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*Araştırma Makalesi*

# Development of a 3D Virtual Welding Simulator Using Weld Bead Created by Voxelization Technique

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## ABSTRACT

In this study, we developed and implemented a cost-reducing, real-time virtual welding simulator to train welder candidates. In order to make a real-time welding simulation, a three-dimensional weld bead form was designed. We used a parabola as the basic bead slice shape, considering the similarity between the parabola and the bead slice. During the welding process, the parameters of the weld bead shape are calculated at each time step using an artificial neural network. This network determines the shape of the weld bead and the depth of penetration, based on inputs received from the sensor device that tracks the motions of the torch. After the parabola's parameters have been determined, the voxel map and corresponding hash-based octree data structure are generated in real-time. By using the voxelized data, a weld bead isosurface consisting of triangles is reconstructed with a marching cubes algorithm allowing us to generate more realistic weld seam shapes. We used multi-threaded programming for voxelization and isosurface extraction to reduce the computation cost on high-resolution virtual scenes. The isosurface extraction times for different thread counts and also a feature comparison with other simulators in the literature are shown in this paper.

***Keywords:*** *welding simulator, virtual reality, weld bead, weld seam, voxel.*

# Vokselleştirme Tekniği ile Oluşturulan Kaynak Dolgusunu Kullanan 3B Bir Sanal Kaynak Simülatörü Geliştirilmesi

## ÖZ

Bu çalışmada, kaynakçı adaylarının eğitiminde kullanılmak üzere gerçek zamanlı ve maliyeti düşük bir sanal kaynak simülatörü tasarlanıp geliştirilmiştir. Gerçek zamanlı bir kaynak simülasyonu yapmak için öncelikle üç boyutlu bir kaynak dikiş formu tasarlanmıştır. Parabol ve kaynak dikişi arasındaki benzerlik göz önünde bulundurularak temel kaynak dikişi formu olarak parabol kullanılmıştır. Kaynak işlemi sırasında, yapay sinir ağı kullanılarak her zaman adımında kaynak dikişi şeklinin parametreleri hesaplanır. Bu ağ, torcun hareketini izleyen sensör cihazından alınan girdilere dayalı olarak kaynak dikişinin şeklini ve derinliğini belirler. Parabolün parametreleri belirlendikten sonra, gerçek zamanlı olarak voksel haritası ve karşılık gelen sekizli-ağaç veri yapısı oluşturulur. Vokselleştirilmiş veriler kullanılarak üçgenlerden oluşan kaynak dikişi eş-yüzeyi, daha gerçekçi kaynak dikişi şekilleri oluşturmamızı sağlayan yürüyen küp algoritması ile yeniden yapılandırılmıştır. Yüksek

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çözünürlüklü sanal sahnelerde hesaplama ve işlem maliyetini düşürmek amacıyla vokselizasyon ve eş-yüzey çıkarma işlemleri için çok iş parçacıklı programlama tekniği kullanılmıştır. Bu çalışmada, farklı iş parçacıkları için eş-yüzey çıkarma süreleri gösterilmiş olup geliştirilen simülatörün literatürdeki diğer simülatörlerle karşılaştırması da sunulmuştur.

***Anahtar Kelimeler:*** *kaynak simülatörü, sanal gerçeklik, kaynak dolgusu, kaynak dikişi, voksel.*

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# I. INTRODUCTION

Welding is an economical joining method used worldwide in many applications, such as shipyards, the automotive industry, steel construction structures, bridges, and machine production. Considering technological concepts such as cost and safety for optimum production, it is required that welders have suitable training to obtain their qualifications and efficiencies. Welder education is divided into technological knowledge and hands-on skill training. Although technological knowledge and experience are essential in welding, hands-on skill training is the most crucial parameter in welding joints [1-2]. This is because weld joints are performed with hand motions and angles. Other important welding factors are weld materials, wire size, shielding gas flow rate, wire feed rate, welding speed, and welding voltage [3-5].

During training, a welder candidate can waste many test parts while working on developing his hand skills. This process is repeated often during a welder's training, and test parts cannot be used again. Because of this, the total cost of used test parts becomes high. If skills and experience are gained via welding simulators before actual welding, this can lead to huge savings of energy, time, materials, security and cost [6-7].

