Real-Time Focus Controller for Laser Welding with Fibre-Optic Non-Invasive Capture of Light

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ABSTRACT

Laser welding is being introduced in the aerospace industry due to its many advantages over traditional techniques. However, welding of parts with complex shapes requires precise control of the focal point of the laser in order to achieve full penetration over the entire seam. In this paper, we present an improved control system for real-time adjustment of the correct focal position, which is based on the monitoring of the light emitted by the process in two different spectral bands. The reported system has been optimized for use in a real environment: it is robust, compact, easy to operate, able to adjust itself to different welding conditions, materials and laser setups, and includes a direct connection to an external PC. Results from recent field trials on complex aerospace structures are provided.

Keywords: Laser welding, focus control, optical sensor, autofocus, optical fibre, chromatic aberration.

1. INTRODUCTION

Laser welding is being successfully introduced in many industrial applications, due to its advantages over other high-quality welding methods (mainly, TIG welding): higher speed, easy integration into an automated process, low distortion, very high aspect ratios, etc. Of particular interest here are aerospace applications, where the industry is seeking to introduce laser welding for the manufacturing of complex parts of the engines.

For the high quality welds demanded by such applications, it is crucial to maintain the correct focal position of the laser beam over the surface of the workpiece for the entire welding seam. If the optimum focal position is lost, the welding process can switch from the efficient keyhole regime (in which the material is vaporized in a stable regime and fully penetrates the workpiece) to a conduction-limited regime with poor penetration through the material. This circumstance can occur with deviations as small as a few millimeters. It might be thought that a proper pre-programmed robotic trajectory of the laser head over the workpiece should avoid the aforementioned problem, but typical tolerances associated with manufacturing and positioning of the parts to be welded can result a significant focal error, especially in a production environment. In addition, focal errors arising due to the unavoidable thermal distortion of the workpiece during the welding should be considered.

For the above described reasons, a control system capable of continuously monitoring and correcting the focal position is desirable. Such a system should be able to operate in real-time, and to be installed easily in an existing welding setup. If complex 3-D-shaped parts are to be welded, the control system should also not intrude into the volume around the laser focusing optics and the workpiece, in order to provide the best possible access for the laser light.

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Among others, one successful technique that has been proposed is the measurement of the capacitance between the laser head and the workpiece, which is dependent on the distance between them [1]. However, due to the strong electromagnetic emission from the generated plasma, most of the techniques based on electrical measurements cannot be used with continuous wave (cw) laser welding, but only with pulsed lasers, taking measurements between pulses. Another technique that has been used is the projection of structured light patterns over the workpiece's surface, that are analyzed by a CCD camera to estimate the relative position between the laser head and the part [2]. This is, however, a method which needs some intrusion in the working volume.

Another successful approach exploits the light emitted by the process itself that is collected by the effector optics whose main purpose is to deliver the laser beam to the workpiece. The spectral content of the light is related, due to the chromatic aberration of the optics, to the position of the workpiece with respect to the laser head, thus allowing the focal position to be estimated. Figure 1 (left) shows this principle: Due to the chromatic aberration of the lenses, the focal plane is different for these spectral bands. An optical fibre is installed with its end-face in the focal plane of the laser wavelength, halfway between the focal planes associated with the two different spectral bands: infrared (IR) and ultraviolet and visible (UV/VIS). When the laser is optimally focused on the workpiece a roughly equal percentage of light in each band is collected by the fibre. However, if the distance to the workpiece changes during welding, one of the bands will be coupled into the fibre more efficiently and the other less so. Thus, by taking the difference between these optical powers, the focal error can be determined. Hence, a simple optical power measurement at two different broad spectral bands gives the focal position thus enabling the proposed control system.

