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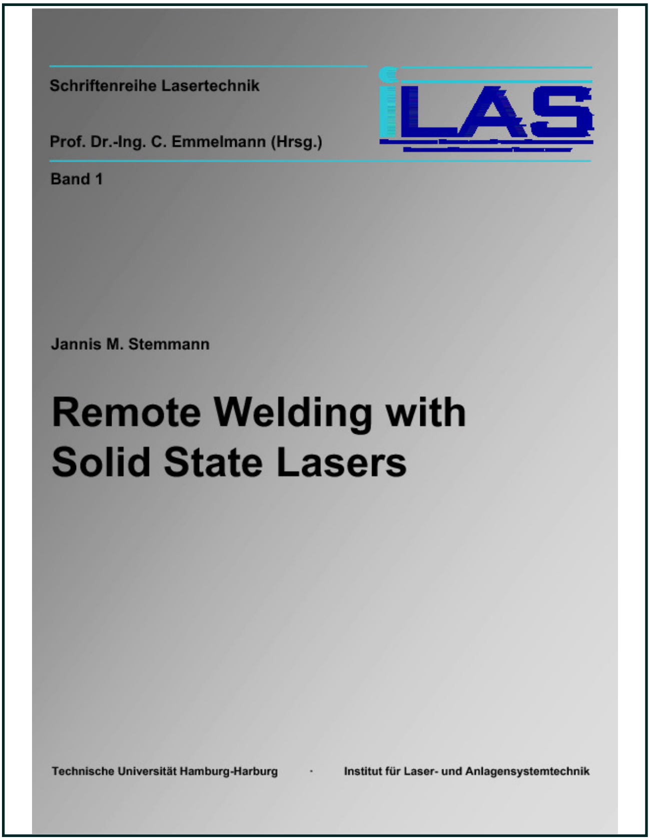
Remote Welding with Solid State Lasers



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1 Introduction

Market economies are built upon the fundament of profit-maximising companies. Successful enterprises sustain national economies by providing products for customers, payment for suppliers, salaries for employees, profits for owners and taxes for the home country. In order to be successful, companies have to feature significant advantages relative to their competitors. These advantages all aim at satisfying customer requirements and can be classified into aspects related to cost, quality and availability of products and services to their dedicated markets.

For industrial manufacturers, all of these criteria mentioned beforehand are affected by the company‘s production. Enhancing the efficiency of production systems therefore can help making a company more profitable. A substantial part of the production of complex products, for instance cars, are joining processes of components. A comparatively new thermal joining process is laser welding. Its introduction to automotive industry commenced less than 20 years ago. The benefits of laser welding are diverse and range from low heat-induced distortion, decreasing the amount of necessary rework, to strong and stiff seams, reducing the required joint area. Achievable feed rates often are ten to twenty times higher than in alternative technologies like riveting, arc welding or resistance spot welding.

Most of these benefits can be used to improve the cost efficiency of production. But laser welding features one major drawback, which is the high investment required for the beam source, beam delivery and safety systems. And due to relatively high secondary processing times, the expensive equipment often is used merely for a fraction of total cycle time, especially in body-in-white production. Auxiliary process times arise whenever repositioning of the optic unit in between welding is necessary. Handling systems usually are not capable of much higher speeds than the already considerable weld feed rate, at least not for short motions. Hence the relation of primary to secondary processing times frequently is very low. All in all, these are the main reasons why joining with lasers is generally used only where technological aspects make other options even less attractive.

Based on CO_2 lasers, several years ago the first remote welding system was developed. Soon afterwards more flexible solid state laser systems with optic units mounted to industrial robots followed. Laser remote welding offers the potential to reduce auxiliary process times to a negligible percentage of what it would be in conventional laser welding. This is made possible by specially designed optic units and some other requirements met by these systems. By an increased capacity, depreciations and imputed interest are distributed among more products, thereby reducing operational expense. Given a fixed market demand, fewer laser systems have to be acquired and necessary investment can be scaled down.