Research in welding simulators started to appear in literature at the beginning of the 1990s. [8] investigated how 2-dimensional (2D) welding simulators affected welder education. They discovered that studying with welder simulators decreased education time and cost. They advised using virtual training before the welder workshop education stage. Top [9] analyzed welding simulations in training. He observed that the students who were educated on welding simulators using MIG (Metal Inert Gas) and TIG (Tungsten Inert Gas) welding methods had better performance during real welding operations, with better welding quality and reduced scrap parts.

Oz et al. [10] divided welding simulators into two categories: older and newer generation. One of the new generation welding simulators, which uses virtual reality (VR) hardware and software technology, is set up for 3D interactive MIG welding [11]. The user can adjust the parameters with a graphical interface, then perform the welding operation and see the results. Another MIG welding simulation system has the combination of a haptic device, a head-mounted display (HMD), a 6-degree-of-freedom tracing system, and a speaker. A torch is connected to the haptic device to track the torch position. It is a real-time simulator and uses an artificial neural network to obtain a welding seam form [12]. White et al. [13] added heat distribution to Fast's work to calculate the penetration. Some simulators such as the VRTEX 360 [14], Soldamatic AR welding simulator [15], and an Electric Arc Simülator [16] use optical trackers for position detection.

This study aims to develop a virtual welding simulator with an ideal design and a working plan with an optimum cost. This welding simulator can be used for MIG and TIG welding applications, both widely used welding methods in various industries. In order to obtain better results in virtual welding applications, all required parameters in welding are determined and stored in a database. A software system is developed to supply interaction with virtual welding models. An HTC Vive controller is used as an input unit, and it perceives the position and inclination of the hand motions of the user. A Vive headset is a head-mounted display used as an output unit. This virtual welding simulator allows welder applicants to perform many applications with different welding parameters. Thus, many visual effects such as feed rate [17], sound, light, and welding seam form met in the real welding applications and are simulated in a shape close to the real welding. After welding, errors made by the candidate can be understood with the performance evaluation system and improved for better performance.

The remainder of this paper is organized as follows: The developed virtual welding simulator is presented in Section 2. Then, we described how we created the weld seam in detail in Section 3. Experimental results and comparisons of our virtual welding simulator system are given in Section 4. Last, we conclude our work in Section 5.

# II. THE DEVELOPED SIMULATOR

For the positive contribution of virtual reality to training [18], a virtual welding simulator was developed in this study to train welder candidates. Figure 1 shows the overall structure of our virtual welding simulator system. Firstly, the welder selects the initial welding parameter values such as current and voltage. Then, the user starts the welding process, and the simulator receives data from input devices. According to the data received from these devices, the virtual welding environment is constantly updated to increase the interaction. The reconstructed virtual scene is sent to the output devices, such as the HMD and 3D monitor.

