

A Vision-Based Path Planning Algorithm for a Robot-Mounted Welding Gun*

SPYROS G. TZAFESTAS, SPYROS RAPTIS, and JOHN PANTAZOPOULOS

*Intelligent Robotics and Automation Laboratory
National Technical University of Athens
Zografou Campus, 15773, Athens, GREECE*

Abstract

This paper deals with the problem of the trajectory formation for the welding gun during the welding process based on image frames obtained by a camera. This trajectory needs to be as accurate as possible in order to meet certain criteria and respect various restrictions imposed by the user or by the process itself. The x- and y- coordinates of this trajectory are determined so as to follow the center-line of the joint while the gun elevation may be used as an additional secondary process variable in order to facilitate the control of the process. Preliminary image scans are used to identify crucial parameters of the 3D model of the welding area so as to simplify the real time control loop by programming off-line as much of the process as possible. Various well known image processing algorithms that are extended and revised to meet the specific needs of the problem at hand, are blended together and integrated into a efficient user friendly shell. This shell that can be used for the simulation as well as for the monitoring of the path planning of a robot mounted gun during the welding process.

1. Introduction

With welding being one of the largest industrial applications, various efforts have been made to automate it. These efforts either addressed the whole problem or specific subparts of it as, for example, the on-line feedback control of the process variables ([2], [3], and [4]), the tracking of the seam ([5]), the advantages by the use of different kinds of sensors ([5], [10], [11]), the on-line feedback control of certain indicative variables of

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the weld ([6-9]), etc. Modern control techniques have also been used to control the process. An indicative list of such research results can be found at [2].

However, the welding process involves some extremely complex physical phenomena and no analytical solution has been found that can describe it accurately enough throughout the domain of its input parameters. So, up to now the automation of the process involves the realization of a sufficient set of experiments whose results are then used to formulate local models of the process. But these models are usually strongly dependent on the specific conditions under which the experiments took place and therefore cannot be easily ported to a cell of different configuration. As a result, the automation of the welding process is still an open research area.

The problem of welding is actually twofold: first the welding gun must be accurately driven to track the welding seam and then the key control variables of the process need to be on-line calculated so as to meet certain physical, thermal and mechanical constraints, as well as specific quality criteria.

The primary control variables are usually the voltage, the gun velocity, and the current (or the wire feed rate). Some parameters, like the transverse and longitudinal angle of the gun, as well as its distance from the welding area, are usually set prior to the beginning of the process and are then kept constant throughout it. However, it is also possible to vary one or more of them so as to meet user or process constraints.

For example, when the gap between the base plates to be welded gets too big (e.g. due to low pre-processing quality) then more filler metal needs to be deposited, while the penetration should remain within the predefined limits. If the gun velocity decreases unlimitedly to compensate for this environmental variation, the welding pool is likely to bypass the gun resulting to the pre-deposited metal to be burned and the penetration to be lower than acceptable. One possible way to overcome this problem, is to vary the elevation of the welding gun.

In many cases the welding trajectory is predefined and fixed for all the successive welds. A robot program for welding is developed and it is downloaded to the robot cell for all plates of the same joint type. This simplified approach is inadequate in the case of important model parameter variations along the plate edges.

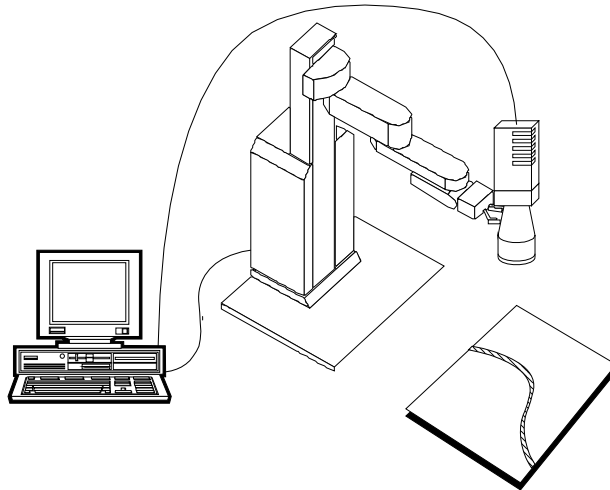


Figure 1: *The overall system*

In the adaptive case, each weld needs special treatment based on data that are either collected during the welding or during a preliminary scan of the joint area. This is actually, the approach taken by our system.

The goal of a vision-based system for a robot mounted welding gun is to *automatically* perform the required *actions* (e.g. moving the robot-mounted camera to appropriate positions, performing rough and fine scanning of the welding area, etc.) and the *image processing* (extract from the obtained image frames the information needed to guide the rest of the process) that will enable the system to off-line formulate a precise path to be followed by the gun during the welding process.

2. The System

The present system concentrates on the trajectory formation for the welding process including control of the elevation of the welding gun.

The system consists of a robot manipulator and a CCD camera connected as shown in Fig. 1. The procedure of trajectory formation consists of the following steps:

- I. Preliminary rough scanning of the welding area
- II. Image pre-processing to filter the noise
- III. Formulation of a rough trajectory for the fine scanning
- IV. Fine scanning

I. Rough Scanning

At the beginning of the procedure, the camera is mounted onto the robot's end-effector and the arm is driven to a location far enough from the area of interest so as to fully include it in an image frame. A noisy image of the entire joint is thus obtained. At this stage, accuracy is not of primary importance since we are only interested in extracting sufficient information to drive the camera *near* the joint during the fine scanning phase.