Currently there is only little doubt that remote welding can become one of the most cost efficient joining technologies in automotive production, even outperforming resistance spot welding. A current survey shows that car manufacturers worldwide are planning to use remote welding for approximately 8% of all joining tasks in 2015 [97]. At present, though, the number of installed systems is still a low double digit figure, almost every one of them being based on CO_2 laser technology.

The expected proliferation of solid state laser remote welding and its novelty make it a worthwhile topic for research. The objectives of the present thesis therefore are as follows:

After the introduction, an overview on existing remote welding systems and process characteristics is given, including a short summary of available literature. In the successive chapter, important aspects of system development are elaborated. A reference of system specifications to customer value in dimensions of cost, time and quality will be established. The prevalent system factor addressed is optic unit layout. Moreover, aspects of production oriented workpiece and clamping device design are covered, as well as the issue of repeatability analysis.

The main section of this report is dedicated to cycle time optimization by means of robot scheduling. A task planning system based on a combinatorial optimization model is introduced. The system is fully integrated into an automated process chain from workpiece CAD data to graphical simulation and offline robot programming. Its performance is validated by a comparison of generated robot paths to those programmed online by operators. Finally, a chapter containing summaries of the research that was conducted as well as an outlook on future perspectives conclude this thesis. Model data and the derivation of kinematic equations for relevant industrial robots are included in the appendices.

2 Laser Remote Welding

Laser remote welding, sometimes termed as remote laser welding, scanner welding or similar, today is one of the newest and fastest joining technologies. It allows to reduce secondary processing times to a negligible percentage of overall cycle time [174, 99]. An ensuing high system capacity helps distributing depreciations and imputed interest on a large number of manufactured parts [231]. The process currently draws a lot of attention to possible users due to its potential for cost efficiency and to research facilities due to its many yet unresolved issues [58, 119, 230]. This chapter will provide an overview on existing remote welding systems and related process characteristics.

The expression Laser Remote Welding (LRW) is widely used today, but up to now not defined in a strict sense of the term. Commonly accepted is the notion of a large distance - explaining the term "remote" - between optic unit and workpiece, compared to conventional laser welding (s. Fig. 2.1). Usually this optic unit incorporates beam deflection components driven by additional axes and is called scanner, in reference to the scanning focus motion on the workpiece.

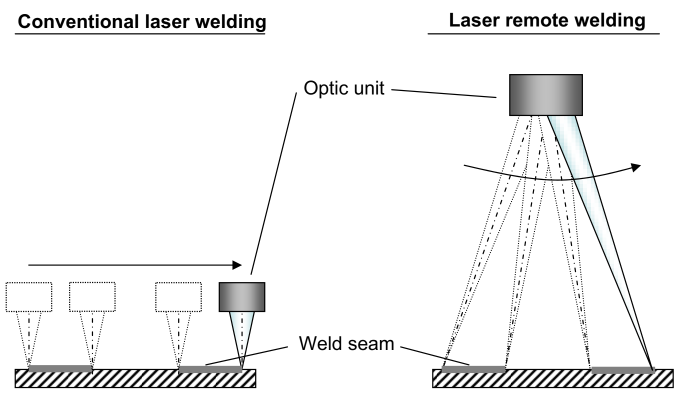

Figure 2.1: Laser remote welding concept

Some remote welding systems (especially older ones), though, only provide work distances equal or even lower than those in laser welding with usual processing heads.

Furthermore, as will be shown, not all remote welding systems are based on scanners. Even the characteristic non-perpendicular beam incidence is not necessarily a feature of all LRW systems: Optic units with telecentric lenses diminish beam inclination so that in the entire workspace beam incidence is nearly normal to the workpiece surface.

In the following, Laser Remote Welding will be understood as any laser deep penetration welding operation that is based on a system with at least one rotating optic component so that tilt angles of this optic component lead to translational displacements of the beam focus.

2.1 Laser Remote Welding Systems

LRW systems can be classified according to numerous specifics. One of the most fundamental properties is the type of laser beam source used. This section will therefore be divided into the description of systems based on CO_2 lasers and those based on solid state lasers. Similar surveys can be found in references [18, 59, 195] and [19].