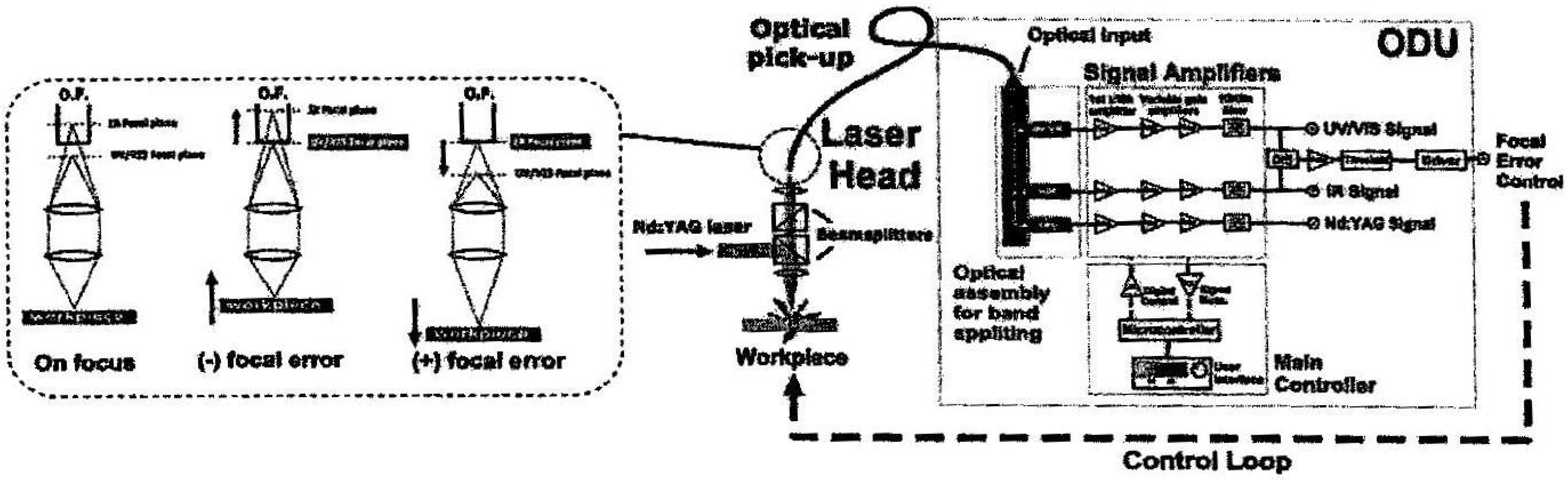

Figure 1: Principle of the focus control system.

This approach offers significant advantages: it is a non-intrusive method, the optical fibre can be long enough to place the optoelectronic part of the system far away from the strong electromagnetic interference generated during the welding process; it is relative easy to set up, and due to the simplicity of the signal processing needed to estimate the focal error, is able to correct the focal position in real time.

This principle has been presented in previous publications and a patent [3],[4]. The authors, in the framework of the European Project "Manufacturing and Modeling of Fabricated Structural Components" (MMFSC), have been working in the development of an *enhanced* focus control system with the aim to improve its performance, to incorporate additional monitoring and control capabilities for different aspects of the welding process, and to resolve some practical issues, mainly: set up time, robustness, compactness, and simplicity of operation. This system has been thoroughly tested in field trials under different welding conditions.

This paper is devoted to the design of the improved focus control system, and to its performance obtained from field trials performed to realistic parts used in the aerospace industry.

2. DESIGN

The optimized control system presented in this paper is made of two blocks: (i) collection optics and (ii) the optical detection unit (ODU), which includes the optoelectronics and signal processing -see Fig. 1 (right)-. The light collected by the optical fibre is split by an optical assembly into three spectral bands: ultraviolet and visible range (UV/VIS, 350~800nm); infrared (IR, 1200~1650nm); and the Nd:YAG wavelength (~1064nm). Light collected at each spectral band is focused on to a photodiode and processed by an electronic front-end with fixed gain (x10k). Further amplification is achieved by a three-stages amplifier with digitally controlled variable gain, ranging the total gain of each channel from x10k up to x1GV/A, with small-signal bandwidth of 10kHz for all gain settings. The focal error module computes the amplitude difference between the IR and UV/VIS signals, thus providing the measure of the focal error of the laser head. From this signal, the unit is able to provide a real-time control signal (Focus Error Control) to drive the translation stage of the laser head focus with the correct amplitude swing.

A digital control module, based on a microcontroller, provides a user-friendly interface that allows the unit to be configured and operated in an easy way through an alphanumeric display. The embedded software includes functions to control the configuration of the amplifiers and of the focus error control module, detection of the welding process; and a procedure for storing and retrieving the configuration of the entire unit. The software inside the unit provides another interesting feature: an iterative algorithm, which takes only a few hundred of milliseconds to complete, seeks the optimum gains of the amplifiers for a specific welding condition or laser arrangement. This way, costly reference weldings after the installation of the system can be significantly reduced.

As an added capability of the system, it includes A/D converters for the signals of the three channels and the focal error output, with a bandwidth of 10kHz. A USB connection to an external computer make possible further signal processing in real-time, as it has been demonstrated that the statistical and Fourier analysis of the dynamic behavior of the signals reveals some interesting information about the welding pool and the welding process itself [5], [6]. A photograph of the final prototype of the optical detection unit is shown in Fig. 2. It has been used in welding trials whose results are briefly described in the next section.

