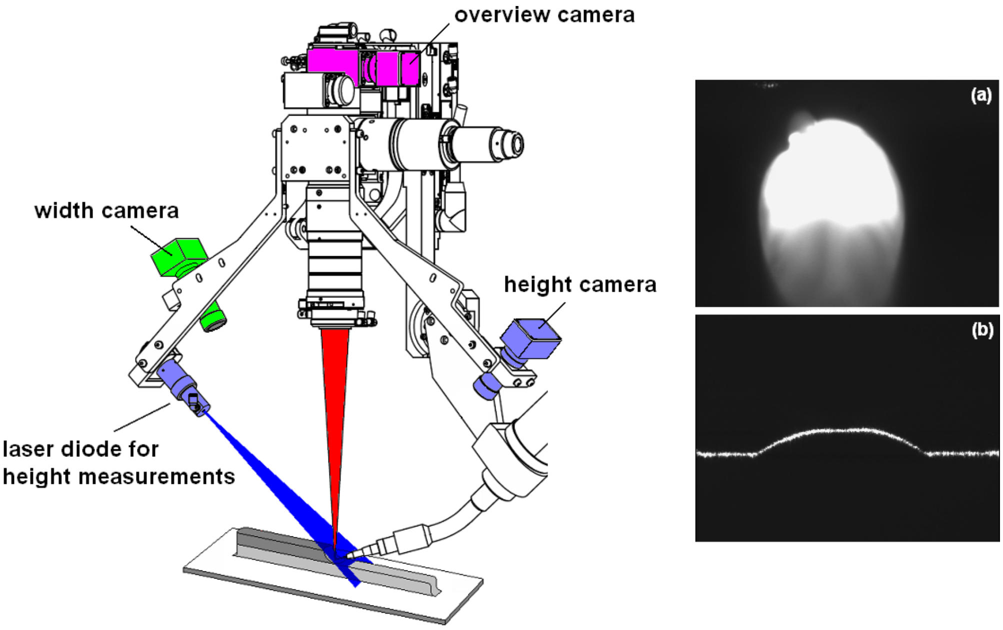


Figure 3.9: Sensor setup for automatic control. Image (a) shows a close-up of the melt pool captured by the *width camera*, while image (b) shows the projected laser line captured by the *height camera*.

the melt pool and the laser stripe is too large for sufficient measurement accuracy. Also, the top-view placement of the measurement camera is not optimal in regards to the possible amount of reflected light from the projected laser stripe. This means that the exposure time of the camera needs to be increased for better contrast between the laser line and the underlying surface, and this might make the width measurements erroneous due to the blooming effect of the camera sensor.

Hence, one camera for each measurement (melt pool width and bead height) was adopted. The new height measurement camera could now be zoomed in on the laser line to improve the accuracy. It was furthermore mounted at the opposite direction of the laser diode, see Figure 3.9. This way the reflection of the laser light going in to the height camera was maximized. The temperature effect on the measurement quality was reduced due to the near-UV wavelength of the diode and a narrow 10 nm FWHM (full width at half maximum) optic band pass filter with a central wavelength of 410 nm. With this setup, the maximum error of the height measurements relative the TCP was estimated to 50 μm.

The width camera was, at first, placed behind the dichroic mirror to give the top-view images of the melt pool. However, during experiments it was discovered that due to the continuous wave laser irradiation, thermal lensing was affecting the focal point. While the process itself is not noticeably affected by this, due to a relatively large Rayleigh range, i.e. depth-of-focus of the laser beam, the

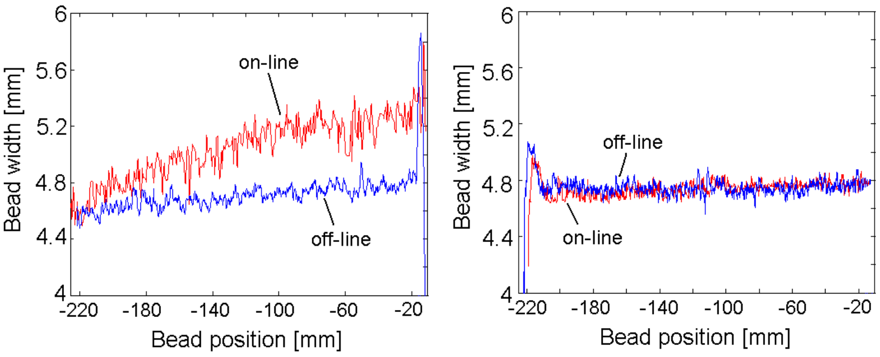


Figure 3.10: Bead width obtained through on-line measurements using the width camera compared with the *real* width (measured off-line using the projected laser line) for a non-clean cover glass (left) and a clean cover glass (right)

width measurement was. Furthermore, to protect the focusing lens from splatter and smoke from the process, a cover glass is mounted in front of the focusing lens. This glass needs to be changed occasionally due to contamination. However, while the process can accept certain degree of contamination, the blurring effect on the top-view camera's images, for the same degree of contamination is significant. A comparison between width measurements using a clean- and a contaminated cover glass is shown in Figure 3.10. In this comparison the degree of contamination was rather high since the process itself was also affected (seen by the change in real width of the bead).

To remedy this problem, the top mounted camera was moved outside the weld tool optics and equipped with its own lens. It was attached to the weld tool above the laser diode as shown in Figure 3.9, also showing an example on the resulting weld pool image. In Paper 2 the difference between placing the width camera inside and outside the weld optics is further discussed. In order to protect the camera from the high-power fiber laser reflections, a band-stop mirror was used in front of the camera optics. The mirror gives >90% reflection in the range 750 to 1200 nm. Automatic width and height control of straight bead deposition using this tool is demonstrated in Paper 2.

The sensitivity to correct exposure and blooming effect require that the exposure time, the sensitivity of the edge seeking algorithm, or the scaling from the measured width in pixels to a real width, is constantly revised based on the current conditions, such as the current process parameters or the material used. The shape of the melt pool also changes if adjacent beads are present. For non-single bead deposition, more advanced width measurement algorithms are therefore needed, including e.g. melt pool temperature feedback, or information about the deposition pattern. However, the shadowing effect from the wire makes the current width measurement approach hard to implement for arbitrary deposition patterns. Moreover, for certain deposition patterns, such as a spiral going inwards, the melt pool might overlap several beads, in which case the width measurements are non-intuitive. Due to these remarks, the width measurement concept was not further developed in this work.