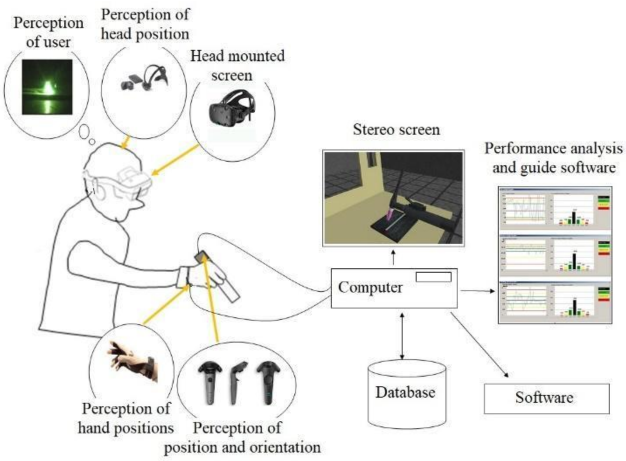


***Figure 1.*** *The general structure of our virtual welding simulation system*

The system consists of five main modules: a graphics module, an input/output (I/O) module, a weld bead parameter decision module, a performance analysis module, and a sound module. Figure 2 shows the architecture of our virtual welding simulator. A virtual welding simulation software was developed with the utilization of the C++ object-oriented programming language, OpenGL graphics library, and Open Audio Library (OpenAL). The developed simulator uses special virtual reality devices: a data glove, an HTC Vive controller, and an HTC Vive headset. The system receives the x, y, z location and roll, pitch, yaw orientation values of the user's hand by the HTC Vive controller. In the weld bead parameter decision module, the motion data is evaluated by an artificial neural network and the parameters of the weld bead are obtained. After processing the data, the system creates and shows the virtual welding scene on the HTC Vive headset. At the same time, the sound engine renders 3D positional audio. After the welding application, the weld seam is analyzed by the performance analysis module.

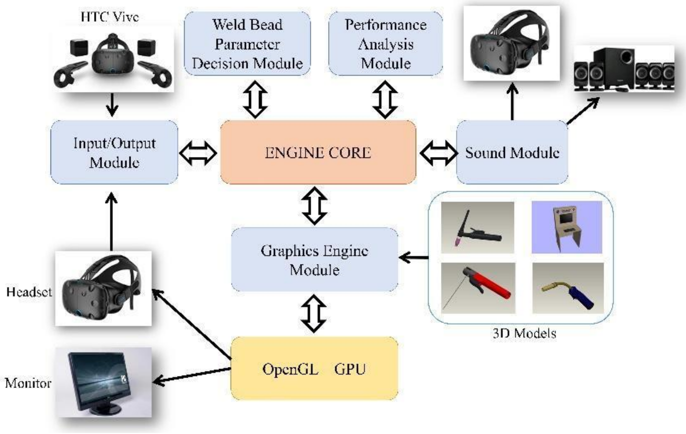


***Figure 2.*** *Architecture of our virtual welding simulator*

## A. INPUT/OUTPUT MODULE

Computer I/O devices are designed to work while sitting on a chair or in a particular sitting position. However, a virtual reality system needs specially designed I/O devices, such as a data glove, a Flock of Birds, and an HMD, to track human motion [19-20]. Our simulator uses an HTC Vive controller device to track the welder's hand motions.

The Cyberglove detects hand gestures with its 18 sensors. These sensors' frequency is 150 Hz, which is high enough to catch every motion of the user's hand.

The welder can see the virtual world through an HTC Vive headset. The virtual welding environment is updated constantly according to the user's head motions, which the Vive headset tracks. In this way, when a user turns his head, the virtual camera moves accordingly. A welding platform was built to increase the interaction between the welder and the virtual environment. Also, an auto stereo 3D screen was mounted on this platform to show viewers the welding process.

The HTC Vive headset has two OLED panels that show the virtual scene through two closely placed cameras. Each of these panels has a display resolution of 1080x1200, which is quiet enough for our simulator. These two displays are placed right before each eye so that users can see the virtual world as they see the real world. When the user wearing a Vive headset moves his/her head, sensors on the Vive headset detect this motion and feed this information to simulator software. The HTC Vive headset uses dozens of infrared sensors to determine the headset's position in a space. Also, the headset has a gyroscope, a proximity sensor and a G-sensor. After receiving head motion information, the virtual software updates the virtual camera's position and orientation, making the user part of the virtual world.

In the simulator, an HTC Vive controller is used to represent a torch. In the simulation, HTC Vive controllers track the user's hand motions with their sensors. When the user holding the controller moves his hand, the torch in the virtual environment moves simultaneously. This way, the user gets the feeling of controlling an actual torch. An HTC Vive controller has 24 infrared sensors, and also to aid its motion tracking ability, it has an InvenSense's MPU-6500 6 DOF sensor. MPU-6500 has a 3-axis accelerometer and a 3-axis gyroscope.

## B. GRAPHICS MODULE

Our simulator uses a graphics engine to draw and update the virtual scene. The graphics engine in the simulator is written in C++ programming language using the OpenGL library. OpenGL is a set of low-level Application Programming Interfaces (APIs) that provide access to a graphics card's capabilities, enabling programs to provide realistic 3D graphics. We use the OpenGL library to send instructions to the graphics card and provide high-performance hardware-accelerated multimedia support.