In Tables 2.1 and 2.2, some, but by no means all, publications on laser remote welding systems are listed. Most of them are formless presentations, with the exception of some short articles. The publications are categorized according to certain specifications of the described system. These are maximum achievable feed rate of the focus on the workpiece, sometimes called indexing speed (v_{max}), the maximum laser beam power (P_{max}), the maximum distance of the optic unit to the workpiece (l_{max}) and the approximate working area dimensions. The comparison is flawed in several aspects, as workspace dimensions are dependent upon scanner handling systems and no beam power losses were taken into account. Nonetheless, it is useful to get an impression of available systems and their development.

2.1.1 CO_2 Laser Remote Welding Systems

Due to their low total cost of ownership, high available output powers and good beam qualities, CO_2 lasers rapidly gained acceptance as industrial machining systems [37]. The first laser welding application in automotive series production was based on these beam sources [164], as well as most laser applications still are today [60].

Therefore it comes as no surprise that the first remote welding systems to be released employed CO_2 lasers [151, 180].

v_{max} ($\frac{m}{s}$)	P_{max} (kW)	l_{max} (mm)	work envelope ($x \times y$, mm^2)	source
4	2.5	2500	1900×1900	[197]
20	3.4	1040	840×840	[151]
2	3.5	1400	1000×1100	[74]
5	1.5	360	270×270	[189]
10	4	300	$> 60 \times 60$	[124]
6	6	1400	1500×1500	[16]
11.7	6	-	762×762	[87]
-	6	-	2400×1500	[149]
2	5	1000	4500×2500	[165]
5.1	15	150	30×30	[97]

Table 2.1: Literature on CO_2 LRW systems

In order to achieve large distances between optic unit and workpiece, generally lasers with a high beam quality are preferred [195]. Hence, in all CO_2 LRW systems known either diffusion cooled or fast axial flow convection cooled lasers are used. Beam quality figures K of these devices usually are near to 0.9 or even higher.

Scanner welding in body assembly processes is proposed by *Ream* [197]. In a rather visionary article, almost all aspects of remote welding still relevant today are covered, and a system with an axial flow RF excited laser is tried for lap welding of mild steel. A single mirror featuring an extremely large focal length is the only moving optical component of the setup, which is derived from a textile cutting application. Due to the high F-number a work zone height of approximately 200 mm is achieved.

The first setup for remote welding including two galvanometers is reported in detail by *Macken* [151]. Radiation of a DC excited slow axial flow laser is redirected by an optical configuration of an afocal parabolic mirror, a set of 2 flat mirrors attached to a linear drive, the focussing elliptical mirror and finally 2 scanning mirrors. By adjusting the axial position of the mirror set, the distance to the workpiece can be changed up to 600 mm.

Frauenpreiss [74] reports on an LRW gantry system using a high frequency excited, diffusion cooled CO_2 slab laser as an alternative to resistance spot welding. A telescope is used for beam expansion, followed by a focussing lens mounted on a direct linear drive which allows an axial focus shift. The lens features an exceptionally large focal length of 1600 mm. Two rotating mirrors deflect the beam to the workpiece. The workspace is described as a pyramid obtuse. Possible applications mentioned include joining of car doors, where 100 stitch seams were welded in less than 1 minute. A slightly improved system version is used for experiments reported by *Bergmann and Kunst* [16], who indicate the workspace with a height of 400 mm.