3.6 RLMwD tool, third generation

The feedback system described in Section 3.5 was developed for straight bead deposition. In order to enable automatic control of the deposition process for arbitrary deposition patterns, new ways of obtaining feedback had to be developed. Experimental results regarding multi-bead multi-layered deposition have shown that, in order to obtain a stable deposition process, mainly the wire feed rate have to be controlled. Therefore, the focus for this tool has been on height feedback for arbitrary shapes and deposition patterns.

3.6.1 Height feedback for arbitrary deposition patterns

In the previous tool configurations, the height was measured on-line, i.e. during deposition. However, obtaining height measurements in the same way for arbitrary deposition patterns is not a straightforward task. Assume that the height of the surface, slightly in front of the melt pool, is desired. If this height is to be acquired on-line, the *height sensor* needs to know which position is considered as being in front of the melt pool, at all times. The *height sensor* must also be able to measure all points of interest despite shadowing, difficult angle of incidence, etc. If the *height sensor* is mounted on the deposition tool, it also needs to know how the desired measurement point on the deposited surface is related to the current tool's position and orientation.

A height sensor mounted on a deposition tool puts therefore high demands on the accuracy of the robot and the TCP definition, as well as on the measurement capability independent from the orientation of the robot relative to the surface of interest. The two requirements are however hard to fulfill due to relative inaccuracy of industrial robots, and a general difficulty of obtaining height measurements of hot, bright, and shiny metal surface (with additional high power laser reflections) at arbitrary angles of incidence. Mounting an external sensor, i.e. on the surrounding substrate, is also less feasible from a production point of view. For each new substrate and each new part (if multiple parts on a same substrate), the sensor should be repositioned and calibrated, which might be complicated and time-consuming. Simultaneous deposition of several parts is also less feasible. Shadowing of the substrate due to the wire and the nozzle is also a major drawback for such a setup.

Due to these problems, an off-line (however in-process) height measurement method is instead developed. It is based on a laser line scanner and linear robot motion. That is, a laser line is projected onto the target surface and the reflected light is captured by a two dimensional sensor from which a single-line height profile is calculated. A 3D height profile is obtained by a relative movement between the scanner and the part, generated by the robot, during which the scanner is triggered to perform measurements. Each profile is then paired with the corresponding robot coordinates to create a point cloud of the scanned surface. The height of the part is scanned this way after each deposited layer.

3.6.2 Scanner integration in the existing system

The line scanner tested in this work is a laser scanner from Micro-Epsilon (scanControl 2810-25). Resolution of the scanner in the vertical direction is specified to 10 μm. The part is scanned with a speed of 5 mm/s, and an in-house developed software, implemented in LabVIEW and incorporated in the aforementioned RLMwD-control system, triggers the scanner and extracts a new profile each 50 ms. This results in 250 μm spatial resolution along the scanned path. At the currently chosen measurement distance (between the scanner and the part), the length of the laser line is around 35 mm. The maximum number of measurement points per scanned line is 1024, however, in order to limit the amount of information generated for each scanning, 256 points/line are used. This gives a spatial resolution of 140 μm along the laser line. The sensor is pre-calibrated and need no further on-site calibration. However, the laser line needs to be related to the robot's TCP in order to correctly orient the obtained point cloud.

The resulting 2D profiles are recorded and saved in the MySQL database along with the robot coordinates. Using an in-house developed height analyzer program implemented in Matlab, the profiles are combined into a point cloud and matched with the real deposition path of the robot. This way, the surface height of the deposited part, along the deposition trajectory, is extracted. A block diagram of the expanded RLMwD system (original version discussed in Section 3.3), is shown in Figure 3.11, and the user interface of the height analyzer program is shown in Figure 3.12. It shows a scanned surface, the deposition path, the extracted height and a suggested control action for the wire feed rate. For further details regarding wire feed rate control based on height scanning see Papers 3 and 5.

During deposition it is important to protect the scanner from the high power laser reflections and the heat radiation from the built part. For this purpose, a linear drive unit, on which the scanner is mounted, is utilized such that it lifts the scanner away from the melt pool during the actual deposition, and lowers it down at the time of scanning, see Figure 3.13. The repeatability of the linear drive unit in the vertical direction is measured to $\leq 30\mu$m.