We designed 3D welding models that are based on real objects used in real welding operations and placed them into the virtual world of the simulator. 3D welding models are composed of polygons. If a model detail is high (close to the real object), then its polygon counts are high and may require more processing power to draw this model [21]. The first step was designing 3D virtual models of real objects using Pro/Engineer software. These objects are torches, metal parts, and a table. After this step, the necessary texture is applied to the models. Some of the 3D objects, such as weld beads, are created dynamically in real-time by the VR graphics engine.

### C. PERFORMANCE ANALYSIS MODULE

Our expert system is used to evaluate and analyze welder performance. Expert systems are one of the common artificial intelligence methods for solving engineering problems like a human expert. Our expert system model rules [22] were created by four experts. These experts were a welder trainer, two mechanical engineers, and a metallurgist. By using this module, virtual welding experiments performed by welder candidates can be evaluated, and the results are shown by scoring or graphics. Based on the rules determined by the welding experts, the trainee's performance score is graded by a comparison of the recorded values of each welding parameter to the ideal values. Any welding operation performed previously can be reconstructed at any time using the recorded data in the database. In this way, welder candidates' personal development can be monitored for current or retrospective welding applications.

### D. WELD BEAD PARAMETER DECISION MODULE

Hand motion data received from the I/O module is evaluated by the artificial neural network, and the parameters of the weld bead are obtained in the weld bead parameter decision module. The details of this module are explained in Section 3, titled “Forming the Weld Seam”.

### E. SOUND MODULE

The sound module in the simulator is written in C++ programming language by using the OpenAL library. OpenAL sound API is used to create sound effects because it is designed for efficient rendering of 3D positional audio. The API's purpose is to allow a programmer to position audio sources in a 3D space around the user. Sound effects recorded from real welding operations are positioned in the virtual environment so that a user in the virtual environment feels as though they are in a three-dimensional world.

## III. FORMING WELD SEAM

The weld seam is a series of deposits of filler metal in the welding process. When performing the virtual welding application, the sensor on the torch detects the user's hand movements. The parameters of the weld bead are calculated using this hand motion data received from the sensor, and the voxel map of the weld shape is generated in real-time. Then, the hash-based octree data structure approach [23] is applied to the dataset to manipulate the corresponding voxels easily. The hash-based octree structure reduces the memory space, computation cost, and tree traversal time. After obtaining the voxel map, the corresponding isosurface is reconstructed during the welding process.

The determination of the weld bead basic shape, the prediction of output parameters, and the voxelization process are described in detail in the following sections below.

### A. DETERMINATION OF THE WELD BEAD BASIC SHAPE

In the literature, welding bead studies [24-39] show that the basic welding bead shape appears in Figure 3. Therefore, we decided to use this general bead shape in this study.

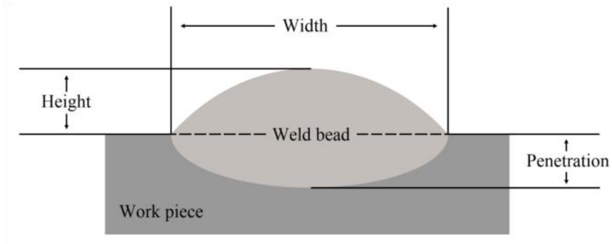


***Figure 3.*** *Weld bead shape and parameters*

In order to obtain the height, width, and penetration values to be used to obtain the model shown in Figure 3, the parameters used during the welding process were examined. Tab. 1 lists the input and output parameters used in academic studies involving MIG and TIG sources in the literature [40-57]. When the studies in Table 1 are analyzed and the suggestions from our expert system mentioned in section 2-C are taken into consideration, it is seen that welding speed, current, arc length, and travel angle directly affect the welding geometry for MIG welding; and welding speed, current, and arc-distance directly affect the welding geometry for TIG welding.

