Computer-aided electron-beam deflection control system

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Abstract. The electron beam processes – 3D selective melting (3D printing), welding, etc. are complex processes with many processing variables, which require integration of interfaces for control of the processes on different levels through hierarchical equipment models, functional data and operation control models. We developed a user interface software application for controlling the electron-beam motion along several types of trajectories and a free complex shape trajectory by controlling the deflection system parameters. Several types of motion patterns with different velocities are realized, together with the possibility of choosing a free trajectory by defining the electron-beam path by a graphical image.

1. Introduction

The electron-beam (EB) processes – 3D selective melting (3D printing), welding, melting and refining, evaporation, surface modification, etc. are complex processes with many processing variables, which require integration of the process control interfaces on different levels through hierarchical equipment models, functional data and operation control models. Many EB processes, especially the selective melting for the development of 3D structures, need very precise management and control of the EB parameters. The choice of EB processing parameters generally depends on the specific process, the properties of the treated materials and the EB equipment available. The existing process controls of EB equipment are typically aimed at controlling the basic machine settings, such as accelerating voltage, EB current, focusing coil current, vacuum level, EB velocity, working distance, etc.

There exist methods of EB focus control and monitoring in EB welding based on registering the secondary emissions from the welding area [1]. The relation used between the secondary emissions and the focusing lens current has an extremum, so that this relation specifically has a dead zone and two values of the focusing lens current providing the same value of the secondary-current signal parameters. Therefore, adaptive systems of EB focus stabilization of this kind use low-frequency scanning, which substantially limits the working speed of these systems. The focus position is extremely important for EB welding and affects the quality and geometry of the welded joints produced [2, 3].

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different focus-control methods is presented in [4]. In [5], a direct fuzzy controller is presented for an EB focusing system. A device for determining the energy density distribution and for EB focus control was also developed [6].

The beam profile is monitored by the enhanced modified Faraday cup (EMFC) diagnostic tool proposed by J. Elmer and co-workers [7, 8]. The benefit of integrating this diagnostic tool into future process-control regimes is that the beam radial current distribution characteristics, as the peak power density, full width at half-maximum and the full width at 1/e² value, can be quantified. The results show that machine performance, in terms of these measured beam characteristics, varies over time.

The emittance is a characteristic of the beam quality that determines the non-laminarity of the particle trajectories in the beam; it is chosen as a suitable parameter for standardizing the electron optical technology systems. Evaluating this parameter is a precondition for achieving good quality, repeatability and reproducible characteristics of EB welds. This parameter forms the basis of transferring a concrete technology from one machine to another, thus minimizing the volume of preliminary experimental tests aimed at achieving satisfactory regime parameters. In [9-11], some methods are analyzed of intense beam emittance evaluation and a new method is proposed for emittance determination utilizing three beam-profile measurements along the beam axis. Another method was also developed using the changes of the beam focusing current during the beam-profiles measurement utilizing a non-movable modified Faraday cup.

In [5, 12], stationary and dynamic models for the deflection distance are considered for EB deflection control in the case of known electric and magnetic field distributions. In [4], a study is presented on the behavior of the current in the plasma formed in the EB operation area. This approach can be used to obtain the amplitude and the phase ratios, as well as to determine the signals dependence of the current in the plasma on the deflecting coil signals during EB welding processes.

In this paper, the development is presented of an EB software control system aimed at integrating the EB equipment and the process management. EB deflection system management software is developed to generate control signals for the EB installation. It gives the possibility to simulate and control the EB motion along different trajectories at different velocities. Special attention is paid on the free EB trajectories option and the possibility to generate such trajectories using images of real objects. The deflection control in this case is based on estimating the control deflection signals implementing the estimated (x, y) coordinates. The generated image-based scaled coordinates can also be used for x0y (two-dimensional) manipulator motion control [13]. The estimated performance and control models and algorithms should be validated experimentally.

2. Electron-beam software control system
The EB software control system under development involves several related directions: EB characterization; management of the focusing and deflection systems; management and control of the manipulators (figure 1). It is part of the total EB equipment and process management integration, involving the development of an engineering support system and incorporating data collection and acquisition (DCA), information analysis (IA), decision support system (DSS) and system management (SM) [14, 15].

![Figure 1. General structure of the electron-beam control software system.](image-url)
The distributed control systems (DCS), programmable logic controllers (PLC), sensors, actuators, etc. ensure the process data acquisition and control through performance models for the process, equipment, materials and controllers.

3. Deflection system control

The EB motion along different paths is determined by the magnetic field formed by the deflection system depending on the process performed and the shape and location of the samples treated. The place of interaction of the electron beam with the material can be controlled by beam deflection or/and by moving the processed samples by a two- (or three-) dimensional CNC manipulator. In [5], it is found that in the cases of rectangular and acute-angle corners, the implementation of a manipulator should be combined with a deflection system control. There usually exist design limitations for the maximum deflection angle of each electron gun. These, together with the dimensions of the vacuum chamber and the distance from the magnetic lens of the gun, define the maximum deflection distance from the axial base beam position. The EB deviation in two mutually perpendicular directions at angles to about 7 – 10 degrees is performed by means of two pairs of deflection coils (figure 2) [12, 16].