The concept of off-line height measurements has been demonstrated in Pa-

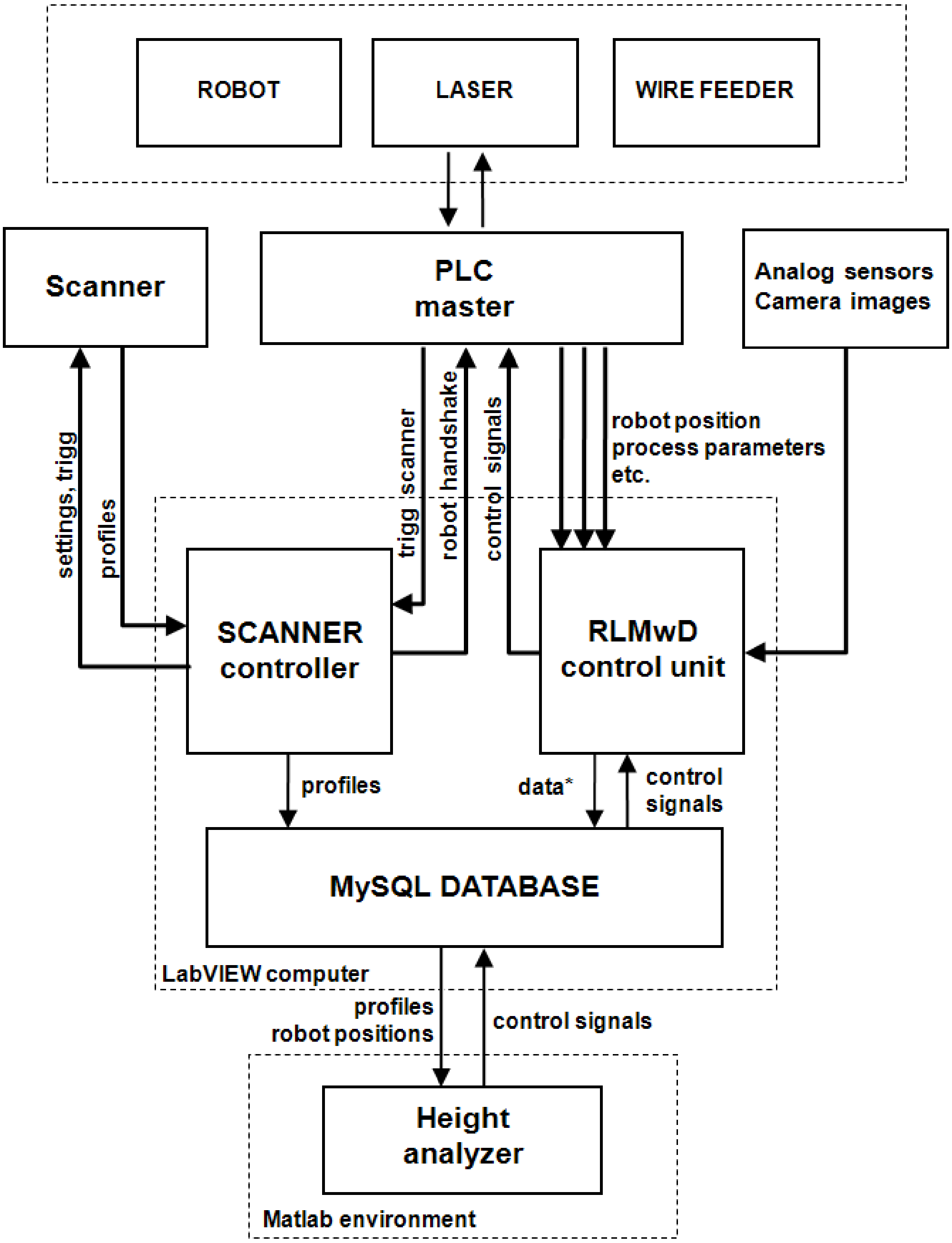
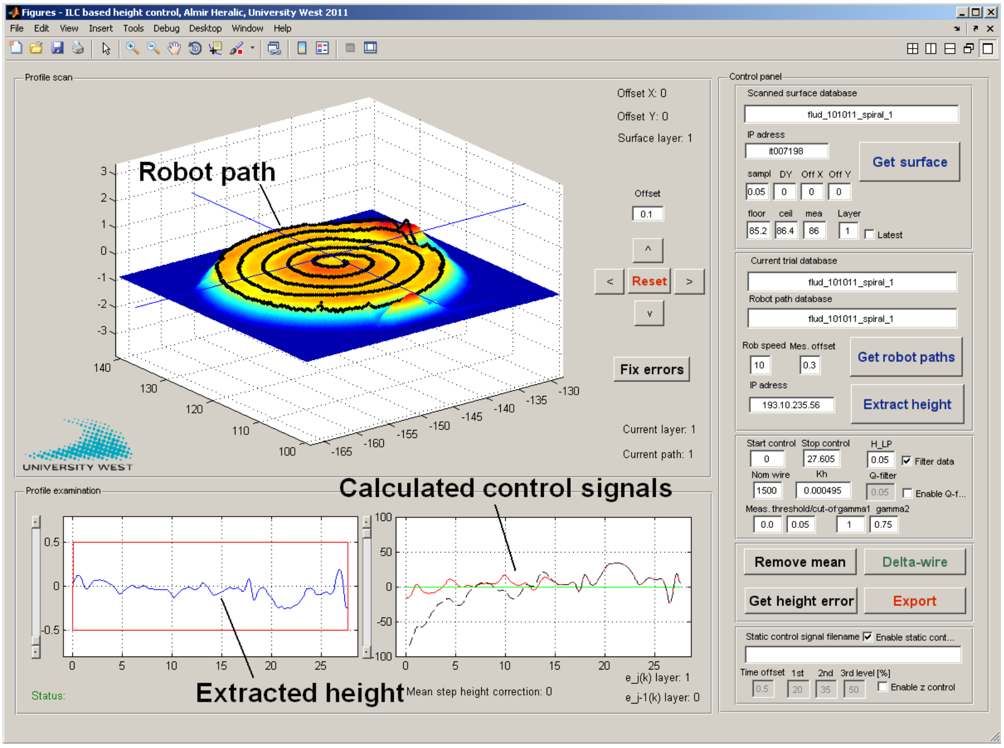


Figure 3.11: Expanded communication architecture due to introduction of the scanner and the height analyzer. data* refers to all data that is measured by the DAQ unit and generated by the RLMwD control unit.

pers 3 and 5. The results are satisfying since the method enables automatic height control of deposition using arbitrary paths. However, it is important to note that the scanner utilized in this work is not optimized for scanning of bright and hot metal surfaces. This has primarily affected the ability to obtain a correct rep-



Offset X: 0
Offset Y: 0
Surface layer: 1
Offset 0.1
Current layer: 1
Current path: 1
Status:
Mean step height correction: 0
e_j(k) layer: 1
e_j-1(k) layer: 0

Scanned surface database: flud_101011_spiral_1
IP adress: it007198
sampl 0.05 DY 0 Off X 0 Off Y 0
floor 85.2 ceil 86.4 mea 86 Layer 1 ☐ Latest
Current trial database: flud_101011_spiral_1
Robot path database: flud_101011_spiral_1
Rob speed 10 Mes. offset 0.3
IP adress 193.10.235.56
Start control 0 Stop control 27.605 H_LP 0.05 ☑ Filter data
Nom wire 1500 Kh 0.000495 Q-filter 0.05 ☐ Enable Q-f...
Meas. threshold/cut-of 0.0 0.05 gamma1 1 gamma2 0.75
Static control signal filename ☑ Enable static cont...
Time offset 0.5 1st 20 2nd 35 3rd level [%] 50 ☐ Enable z control

Figure 3.12: A screen-shot of the height analyzer program developed in this work.

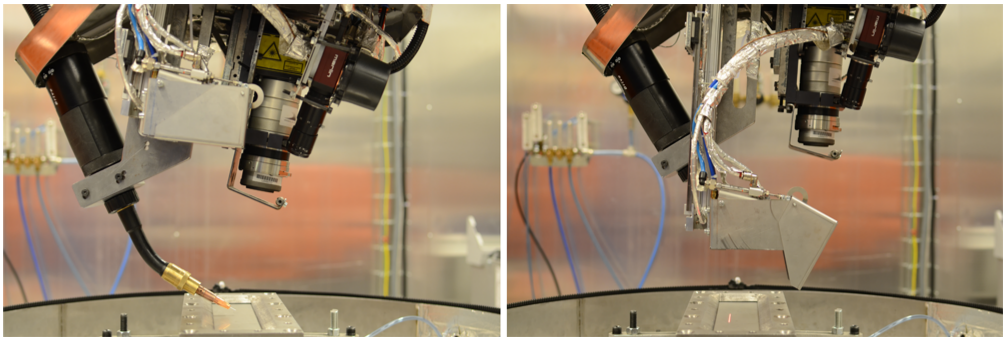


Figure 3.13: The third generation deposition tool developed in this work with a laser scanner mounted inside a protective housing. Left: In deposition mode the scanner is lifted away from the process to protect it from heat radiation and high-power laser reflections. Right: In scanning mode a liner drive unit lowers the scanner down before scanning.

resentation of the outer contour beads. Hence, for this measurement approach to be adopted in real production, the actual sensor must be revised, based on measurement accuracy for bright and hot surfaces, ability to capture chamfered edges, measurement time, and calibration requirements.