***Table 1.*** *Input/Output parameters for MIG and TIG welding*

| | | **Input Parameters** | | | | | | **Output Parameters** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Welding Type** | **Reference** | **Welding Speed** | **Current** | **Voltage** | **Arc-Length** | **Travel Angle** | **Wire Speed** | **Penetration** | **Width** | **Height** |
| MIG | [40] | √ | √ | √ | | | | √ | √ | √ |
| MIG | [41] | √ | | √ | | | | √ | √ | √ |
| MIG | [42] | √ | √ | | √ | √ | | √ | √ | √ |
| MIG | [43] | √ | √ | √ | | | | √ | √ | √ |
| MIG | [44] | √ | √ | √ | | | | | √ | |
| MIG | [45] | √ | √ | √ | | | | √ | | |
| MIG | [46] | √ | √ | √ | | | | √ | | |
| MIG | [47] | √ | √ | √ | | | | √ | | |
| MIG | [48] | √ | √ | | | | | √ | √ | √ |
| TIG | [49] | √ | √ | | | | | √ | √ | √ |
| TIG | [50] | √ | √ | √ | | | √ | √ | √ | √ |
| TIG | [51] | √ | √ | | √ | | √ | √ | √ | √ |
| TIG | [52] | √ | √ | | √ | | | √ | | |
| TIG | [53] | √ | √ | | √ | | | √ | √ | √ |
| TIG | [54] | √ | √ | | √ | | √ | | √ | √ |
| TIG | [55] | √ | √ | √ | | | | | √ | √ |
| TIG | [56] | √ | √ | | | | | √ | √ | √ |
| TIG | [57] | √ | √ | | | | | √ | √ | |

When Figure 3 and Table 1 are evaluated together, and when we examined how to create Fig. 3 with the parameters obtained from Table 1, it was thought that this shape could be created with 2 parabolas. Also, Chambers and Wu [58-59] stated that the welding seam section resembled a parabola. They use a welding seam volume by rotating the y-axis with the centre of the parabola (0,0). Mavrikios [11] also used an ellipsoid in his study to find welding seam volume.

The parabola is known in algebra as the graph of the second-order functions, as shown in Eq. 1.

$$y = a(x-r)^2 y = a(x-r)^2 + k \tag{1}$$

Here, $a$ denotes the direction of the parabola, while the point ($r$, $k$) indicates the peak of the parabola. The graph of this equation is shown in Figure 4-a. In this study, the parabola form in Figure 4-b is used because of the resemblance of the weld seam section to a parabola. Here, $h$ is the height of the weld seam section, and $w$ is the width of the weld seam section. When the welding application is performed with the virtual welding simulator, the parabola equation is calculated using the input values $w$, $h$ and $p$. An actual weld bead slice shape generated by our simulator is shown in Figure 4-c.

If parabola values in Figure 4-b are substituted in Eq. 1, then $r$ = 0 and $k$ = $h$, and Eq. 2 is:

$$y = a(x)^2 + h \; y = a(x-r)^2 + k \tag{2}$$

Eq. 3 is created when we want to reach the value $a$:

$$x = \frac{y-h}{(x)^2} y = a(x-r)^2 + k \tag{3}$$

Again, if $x$=$w$/2 value of parabola in Figure 4-b is written in Eq. 3 for $y$ = 0, then we find Eq. 4, then value of $a$ is obtained in Eq. 5:

$$a = \frac{0-h}{(w/2)^2} y = a(x-r)^2 + k \tag{4}$$

$$a = \frac{4h}{(w)^2} y = a(x-r)^2 + k \tag{5}$$

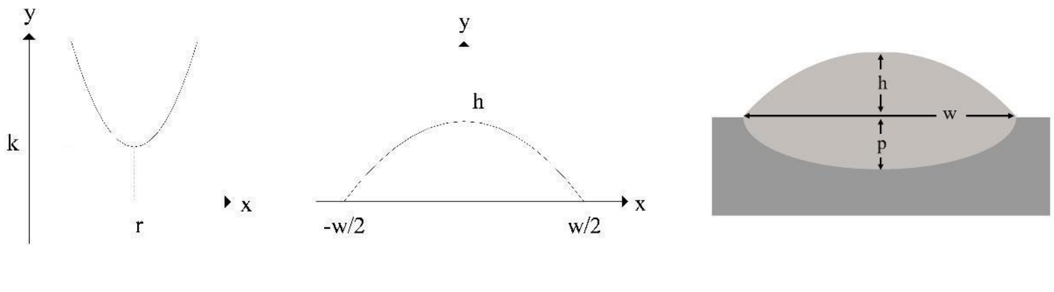


***Figure 4.** Parabola to weld bead slice simulation**. (a)** Graph of a parabola **(b)** Parabolic shape decided for weld bead **(c)** Weld bead slice shape and its parameters*

## B. PREDICTION OF OUTPUT PARAMETERS BY ARTIFICIAL NEURAL NETWORKS

TrainLM was used as an educational function when planning the artificial neural network structure because it works effectively in network training [60-62]. In determining the transfer function, it was found that the LogSig() and TanSig() transfer functions produced close results, but the LogSig() function gave the best result.