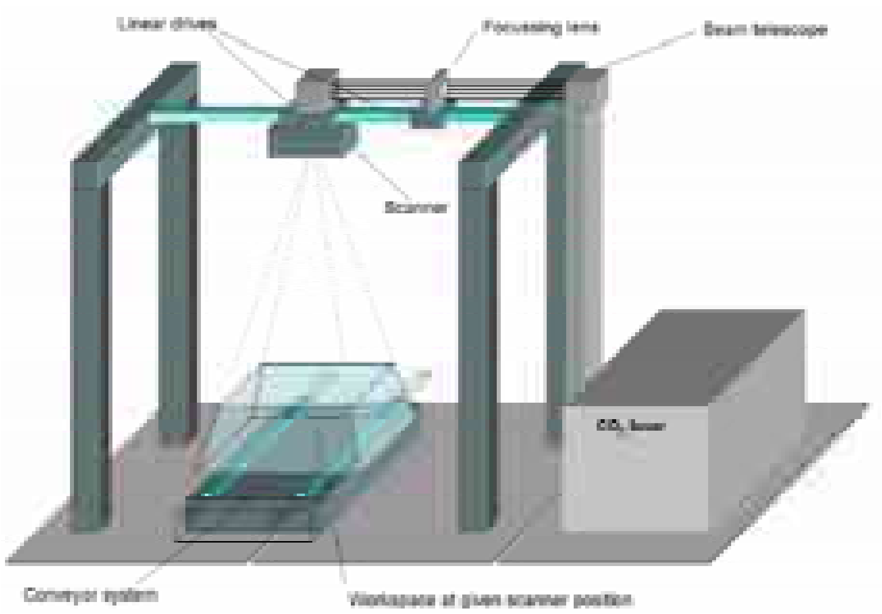

Figure 2.2: Structure of a typical CO_2 laser remote welding system

A further developed variant, in which a linear direct drive for scanner movement is added and a single gimbal mounted scanning mirror is used, is presented by *Rauschdorf and Lingner* [196]. The additional axis provides a larger workspace. Applications include the welding of car sliding doors in three shift operation. Further information on it can also be found in references [149, 75], where cycle times of 22 seconds for 56 stitch seams of 15 mm length are specified. Welding of an impact member with 12 overlap joints in 15.3 seconds is reported in [134]. A sketch of the system design can be seen in Fig. 2.2.

An entirely different structure is presented by *Poehler et al.* [189]. A DC excited diffusion cooled laser is used as beam source. Two galvanometer driven mirrors deflect the beam, while a subsequent flat field lens is applied as objective. Basically the same system with slightly improved specifications is used for welding and consecutive marking of steel casings [251].

This fundamental scanning unit design (s. Fig 2.3) is still one of the most common, as it permits dynamic and precise focus positioning. Furthermore, the flat field lens offers an inherent correction of the spherical focal plane created by the rotating mirrors, thus simplifying programming. On more information about galvanometer scanning, see Section 3.1.3 or references [207, 10, 110] and [234]. Datasheets of available scanners can be found, e.g., in [9, 245]. Instead of a lens objective, *Klotzbach et al.* [124] use a parabolic mirror for beam focussing in a galvanometer scanner [123]. It was applied to welding of exhaust gas coolers in series production.