Chapter 4

Utilization of additive manufacturing

Several areas have been identified within which additive manufacturing show great potential, such as rapid prototyping, repair or modification of high-value components, and fabrication of complex structures. In this section, two examples are presented that demonstrate possible applications for metal deposition technique. Both examples are made using the equipment presented in this thesis. Based on the results, the technology is expected to be beneficial in almost any company where hardfacing is done on regular basis, e.g. die repair, or in production where milling of oversized components is a common manufacturing step, i.e. by adding features onto substrates can reduce the need of milling.

4.1 Fabrication

One of Volvo Aero's component specializations is aircraft engine structures. These are large static components that act as casings and attachments for the moving parts of aero engines. For many years, these structures have been manufactured as one-piece castings. An example of a casing is shown in the right part of Figure 4.1. In the recent time, there have been a growing market demand on reduced fuel consumption with maintained or increased cargo capacities. This has created a need for new manufacturing techniques that can deliver structures that are both light and high-strength at the same time, in order to compensate for a relatively low strength/weigth ratio of the casted components.

During the past few years, Volvo Aero has therefore been developing the fabrication concept [1, 2]. A fabricated structure is built by joining smaller subcomponents made of several different material forms and alloys, see the left part of Figure 4.1. The parts are mainly combined using welding. The weight of the final component is reduced by efficiently exploiting the different mechanical

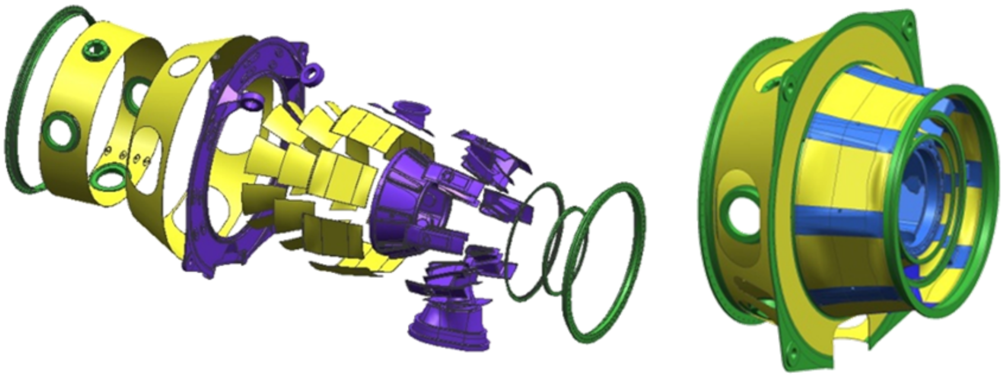


Figure 4.1: Fabrication concept: A number of smaller sub-components made of different material forms (left) are joined by welding into a final casing (right).

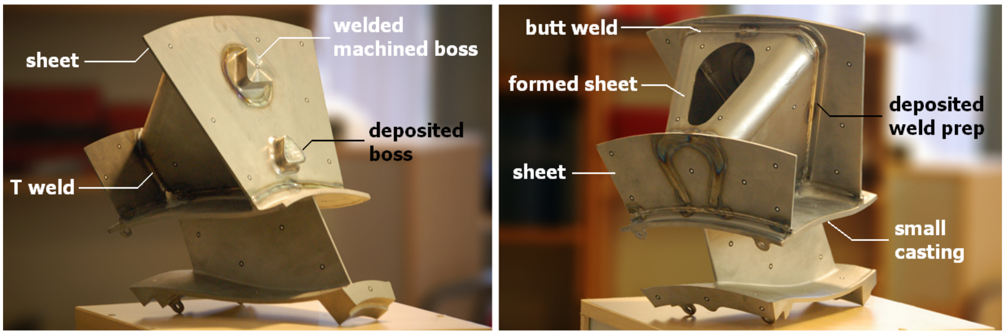


Figure 4.2: Fabricated segment consisting of sheet metal, a small casting, a machined and a deposited boss.

properties and achievable geometrical tolerances for castings, forgings and sheet material. In a recent study, the substitution of cast material with sheet, forged and deposited material was estimated to give a weight reduction potential up to 15% [1]. The fabrication concept was evaluated on a sector demonstrator shown in Figure 4.2 with promising results. The equipment developed in this work was used to deposit a weld prep, which allowed a butt weld to be performed between two sheet metals, resulting in less heat input than if a T-weld should have been performed. A boss was also deposited on one of the sheet metals. The process was compared to the inserted boss. While metal deposition basically consists of two operations, deposition and post-machining, inserting a boss by welding gives a number of different steps, such as machining, joint preparation, fixation of the part, and welding. The higher number of operations result in an increased production cost and introduces more error sources.

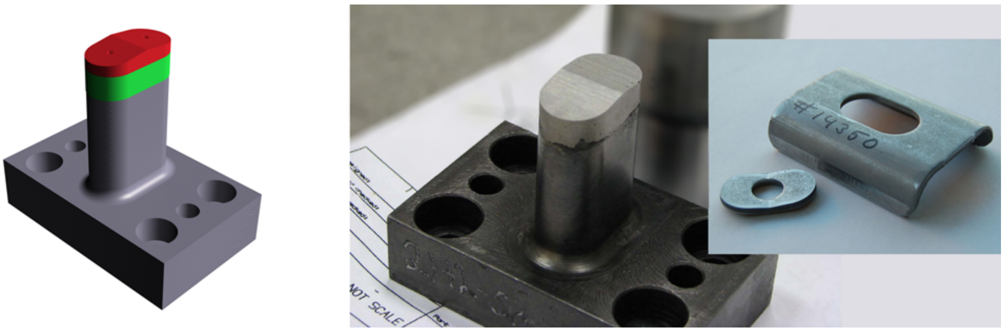


Figure 4.3: Left: A CAD drawing of the punching die. Right: The final die obtained by deposition high grade steel onto a mild steel die shoe. The image also shows the punched part with the removed piece lying aside.