The schematic representations of the neural networks for the MIG and TIG weldings are shown in Figure 5. The MIG welding data used for network training, verification, and testing were taken from Sreeraj's 32 real MIG welding applications [42]. The TIG welding data used for network training, verification, and testing were taken from Esme's 16 real TIG welding applications [53]. 70% of the data was used for training, 15% for verification, and 15% for testing. For the MIG welding application, the input layer consists of current, welding speed, arc-length, and travel angle variables. The input layer consists of current, welding speed, and arc-length variables for the TIG welding application. The number of hidden layers and the number of process elements (neurons) in each hidden layer were investigated by a trial method and it was determined to be 14 neurons for MIG and six neurons for TIG welding in one layer.

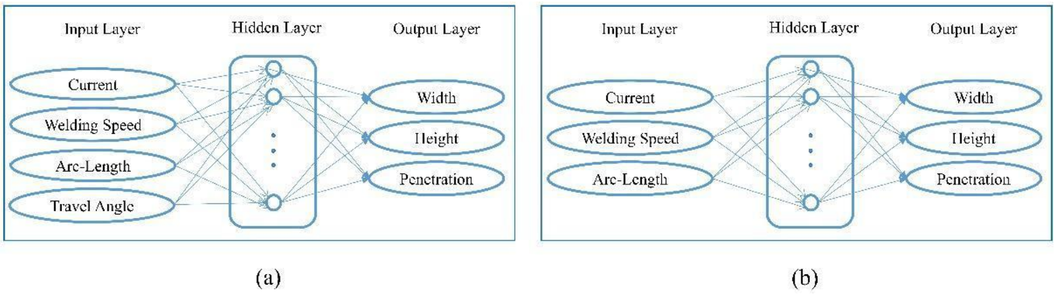


***Figure 5.*** *Schematic representation of the artificial neural network used for the prediction of weld seam dimensions* ***(a)*** *MIG welding* ***(b)*** *TIG welding*

## C. VOXELIZATION

One of the major features of voxel data is that it can contain physical properties such as heat, temperature, colour, density, and hardness. Therefore, we preferred to use a volumetric voxelization approach to represent the weld seam data. We used a triangular mesh model for a 3D weld bead image, and to obtain this model, a voxel map [63] of the weld bead was needed in the background. In order to examine the weld seam, surface, and volume, voxel information was needed. First, we voxelized our bead's parabola model and then we used a flood-filling algorithm [64] to fill the model's interior volume. We used optimized hash tables to store the volumetric voxelized weld seam data.

Voxel shapes are not suitable for representing 3D models because of aliasing problems. For this reason, we used a marching cubes algorithm [65-67] on voxel-based octree data to reconstruct the weld seam surface.

The processing time of interior volume filling was reduced by using the multi-threaded programming approach [21, 68]. Tab. 2 gives the voxelization times of the weld seam model. The voxelization times in this table are calculated according to the parabolas, resolutions, and thread numbers. The results given in this table were obtained with a PC with an Intel I7 5700HQ 2.7 GHz processor with four physical cores and eight logical threads. When the table is examined, it is seen that multi-threaded programming performs better on high-resolution models.

After filling the interior volume, the model's surface was reconstructed using the Marching Cubes algorithm, the most popular isosurface extraction algorithm. The Marching Cubes algorithm method creates triangles by generating a lookup table from volumetric cube data. It is the most preferred technique because of its ease of application [66, 69-73].