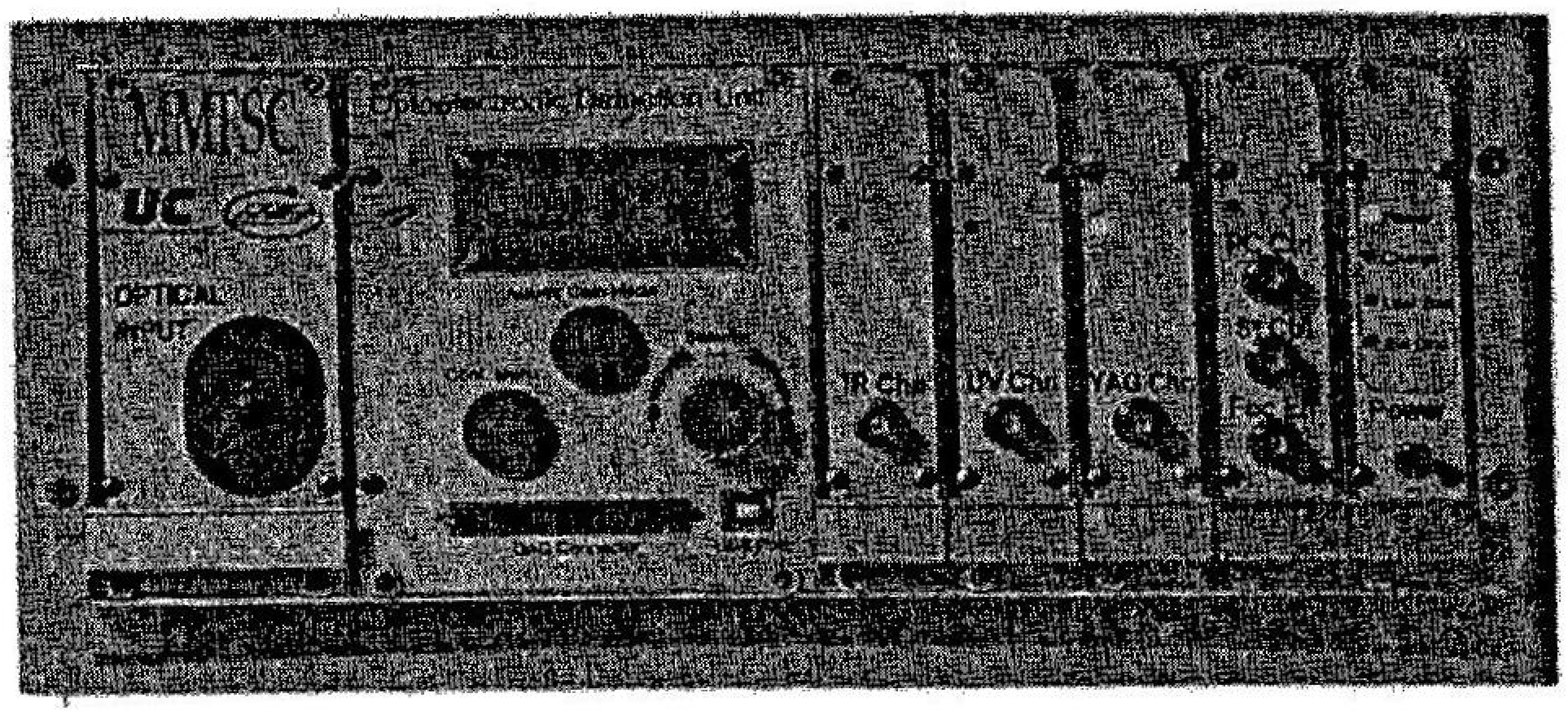

Figure 2: Photograph of the optoelectronic system.

3. RESULTS

The focus control system has been tested in welding trials in the framework of the MMFSC project, both at the Cooperation Laser Franco-Allemande (CLFA) and University of Trollhättan/Uddevalla (HTU) facilities. Trials have been performed on parts with different geometries of Inconel 718 alloy with a CW Nd:YAG laser of several kilowatts of fibre-delivered optical power.

Firstly, the automatic setup algorithm for the amplifiers' gains has been checked, demonstrating good performance: it reaches the reference value at zero focal error output (0+/-0.3Volts) in about 0.6seconds. The performance of the focus control loop has also been tested with several test welds, for example, the workpiece shown in Fig. 3, which is tilted with respect to the nominal movement of the laser focusing head, and incorporates sections of different thickness, from 1.1mm to 3.15mm. To the left, the geometry and setup of the piece is shown, while the displacement of the laser head generated by the control system in order to follow the correct focal position is shown to the right. The results show a maximum correction range –5 to +5mm with accuracy of +/-0.4mm.