4.2 Tool repair

In stamping tool shops in the manufacturing industry, manual metal deposition using various weld sources has been used for many years. Common applications are die repair and die changes. Trim dies typically consists of a die made of mild steel and insert steels of high grade, i.e. with better wear properties. As the trim steels wear, they should be repaired or changed. An alternative to insert steels and a mean to lower investment costs, is to manufacture the trim edge by welding on the die shoe directly, a process known as hardfacing. In order to minimize the deposit, it is desirable to start with a geometry that is as close to the finished part as possible. However, the final deposited area must fulfil the mechanical properties of a trim edge. Using an RLMwD system could potentially minimize the amount of material deposited for each repair/modification, compared to manual operations, and thereby also minimize the post-milling time.

In order to test the developed RLMwD system in a repair application, a punching die was manufactured in collaboration with Saab Automobile. A die shoe was made in mild steel without the trim edge, and a number of layers of a high grade steel material were deposited in order to fill the missing trim edge volume. After milling, the final trim edge could then be obtained, see Figure 4.3. The punching die was tested on 3.5 mm thick plates (also shown in the figure) with great success. The final number of punching operations before the tool had to be repaired, exceeded the number of operations obtained for the original tool (made completely of the high grade steel material).

Chapter 5

Iterative learning control

The repetitive character of the deposition process calls for a control scheme that takes this behavior into account, and iterative learning control (ILC) has shown to be very useful. The concept of iterative learning control is here shortly described with focus on discrete-time linear systems. A description of ILC updating formulas is presented and stability and convergence properties are discussed. Finally a design method is presented.

5.1 Introduction to ILC concept

The concept of ILC has its origin in industrial robot applications where the same task is performed repeatedly. The idea is that the performance of such systems can be improved by learning from previous executions. ILC differs from other learning-type control strategies, such as adaptive control and neural networks, because ILC modifies the control input, which is a signal, whereas the other methods modify the controller itself, which is a system [65]. The ILC concept was mathematically formalized three decades ago [66], [67]. Since then, it has been utilized in a variety of applications, see e.g. [68] for an overview.

The goal of ILC is to generate feed-forward control that suppresses a repeating disturbance. By learning from previous iterations, ILC does not require that the disturbances are known or measured, only that these signals are recurring from iteration to iteration. Because ILC generates its open-loop control in the time domain through experience, i.e. feedback in the iteration domain, high performance can be achieved despite large model uncertainty and repeating disturbances [65]. Moreover, the iteration-to-iteration learning of ILC provides opportunities for advanced filtering and signal processing. One example is zero-phase filtering [69], which is commonly used in ILC. The filter is noncausal and allows for high-frequency attenuation without introducing lag.

Note that, since ILC uses open-loop control action only, it cannot compensate for nonrepeating disturbances when applied to iteration independent processes. Thus, in many physical implementations, a feedback controller is often used in combination with ILC. Usually, a feedback controller already exists for the intended system to which an ILC algorithm is applied. However, this is not an issue since ILC can be implemented without modifying the feedback controller. A common example is motion control of industrial robot arms for increased position accuracy, where ILC can be applied to the reference signal and thereby influence the motion of the robot without modifying the robot's existing feedback controllers [70], [71] and [72].

5.2 ILC updating formula

In this section the updating of the ILC output signal is discussed. The ILC updating formulas can be generalized into two groups, according to how the information from previous iterations is utilized. If the updating formula only uses measurements from the previous iteration, the ILC algorithm is called a *first order* ILC. When the ILC updating formula uses measurements from more than the previous iteration, it is called a *high order* ILC [73]. In order to emphasize the number of previous iterations used in the updating formula, the term second order, third order, etc., is used. Note that an ILC algorithm is not only characterized by whether it is a first order or a high order ILC algorithm, but also if it is a linear or a nonlinear. In this chapter, only linear ILC algorithms are considered.

5.2.1 First order ILC

A number of different ILC algorithm structures have been suggested in literature. Common for most of the suggested algorithms, [65], [66], [73], [72], is that the structure is given by

$$u_{j+1}(k) = Q(q_k)(u_j(k) + L(q_k)e_j(k)) \tag{5.1}$$

where $Q(q_k)$ and $L(q_k)$, defined as the Q-filter and learning function, respectively, are filters in the time shift operator q_k (${q_k}^{-1}u_j(k) = u_j(k-1)$). Furthermore, u_j is the control signal, e_j is the error, i.e. the deviation from the reference, j is the iteration index, and k is the discrete time. The Q and L-filters are discussed in the following

5.2.2 Higher order ILC

Higher order ILC algorithms were first introduced in [74]. The authors conclude that the rate of convergence can be improved when incorporating errors from previous iterations. According to [73], a general linear time invariant high order ILC can be written according to

$$u_{j+1}(k) = \sum_{l=j-N+1}^{j} \left(Q_{j-l+1}(q_k)\left[u_l(k) + L_{j-l+1}(q_k)e_l(k)\right]\right) \tag{5.2}$$

where $Q_l(q_k)$ and $L_l(q_k)$, $l = 1, ..., N$ represent linear transfer operators. That is, the control signal for the next iteration is calculated from the control signals and the errors in the N previous iterations. This represents an Nth order ILC algorithm. Increasing the *order* of the ILC algorithm can be interpreted as introducing iteration-domain filtering, which might be useful as a way of e.g. reducing the effect of measurement disturbances [75].

5.3 Convergence properties

In this section convergence properties of ILC algorithms are considered. The effect of disturbances are not covered in this overview. Instead an ILC algorithm applied to a disturbance-free system is studied. A thorough investigation of convergence properties of ILC algorithms can e.g. be found in [76].

Consider a disturbance-free linear time- and iteration-invariant system T with two inputs; a reference signal $r(k)$ and an externally-generated control signal $u(k)$, and one output $y(k)$, which in discrete time can be described as

$$y_j(k) = T_r(q_k)r(k) + T_u(q_k)u_j(k) \tag{5.3}$$

where transfer operators T_r and T_u are assumed to be stable. Define the vector **r** of the N-sample sequence of the reference signal $r(k)$ as

$$\mathbf{r} = (r(0), ..., r(N-1))^T \tag{5.4}$$

The vectors **u** and **y** are defined analogously. The system in (5.3) can then be rewritten in matrix form as

$$\mathbf{y}_j = \mathbf{T}_r\mathbf{r} + \mathbf{T}_u\mathbf{u}_j \tag{5.5}$$

where

$$\mathbf{T}_r = \begin{bmatrix} g_{T_r}(0) & 0 & \cdots & 0 \\ g_{T_r}(1) & g_{T_r}(0) & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ g_{T_r}(N-1) & g_{T_r}(N-2) & \cdots & g_{T_r}(0) \end{bmatrix} \tag{5.6}$$

and $g_{T_r}(k)$, $k \in [0, N-1]$ is the impulse response of the transfer operator $T_r(q_k)$ in (5.3), and the sampling time is assumed to be 1. The matrix $\mathbf{T}_u$ is given in the same way.