The deflection voltages \( U_{\text{defl}} \) applied to the two pairs of deflection coils (signal 1 and signal 2 on figure 2) are:

\[
U_{\text{defl},x}(t) = A(t) \cdot \sin(\omega_x(t) \cdot t + \phi_x(t)), \quad U_{\text{defl},y}(t) = B(t) \cdot \sin(\omega_y(t) \cdot t + \phi_y(t)),
\]

where \( A \) and \( B \) are the amplitudes, \( \omega \) are the oscillations frequencies, and the phase difference \( \delta(t) = \phi_x(t) - \phi_y(t) \) is defined by the phases of the two signals. The amplitudes, frequencies and phase differences of the two signals may be constant or may vary over time in a particular pattern. The period \( T \) (the time needed for one full turn of the electron beam) at a constant frequency value is \( T = 2\pi/\omega \). If the working time is \( T_0 \), the number of turns is \( T_0/T \).

Figure 3 presents the module of the EB control software system for deflection control. Several types of motion patterns with different velocities are realized: line; several lines at different angles,
circle, ellipse spiral, spiral (ellipse), Lissajous figures, etc. The parameters for Signal 1 and Signal 2 can be set by the user. The current coordinates of the overall effect of the two signals can be observed as values and a graph. The example shown in figure 3 represents a spiral with amplitude of 2 for Signal 1 and 7 for Signal 2; a frequency ratio of 6/3; a phase difference $\delta = \pi/2$; a working time $T_w = 20$ s increasing at a step $s = 0.01$; and a period $T = 1.05$ Hz.

4. **Free electron-beam trajectory**

The option of free EB trajectories gives the possibility to generate trajectories based on images of real objects (or software generated 3D model structures). The deflection control in this case is based on estimating the deflection control signals that will implement the estimated ($x$, $y$) coordinates. The first stage is to estimate the coordinates of the desired EB path connected with the real object. There are two possible patterns, namely, scanning or outlines (or combined). Figure 4 presents an example of an outlined EB trajectory. From the original greyscale image, a binary image is obtained and the outlines’ coordinates of the object are estimated after scaling to real object dimensions.

Figure 5 presents the desired EB trajectories for multiple objects. The image needs rescaling before the true object coordinates are obtained.

![Image](figure4.png)  **Figure 4.** Original greyscale image, binary image obtained of the object outlines, and desired EB trajectory of motion (unscaled).

![Image](figure5.png)  **Figure 5.** EB trajectories of motion (unscaled) for multiple objects.

![Image](figure6.png)  **Figure 6.** Calculated values of Signal 1 (a) and Signal 2 (b) for managing the voltage of the two pairs of deflection coils; two trajectory patterns ‘outlines’ (c) resulting from Signal 1 and Signal 2; and ‘scanning’ trajectory pattern (d).

The second step is transforming the coordinates into signals for the deflection coils. Figure 6 shows the calculated values of Signal 1 and Signal 2 and their combined effect of managing the voltage of the two pairs of deflection coils (scaling is not performed). The image-based coordinates generated can also be used for direct $x/y$ (two-dimensional) CNC manipulator motion control.
Figure 7 is a generalized schematic diagram of the electron-beam deflection control system. Initially, the choice should be made of the electron-beam motion trajectory between the type of motion pattern or a free-trajectory motion. Additional types of trajectories can be defined by a user defined model (flower, etc.). The free-trajectory motion pattern can be provided by a photograph, by a drawing produced by 2D design software, or directly by inserting the object outline coordinates. In the cases of starting with a photograph, the 2D outline coordinates can be obtained either by processing the image into greyscale and binary image, or by also by model estimation of different parts of the outlines of the object with first-, second- and third-order equations of the type:

$$\hat{y} = b_0 + \sum_{i=1}^{k} b_i f_i(x),$$

where $b_i$ are estimated polynomial equation coefficients, $f_i(x)$ are the functions of the coordinate $x$ ($x$, $x^2$ and/or $x^3$), depending on the order $k$ of the polynomial model. Then, once the work mode is selected – direct outline mode or scanning mode, the center of the coordinate system is moved to the center of the object (figure 6 c) and new coordinates are evaluated. The next step involves the transformation of the new coordinates obtained into control signals defined either by a constant amplitude and varying frequency or by varying amplitude and constant frequency. The combined effect of the two signals and the deflection of the electron beam ($x$, $y$ coordinates) will be the same in both cases.
5. Experimental measurements

We verified experimentally the parameters of the EB equipment (figure 8) (figure 9), namely, the parameters of the EB installation deflection system, the electron beam, the electron gun and the vacuum chamber. Experiments were performed to validate the model estimates concerning the correspondence between the process parameters and the exact EB positioning (needed for scaling the coordinates).

Figure 10 presents the measured values of the voltages of Signal 1 and Signal 2 (phase difference is $\pi/2$) for the deflection coils and the resulting real EB trajectory.

![Figure 8. Electron-beam installation with power 2 kW, pressure 7x10^-3 Pa.](image)

![Figure 9. Circle trajectory mode of the electron beam in the vacuum chamber.](image)

![Figure 10. Measured values of the voltages of Signal 1 and Signal 2 (phase difference $\pi/2$) for the deflection coils and the resulting electron-beam trajectory.](image)

6. Conclusions

EB deflection system management software is developed to generate control signals for an EB installation. It allows one to simulate and control the EB motion along various trajectories at various velocities. The free EB trajectories option offers the possibility to generate trajectories based on images of real objects. The generated image-based scaled coordinates can also be used to control $x$,$y$ (two-dimensional) manipulator motion. In order to realize the management, the estimated performance and control (PID, adaptive, neural, fuzzy etc.) models and algorithms should be validated experimentally. The beam pattern used in each case depends of the process (3D selective melting, welding, melting, etc.) and the shape of the concrete sample.

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