***Table 2.*** *Voxelization times for different thread counts for a sample parabola*

| Resolution | Number of Voxels | Process Time of Parabola Voxelization(ms) | | | |
|---|---|---|---|---|---|
| | | Number of Threads | | | |
| | | 1 | 2 | 4 | 8 |
| 256x256x256 | 140 | 0,232 | 0,171 | 0,154 | 0,142 |
| 512x512x512 | 280 | 0,505 | 0,328 | 0,296 | 0,268 |

| | | | | | |
|---|---|---|---|---|---|
| 1024x1024x1024 | 560 | 0,904 | 0,626 | 0,579 | 0,535 |

# III. EXPERIMENTAL RESULTS AND COMPARISON

In this study, we developed a virtual welding simulator. The virtual welding simulator and a sample of welding are shown in Figure 6.


(a) (b)

***Figure 6.*** *Welding with virtual welding simulator* ***(a)*** *Developed virtual welding simulator* ***(b)*** *Welding sample with virtual welding simulator*

Figure 7 (a) and (b) show a parabolic and voxelized view for a weld seam sample. This illustrates how the welding seam gains volume. During welding operations, a weld seam is created in real-time, and to enhance the sense of reality, we created welding sound, light, and sparks. After the virtual welding application, voxelized welding seam forms can be evaluated. Figure 7-c and 7-d show a voxelized seam form after welding operation.

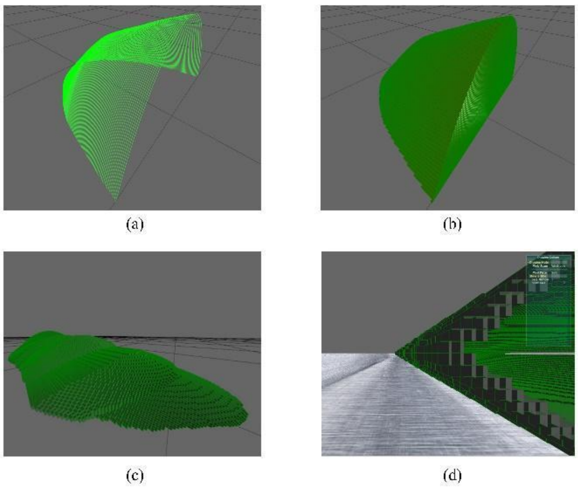


***Figure 7.*** *Parabolic and voxelized weld seam views* ***(a)*** *parabolic view,* ***(b)*** *voxelized view,* ***(c)*** *top view,* ***(d)*** *side view*

Multi-threaded programming makes welding seam drawing even more suitable for real-time applications. Considering that real-time images should have a 30-60 frame per second display, one frame should be drawn under periods of 16.7 ms - 33.3 ms. As shown in Tab. 3, the total drawing time for one parabola meets the real-time image criteria.

*__Table 3__. Total Process Time of a Parabola*

| Resolution | Number of Voxels | Total Process Time of Parabola (ms) | | | |
|---|---|---|---|---|---|
| | | Number of Threads | | | |
| | | 1 | 2 | 4 | 8 |
| 256x256x256 | 140 | 3,00 | 1,84 | 1,22 | 1,12 |
| 512x512x512 | 280 | 5,75 | 3,54 | 2,38 | 2,10 |
| 1024x1024x1024 | 560 | 11,78 | 7,10 | 4,76 | 4,27 |

Our welding simulator has a 3D view concept that makes the user feel as though they are genuinely welding. The welding operation has boundaries such as welding area and arc-length. Trainees use stereo HMD to immerse themselves in the welding environment. The audience and welder trainer see the welding operation on an auto stereo screen in 3D.

Most of the analyzed simulators, such as the VRTEX 360 [14] and Soldamatic AR welding simulator [15] in the literature, use third-party commercial graphics libraries, however, we used only free libraries and created our own graphics engine. Thus, the total cost of the simulator was decreased. Using a haptic device [12] narrows the field of work, and the data-glove [11] tracks finger positions that are not directly necessary for torch position. Using cameras [13] for position detection requires additional calculations compared to the HTC Vive, which needs no additional computation. The absence of particular performance scoring reduces the benefits of a simulator. Also, many simulators in the literature implement only MIG welding. A detailed comparison of the analyzed simulators is given in Tab. 4.