The stability analysis of ILC algorithms will be based on the use of a class of systems called linear iterative systems [76], defined on a discrete and limited time interval.

$$\mathbf{z}_{j+1} = \mathbf{F}\mathbf{z}_j + \mathbf{F}_r\mathbf{r} \tag{5.7}$$

where the vectors $\mathbf{z}_j$ and $\mathbf{z}_{j+1}$ are defined from the N-sample sequence of the corresponding signals, similarly as in (5.4).

In order to apply the ILC algorithm in (5.1) to the system in (5.5), the ILC algorithm is first rewritten in matrix form according to

$$\begin{aligned} \mathbf{u}_{j+1} &= \mathbf{Q}(\mathbf{u}_j + \mathbf{L}\mathbf{e}_j) \\ \mathbf{e}_j &= \mathbf{r} - \mathbf{y}_j \end{aligned} \tag{5.8}$$

That is, the ILC is applied to iteratively update the control signal $u(k)$ such that the output $y(k)$ tracks the reference $r(k)$. Applying (5.8) to the system in (5.5) gives

$$\mathbf{u}_{j+1} = \mathbf{Q}(I - \mathbf{L}\mathbf{T}_u)\mathbf{u}_j + \mathbf{Q}\mathbf{L}(I - \mathbf{T}_r)\mathbf{r} \tag{5.9}$$

By substituting $\mathbf{z}_j = \mathbf{u}_j$, $\mathbf{F} = \mathbf{Q}(I - \mathbf{L}\mathbf{T}_u)$ and $\mathbf{F}_r = \mathbf{Q}\mathbf{L}(I - \mathbf{T}_r)$ it can be seen that the ILC system in (5.9) is a special case of the linear iterative system (5.7).

5.3.1 Stability

An essential property of a linear iterative system is asymptotic stability. Consider the linear iterative system given in (5.7). The system is asymptotically stable if and only if

$$\rho(\mathbf{F}) < 1 \tag{5.10}$$

where $\rho(\mathbf{F})$ is the spectral radius of the matrix $\mathbf{F}$ defined as as follows

$$\rho(\mathbf{F}) = \max_{i=1,\ldots,N} |\lambda_i(\mathbf{F})| \tag{5.11}$$

with $\lambda_i(\mathbf{F})$ denoting the ith eigenvalue of the matrix $\mathbf{F} \in \mathbb{R}^{N\times N}$. Based on this, the ILC system in (5.9) is asymptotically stable if and only if [76]

$$\rho(\mathbf{Q}(I - \mathbf{L}\mathbf{T}_u)) < 1 \tag{5.12}$$

However, for the process considered in this work, the iterations, i.e. the layers, are not independent from each other. This, since the deposition process is not started on a new flat substrate for each new iteration, but rather continues on the last deposited layer. Hence, the errors from one iteration are inherited to the subsequent iterations. This means that the ILC system in (5.9) cannot be represented without the output $\mathbf{y}_j$. Hence, the stability criteria in (5.10) requires an augmented representation of the ILC system, which includes the plant dynamics. This is further discussed in Paper 3.

5.4 Design methods

The goal of the ILC it to generate an open-loop signal that approximately inverts the plant's dynamics in order to track the reference and reject repeating disturbances. The reference in this work is a flat surface of the deposited layers throughout the deposition process. There are several ILC design techniques which can be used depending on the level of system knowledge, e.g. the ability to obtain a good inverse of the plant. Some of these techniques are e.g. discussed in [68]. In this work a tunable ILC design is utilized to minimize the need for extensive modeling and analysis.

Normally in ILC design, asymptotic stability is not a sufficient criterion because it does not explain the transient learning behavior. To avoid large transients, monotonic convergence is therefore desirable. However, for the *additive* process considered in this work, i.e. where errors are inherited from iteration to iteration, it is presumably too demanding to require monotonic convergence. This should be taken into account when tuning the ILC algorithm in this work.

The ILC algorithm presented in Paper 3 and 5 is a *second* order ILC according to (5.13). A higher order structure is adopted since a stable first order ILC could not be obtained for the intended deposition process.

$$u_{j+1}(k) = Q(q_k)[u_j(k) + q_k^d(\gamma_1 e_j(k) + \gamma_2 e_{j-1}(k))] \tag{5.13}$$

where u_j is the control input that controls the wire feed rate on layer j, γ_i are the so called learning gains, and k is the discrete time. Furthermore, a time shift operator, q_k^d, acts on the two error signals, $e_j(k)$ and $e_{j-1}(k)$, where d denotes the number of samples the corresponding signal is shifted in time.

In order to get reasonable transients during the learning process, a common approach is to define the Q-filter as a low pass filter [77]. The low pass Q-filter disables learning at high frequencies which is useful towards satisfying the monotonic convergence. It also has the benefits of added robustness and high-frequency noise filtering. However, the increased robustness comes with a cost of decreased performance. In order to enable high frequency attenuation without introducing lag, the Q-filter is here chosen as a zero-phase low pass filter based on a 2nd order Butterworth filter, [69].

Hence, there are 4 parameters to tune, namely the Q-filter, the time shift d

in q_k^d, and the learning gains γ_1 and γ_2. In this work, the learning gains are first tuned, with Q=1 and $d = 0$ ($q_k^d = 1$), by investigating asymptotic stability of the ILC algorithm (5.13) for a number of different γ_1 and γ_2 combinations. A special care is taken to produce a controller that will have low control action, i.e. a slow response, in order to obtain as smooth deposition process as possible. When a suitable (γ_1, γ_2) pair is found, an appropriate Q-filter and time shift are added to increase the robustness. Details for this are given in Paper 3 and 5.

Chapter 6

Summary of Appended Papers

This chapter gives a brief summary of the papers that the thesis is based on. In Part II, the papers are appended in their complete versions, reformatted.

Paper 1

A. Heralić, M. Ottosson, K. Hurtig and A.-K. Christiansson, Visual feedback for operator interaction in robotized laser metal deposition, *Proceedings of the* 22^{nd} *Conference on Surface Modification Technologies*, 2008,Trollhättan, Sweden

The paper presents a way of using visual feedback to facilitate for operator interaction in laser metal wire deposition. A data acquisition and monitoring system is developed, which enables an operator to observe and control the process from a safe distance. Mainly the interaction between the wire and the melt pool is discussed, and how situations where there is an increased probability for lack-of-fusion defects can be observed from the melt pool images.