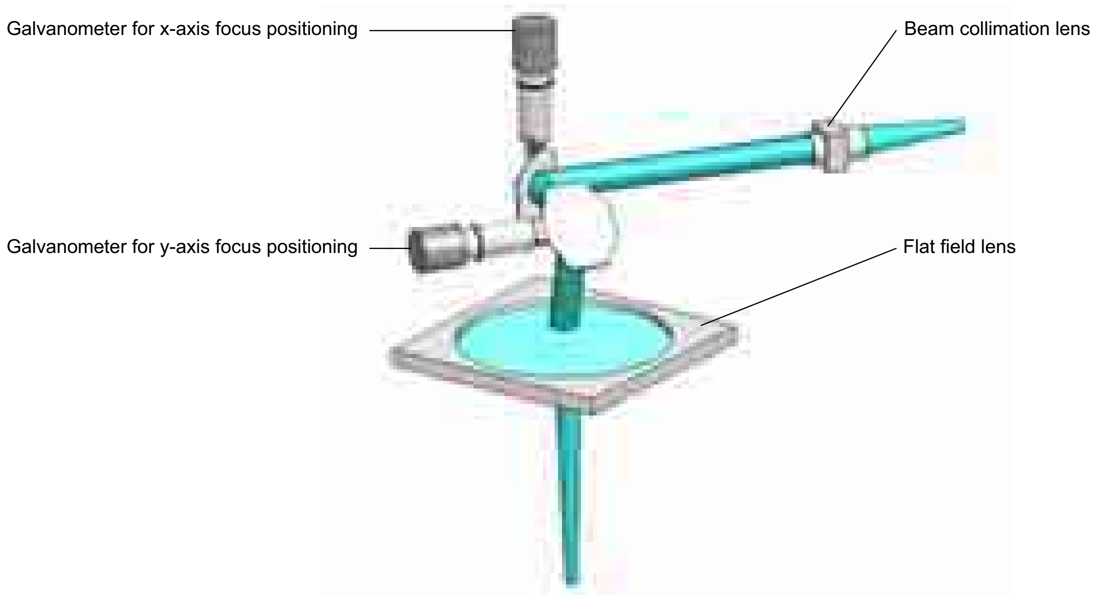

Figure 2.3: Structure of a typical galvanometer scanning unit (image: Carsten Wagner)

Another LRW setup with 2 scanners and a diffusion cooled slab laser is used for welding of reinforcements to inner panels of a car rear side door. 56 welds in 32 seconds can be performed according to *Mason* [162]. Reportedly, this is the first remote welding system developed for automotive requirements, starting in 1996 [103, 38]. Unfortunately, no system specifications could be found.

The open machine bed system used by *Grupp et al.* [87] is based on a fast axial flow laser coupled to a fixed scanner. The optic unit consists of a shiftable focussing mirror with a maximum travel of 250 mm and a focal length of 1500 mm. It is followed by two galvanometer driven scanning mirrors [243, 242]. Again, the workspace is described as a truncated pyramid. The same system is applied to welding of reinforcements on separating panels of car bodies, where 22 step seams are processed in 5 seconds, as reported by *Hornig* [103]. Furthermore, *Neumann* *et al.* [173] studied various weld sequences with this setup, aiming at minimized distortion.

A first CO_2 laser remote welding system based on an articulated six axis robot is presented by *Bolwerk* [21]. Beam delivery is realized with aluminum tubings through which the beam can safely propagate. The pipes are connected by flexible joints with a series of redirection mirrors placed inside . This rather complicated solution may be the reason why up to now no application of the setup could be found. Performance data of the scanning system is not published. *Herfurth and Heinemann* [97, 94] show a similar setup for high power axial flow lasers with lower beam qualities. This system is equipped with an autofocus optic capable of compensating up to 38 mm of axial misalignment.

Menin [165] shows a large scale setup incorporating a three axis scanner with shiftable focussing lens, which is integrated into a gantry system with 3 additional linear main axes. It is based on a diffusion cooled laser and deployed in series production of front and rear car side doors, where cycle times of 96 seconds for 118 stitch seams are reported . Data of this system is also given by *Ostendorf* [180].

To sum it up, most CO_2 laser systems only offer limited three dimensional welding capability - a drawback that reduces flexibility, as there is at most one possibility to reach a given point on the workpiece with the laser beam. Shadowing effects of fixtures or workpiece geometry cause regions that can not be reached at all. The reason for this limitation is the reluctant use of additonal axes for scanner movement. This in turn can be traced back to the fact that, up to now, no light fibre cable for far infrared laser radiation could be invented. Beam delivery therefore is restricted to rather inflexible mirror configurations, which also explains the preferred use of cartesian axes in CO_2 laser systems. Additional linear axes generally lead to gantry constructions with large footprints and high original costs compared to standard industrial robots, though. Thus in parallel to the CO_2 laser counterparts, solid state laser remote welding systems assisted by articulated robots were developed.

2.1.2 Solid State Laser Remote Welding Systems

The only high power solid state (HPSS) lasers prevalent in industry are all based on YAG crystals doped with rare earths, commonly Neodymium or Ytterbium. The most widespread crystal geometry today is the Nd:YAG rod, excited with either flashlamps or semiconductor lasers. Apart from these, diode pumped Yb:YAG disc and Yb fibre lasers are gaining acceptance due to their relatively high beam quality and efficiency factors. The main disadvantage of all HPSS lasers is the high total