*__Table 4__. Comparison of analyzed simulators*

| Simulator | Welding type | Graphics support/ engine | 3D view | Weld puddle | HMD in helmet | Position detection | Welding sound | Performance scoring |
|---|---|---|---|---|---|---|---|---|
| Current Study | MIG, TIG,EA | own | √ | √ | √ | HTC Vive | √ | √ |
| [11] | MIG | Infinite Reality 2 | √ | √ | √ | Data glove | X | √ |
| [12] | MIG | Endea VR | √ | √ | √ | Haptic device | √ | X |
| [13] | MIG | own | √ | √ | √ | Cameras | √ | X |
| [14] | MIG | VRSIM | √ | √ | √ | Optic tracker | √ | √ |
| [15] | MIG, TIG | Unknown | √ | √ | √ | Optic sensors | √ | √ |
| [16] | EA | Unity 3D | √ | X | X | Optic sensors | √ | X |

When the *Welding type* column of Table 4 is examined, it is seen that the developed simulator performs both MIG and TIG welding, and there is only one reference with this feature, but in this study [15], it is not mentioned how the graphics engine was created.
When the column titled *Graphics engine* in Table 4 is examined, it is seen that there is only reference [13] which creates its own graphics engine like us. Although coding a graphics engine is a long and laborious task, coding our own engine has advantages in terms of mastering the simulator.
The 3D view of the simulation, the ability to show the weld puddle, the use of the HTC Vive technological device, and the integration of welding sound into the simulator reveal the difference of the proposed study from other simulators. In addition, having performance indicators is the most important indicator that this simulator is an educational simulator that can perform "measurement and evaluation".

Our developed virtual welding simulator system has been tested on welder trainees at Sakarya University. Figure 8 shows the average scores of two different groups of 40 users for each welding task. The scores are marked by the course instructors. Regardless of ability, an increase in users' performance levels and achievement was observed. Also, we observed how candidates' welding skills changed from using our simulator. The results showed that trainees effectively improved their welding capabilities [22].

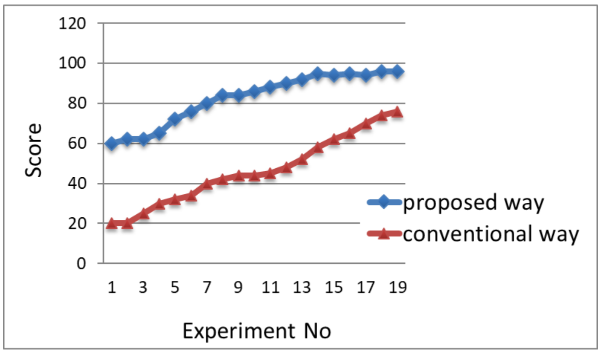


***Figure 8.*** *Real welding operation scores of trainees [22]*

# V. CONCLUSIONS

When a welder candidate uses a welding simulator before a real welding operation, waste in the form of energy, time, and materials is reduced. Also, a welder can work in an environment with no risk of electric shock, burns, or eye burns. The welders are also prevented from having psychological symptoms such as shyness, despondency, and loss of self-confidence.

In this study, a virtual welding simulator was developed to train welder candidates. The work is based on welding simulation without a need for a real welding environment. Trainees can learn welding techniques or practice their skills in safe conditions without the risk of injury and can complete more practice welds in a short period for both MIG and TIG welding types.

In this study, the hand motion data received from I/O devices were examined by the weld bead parameter decision module. We calculated the necessary parabolas that represented the weld bead, and a voxel map was created from these parabolas. A hash-based octree data structure was created to control the corresponding voxels. Then, the triangular mesh model representing the weld seam was constructed employing the hash-based octree data structure using the marching cubes algorithm. As the welding process continues, the hash-based octree structure is updated, and the triangular mesh model of the weld seam is reconstructed in real-time. We used multi-threaded programming for voxelization and isosurface extraction to reduce the processing time on high-resolution virtual scenes. Thus, we generated more realistic weld seam shapes by using voxelized parabolas.

We did not use any third-party commercial libraries, and we created our own graphics engine, decreasing the total cost of the simulator. We made the simulator more economical and commercially available by reducing the cost.

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