Lack-of-fusion defects are a result of insufficient melting of the wire, which is due to e.g. low energy input, high wire feed rate, or improper setup of the wire nozzle relative to the melt pool. When the wire feed rate is too high in respect to the energy input, the wire reaches the surface still solid. This can be observed by an oscillating motion of the wire tip (due to the stubbing of the wire tip against the surface). It is a first indication that the upper limit of the process window for the chosen energy input has been reached. It is then crucial to change the process parameters in order to avoid lack-of-fusion defects.

The paper also investigates the process window of the titanium alloy Ti-6Al-4V for a single traverse speed. The process window is obtained by depositing single beads and varying the laser power and wire feed rate around a nominal value. If the wire feed rate is too low in respect to the laser power, the metal transfer becomes globular, i.e. droplet-like. If the wire feed rate is too high, the lack-of-fusion defects emerge, and for even higher feed rates the wire bounces out of the melt pool completely, leaving large areas undeposited.

Based on this knowledge, the paper finally discusses how the monitoring system can be used for manual on-line control during deposition. The method is demonstrated by depositing a multi-layered wall.

Paper 2

A. Heralić, A.-K. Christiansson, M. Ottosson, and B. Lennartson, Increased stability in laser metal wire deposition through feedback from optical measurements, *Optics and Lasers in Engineering, 48(4), pp 478-485*, 2010

Automatic bead height and width control is described in this paper. A monitoring system, comprising two cameras and a projected laser line, is developed for on-line measurement and control of the deposition process. One camera is utilized for measuring the melt pool width from which the solidified bead width is derived. The other camera is utilized for observing the projected laser line in order to extract the height variations of the previous layer.

The controller is a combination of a PI-controller for the bead width and a feed-forward compensator for the bead height. The laser line is here projected in front of the melt pool in order to obtain the feed-forward compensation signal. The combined controller is evaluated through deposition of single-bead walls. It ensures constant width and height during deposition by controlling the laser power and the wire feed rate, respectively. Through height control, the risk for droplets or stubbing is decreased and the stability of the process is improved. For the measurement system described in this paper, feedback is only possible for straight bead deposition.

The results show that camera based feedback can preferably be used for online control of the laser metal wire deposition, however with certain caution due to measurement disturbances. Major problems were detected for visual monitoring through the focusing optics of the deposition tool, i.e. through a dichroic mirror. Due to thermal lensing, the focus of the images were affected which lead to erroneous measurements. The cameras were therefore moved outside the deposition optics and equipped with their own focusing optics improved results.

The overall difference in bead width between the controlled and uncontrolled wall was rather small, indicating that width control might only be needed for extreme situations where the pause between the layers is short so that considerable heat is accumulated in the part.

Paper 3

A. Heralić, A.-K. Christiansson, and B. Lennartson, Height control of laser metal-wire deposition based on iterative learning control and 3D scanning, *Accepted for publications in Optics and Lasers in Engineering*

In this work a 3D scanning system is developed and integrated with the robot control system for automatic in-process control given arbitrary deposition patterns. The goal in this paper is to ensure stable deposition, by means of choosing a correct offset of the robot in the vertical direction, and by obtaining a flat surface, for each deposited layer.

The scanning system is based on a laser line scanner that produces 2D profiles. By moving the robot in a linear motion across the deposited part, a number of 2D profiles are obtained. These are combined into a point cloud of the scanned surface. By merging the obtained point cloud with the real deposition path of the robot, the height variations along this path are obtained. After each deposited layer a new scanning is performed.

The deviations in the layer height are compensated by controlling the wire feed rate on subsequent deposition layer, by means of iterative learning control. The iterative learning controller (ILC) learns the different traits of the current deposition on-line and ensures that the height variations are maintained around a few tenths of a millimeter.

In this paper, a model of the deposition process dynamics is derived based on step response experiments. Using the obtained model, the stability of the ILC is evaluated for varying controller parameters. Based on the stability analysis a set of controller parameters are derived such that robustness is prioritized over performance. The controller is tested by depositing a small circular cylinder for successful 35 layers.

Because the height measurements are obtained off-line, i.e. in-between the layers, the ILC is able to handle arbitrary deposition patterns, which is an important development from the controller presented in Paper 2. The experimental results show that iterative learning control, including 3D scanning, is a suitable method for automatic deposition of *small size* structures such as bosses. The utilized scanner is however not adapted for scanning of bright and hot surfaces. Moreover, the chamfered edge of the contour bead could not be reproduced in a reliable way, why the contour bead was not controlled. Obtaining reliable height measurements is therefore an important issue for future work.

A summarized version of this paper was presented at the 30th International Congress on Applications of Lasers and Electro-Optics, ICALEO'11, where it was chosen for the 2nd Place award in the Student Paper Award Contest.

Paper 4

A. Heralić, C. Charles Murgau, Dž. Imamović, A.-K. Christiansson, and B. Lennartson, Towards stable high-speed metal-wire deposition, Part I: Parameter study, *Submitted to Journal of Laser Applications*

This paper focuses on the problem that the deposition process is still controlled manually in industry, and hence the outcome is strongly dependent on the skills of the operator. The paper focuses specially on high traverse speeds, since the possibility of proper manual control action in these situations is likely to be decreased. The paper investigates the stability issues related to high-speed deposition, as a first step towards developing an automatic process controller.

A comparison between different deposition speeds for single beads and multi-bead single layers is made, by means of heat affect in the substrate, surface temperatures, microstructure, hardness, and layer height variations. The study shows that high-speed deposition generates less heat input into the substrate (for maintained bead width and height). The process is however more likely to be unstable, unless process parameters are carefully tuned. There is also a notable difference between the prior beta grain sizes for the compared samples, such that the size of the grains are decreased with higher traverse speed. The microstructure analysis in this paper was not performed by the thesis author.

The stability issues come from the high variations in the layer height, probably due to the acceleration of the robot, or the energy residuals' effect on the shape of the solidified beads because of a higher laser power. If there are large height variations on the deposited layers, the subsequent deposition might suffer from lack-of-fusion defects or globular transfer. The deposition process is evaluated by depositing single-layer circular cylinders as those deposited in Paper 3.

The results indicate that the high-speed deposition can be favorable from a heat affect point of view. However, high traverse speeds require careful tuning of the process parameters, and preferably also process control, in order to obtain a flat surface of the deposited layers, and thereby obtain a stable deposition process.

Paper 5

> A. Heralić, A.-K. Christiansson, and B. Lennartson, Towards stable high-speed metal-wire deposition, Part II: Automatic deposition using feedback control, *Invited submission to Journal of Laser Applications*

This paper discusses the stability problems related to high speed deposition (derived from Paper 4) and suggests a control strategy for handling these problems. The main idea is to ensure a flat top surface of the deposited structure, throughout the deposition, in order to keep the process conditions as constant as possible.