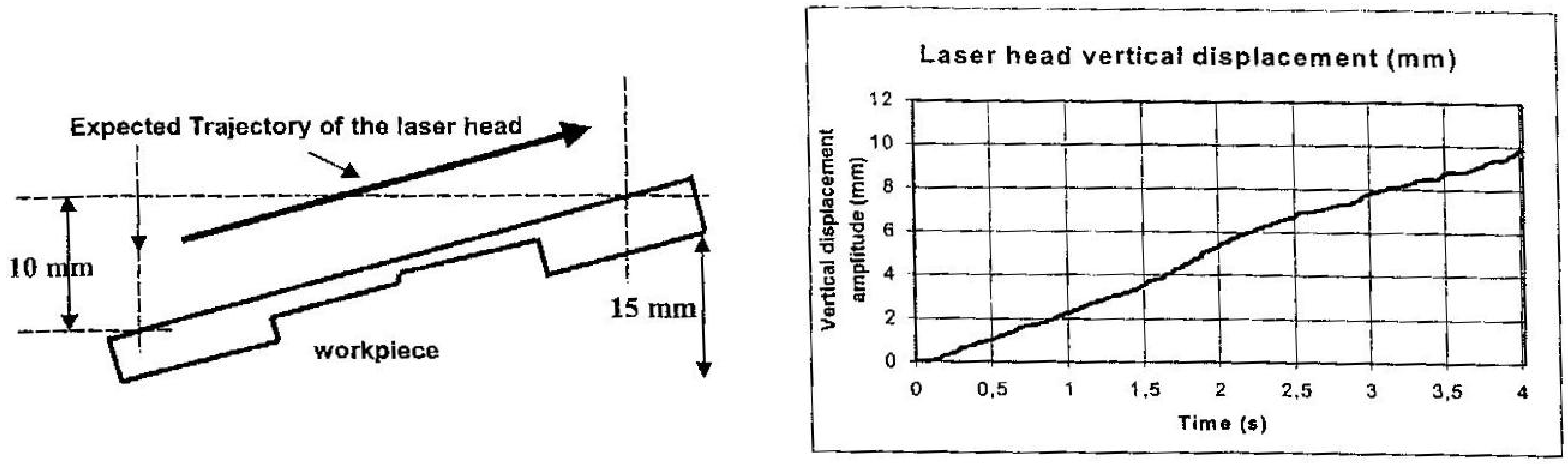

Figure 3: Test of the focus control system on a tilted workpiece.

Additionally, the behavior of the system has been tested with real parts of engines, such as the airfoil shown in Fig. 4 (left). This has run-on and run-off plates attached; this is normal for such welding processes to prevent 'edge-effects'. Such plates would be removed after welding. The relative movement of the laser head is shown (right): it correctly follows the surface of the workpiece.

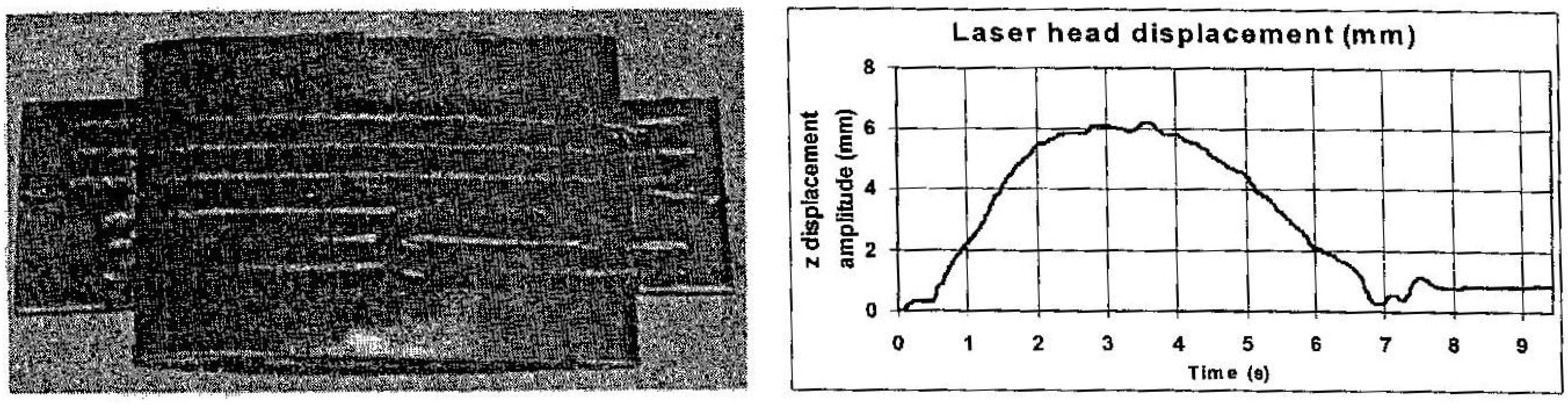

Figure 4: Performance of the focus control system tested with an airfoil.

4. SUMMARY

A real-time focus control system with non-intrusive optical-fibre capture of light for the laser welding process has been presented. The design of an optimized prototype of the system, along with welding trials on real parts of the aeronautic industry, has been discussed. Results show good performance for the real-time correction of the focal point on complex workpieces.

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