The deviations in the layer height are compensated by controlling the wire feed rate on the subsequent deposition layer, based on 3D scanned data, by means of iterative learning control. The controller is hence based on the results from Paper 3. However, in order to better handle the large initial height deviations, resulting from the high traverse speed, a feed-forward compensation signal is added to the ILC control action. The feed-forward signal is based on height deviations of a single layer, deposited using nominal parameters. Using the feed-forward compensator the emerging height deviations during deposition of successive layers are moderate and resembles a more stable slow-speed deposition.

The stability of the controller is investigated by examining the eigenvalues of the system matrix, which describes the plant dynamics and the learning dynamics of the ILC. It is found that the ILC needs to incorporate height measurements of at least two previous layers. For robust control, the bandwidth of the controller should also be limited to low frequencies.

To obtain a flat surface for the intended component and deposition pattern, large changes in wire feed rate have shown to be necessary, which might lead to instability during deposition. To ensure stability in these conditions, a dynamic TCP (Tool Center Point) offset controller is suggested, such that it controls the robot's TCP in the vertical direction, based on current wire feed rate and height deviation from a mean layer height. The TCP offset ensures that appropriate heat input into the wire is obtained at all times. The results are satisfying and indicate a usefulness of such control systems.

In this work the TCP controller is tuned manually based on experimental results. It is therefore hard to generalize the presented results to other tool configurations and materials. A more thorough investigation about the mechanisms behind stable metal transfer for different tool setups, wire diameters and materials are therefore needed.

Chapter 7

Concluding remarks

The objective of this research is to develop an understanding of the novel laser metal-wire deposition process and to obtain stable deposition through manual and automatic process control. Standard industrial laser welding equipment has been used with small modifications. This work shows that it is possible to monitor and control the wire based deposition process, both manually and automatically. These results are of great interest for future work towards developing a robust and automated manufacturing process, certified for demanding applications such as those found in the aerospace industry.

7.1 Conclusion

This thesis highlights what needs to be monitored in order to ensure stable deposition of the titanium alloy Ti-6Al-4V. The key point is to ensure proper interaction between the wire and the melt pool at all times during deposition. The process parameters and the tool setup should therefore be carefully tuned, with emphasis on the wire nozzle setup in relation to the laser power, wire feed rate, and the traverse speed.

In order to maintain good process conditions during deposition, the surface of the deposited layers should be as flat as possible. One way to ensure this is by controlling the wire feed rate based on height variations. For large wire feed rates (due to large height variations) the robot's TCP should be adjusted in the vertical direction in order to maintain correct relation between the wire and the melt pool at all times.

Because of the heat radiation from the deposited part and the high-power laser reflections, contact sensors, or sensors requiring close distance to the area of interest, are not feasible for this process. Hence, only optical sensors placed at a significant distance from the process have been evaluated with success. Use of ordinary cameras appears to be a good choice for visual feedback of the wire/melt pool interaction, based on which manual control of the process is demonstrated in this work.

The process is examined for moderate to high deposition speeds. It is shown that increasing the deposition speed might be favorable from a heat input point of view, since higher traverse speeds give less heat input for maintained bead dimensions, and thereby less heat affect on the substrate material. Higher deposition speeds are of course also interesting in order to minimize the production time. However, it is found that high traverse speeds might require even more careful tuning of the process parameters than for moderate speeds, and preferably also *automatic* process control. The latter is needed because *manual* on-line interaction is less feasible due to high traverse speeds.

For automatic control of the deposition process, the primary focus has been on maintaining a flat surface throughout the deposition. The main and novel contribution in this thesis is a height controller for multi-bead deposition of arbitrary deposition patterns. It is based on iterative learning control and 3D height scanning of the top surface of the deposited part. The surface is scanned between each layer and the iterative learning controller learns the process characteristics on-line, which thereby compensates for the lack of process knowledge. Results show that the proposed controller can maintain height variations below few tenths of a millimeter throughout the deposition (of a circular cylinder deposited using an outward going spiral). Corresponding height variations for open-loop deposition are several millimeters, which is enough to cause defects such as lack-of-fusion.

However, in order to ensure a flat surface on each layer, the height controller might locally require a significant change in the wire feed rate. This causes the important relationship between the wire and the melt pool to change, which might introduce defects in the deposit. In order to ensure defect-free deposition of Ti-6Al-4V during automatic control, a novel tool center point (TCP) offset controller is suggested. It controls the robot's TCP in the vertical direction, based on current wire feed rate and height deviation from a mean layer height. The TCP offset thus ensures that appropriate heat input into the wire is obtained at all times.

To summarize, the findings in this research work and experience from industrial applications indicate that manual deposition is concentration intense and requires skilled operators with adequate knowledge in both welding and robot control. Introducing an automatic process controller, such as the one presented in this thesis, offers great potentials to cost savings and quality assurance, the latter being a necessity in demanding applications such as aerospace. However, in order to fully exploit the potentials of robotized laser metal wire deposition, it is important to gain more knowledge about the process dynamics, and the relations between process parameters and resulting material- and metallurgical properties of the deposit. A number of multi disciplinary issues need thus to be solved, and this requires a joint effort from several research areas.

7.2 Future work

In this work the focus has been on the titanium alloy Ti-6Al-4V. The monitoring and control methods for obtaining flat surface of the deposited layers presented in this thesis are nevertheless suitable for other materials as well. However, some materials are more sensitive to e.g. the temperature of the deposited part and thereby more crack susceptible, in which case the proposed controllers are not enough to ensure defect-free deposits. That is, temperature control and temperature prediction is an important issue to address in future work.

The temperature seams also to affect the geometrical profile of the deposited parts why better understanding of the underlying mechanisms should be developed. With better process knowledge, the process planning tools should be further developed to incorporate experience, theoretical knowledge, and simulations into the automatic generation of deposition patterns and corresponding process parameters.

The iterative learning controller developed in this work is dependent on reliable height feedback from the deposited layers. However, the tested scanner is not suitable for real industrial use, why other scanners or new measurement methods should be examined. The requirements are to obtain reliable height measurements within a few seconds, in order to enable short pauses between the layers, with the ability to measure hot shiny surfaces and preferably also chamfered edges (to incorporate contour beads in the height feedback).

The TCP offset controller described in Paper 5 is tuned manually based on experimental results. It is therefore hard to generalize the presented results to other tool configurations and materials. A more thorough investigation about the mechanisms behind stable metal transfer for different tool setups, wire diameters and materials are therefore needed.

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