On the image obtained it is possible either to interactively define a starting and ending point for the welding or to let the system determine their physical boundaries. Moreover, in the presence of multiple joints, the user may choose the joint to be treated.

II. Image Processing

Due to various reasons, the image obtained at the previous phase is very noisy and of rather low quality. These reasons include: the low quality of the camera, the specific light conditions, the fact that it may be out of focus, a bad internal threshold leading to a poor black-to-white ratio, etc.

For the needs of the present application a simple *windowing filter algorithm* proves to be quite efficient: we define a window of dimension $n \times n$ for each pixel where $n = 2k + 1$ (see Fig. 2). If the majority of pixels in the window have the value 1, then we assign a 1 to the center pixel, else we assign a 0. Similarly, we proceed to the next pixel scanning sequentially all the image line-by-line.

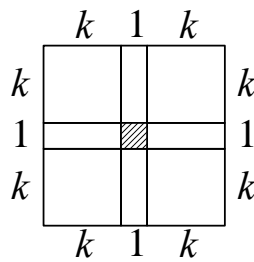


Figure 2: *The window filter*

First, we transform the image using this simple filter with $k = 1$ ($n = 3$) so as to eliminate isolated noise pixels as shown in the figure 3. This noise is known as *salt 'n' pepper noise*.

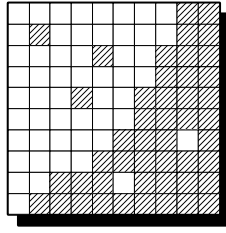


Figure 3: *Salt 'n' pepper noise*

Due to the random nature of the noise, this filter performs well, but we may further refine the resulting image by successively applying filters with the same or greater values of k . It is important to note that multiple passes of the same filter do have effect on the image.

III. Extracting the Fine Scanning Trajectory

After the image has become clear enough, an edge-detection algorithm is in order. Finding the edge is quite important since this will enable us to find the center line in the next step for the fine scanning procedure to follow. Our accuracy at this stage is limited solely by the resolution of the camera.

Although it appears to be trivial, extracting the center trajectory of an arbitrary closed curve is not a straightforward task. The steps required are the following:

1. *Extract the object of interest from the camera image*

In our case, it is the joint area. For this task recursive or sequential labeling algorithms are used (region labeling algorithms). One acceptable approach would extract the object laying nearest to the center of the image while a more “sophisticated” one would extract all objects and prompt the user to graphically select one of them. The current implementation of the system supports both.

The filtering phases that precede the object extraction phase ensure that the object’s region will be *simple*, i.e. it will contain no holes, as long as no major gaps appear in the original object (which is the case for welding areas). This characteristic will enable us to internally represent this region as a connected list of 2D points.

For the mathematical convenience of the discussion below, we define the *space* of a region R , say $S(R)$, as the 2D area wherein the region lies.

2. Find the perimeter of the extracted objects as a closed curve

Algorithms based on 8- or 4- connectivity may be used. The idea behind such algorithms is as follows. Starting from a random point laying on the boundary we locate and proceed to the next boundary point in the way a man walks around an island. The process stops when the initial point is revisited. At the end of the algorithm, an ordered list of the points laying on the boundary of the region has been constructed. From this point and below, we will call this ordered list *perimeter* of a region R , say $T(R)$.

It is clear that a point belongs to the perimeter of a region R iff it belongs to its space, $S(R)$, and at least one of its neighboring points does not. Neighboring points are defined as the image pixels (x,y) whose distance from the current point (x_0,y_0) equals 1 with respect to the metric:

$$d((x,y),(x_0,y_0)) = \max\{|x - x_0|, |y - y_0|\}$$

3. Find a set of center-points for the resulting curve

The algorithm used here is an extension of the *Dirichlet classification algorithm*. As opposed to the latter, this algorithm calculates points equidistant from two *unknown* point classes representing the “left” and “right” boundaries of the curve.

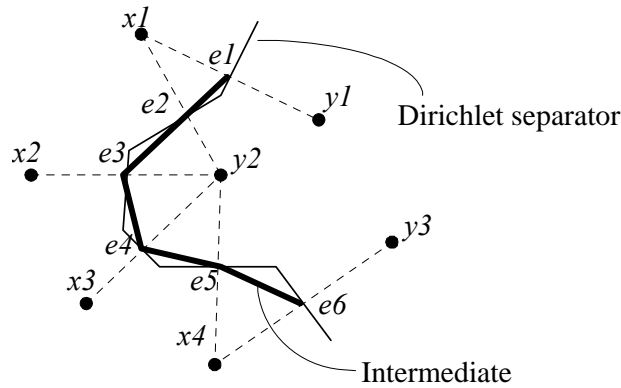


Figure 4: From ω_1 and ω_2 we calculate the center points $e_1...e_6$ which form the center path

Let us consider a region A with space $S(A)$ and perimeter the ordered set $T(A)$. An image point $p=(x,y)$ is a *center point* of A iff:

1. $p \in S(A)$

2. Let t_1 and t_2 be the two closest perimeter points to p , considering the Euclidean metric, i.e.:

$$t_1 = \min_{t \in T} \|t - p\| \text{ and } t_2 = \min_{t \in T - \{t_1\}} \|t - p\|$$

Then the following should hold:

$$p = \frac{t_1 + t_2}{2}$$

Because of the discretization of the image, the second condition is true only for a limited number of points in the image, preventing the construction of good paths of the region. To increase the number of center points, we need to alter this condition by introducing a threshold $\varepsilon > 0$. In this case the second condition takes the form:

$$\|2p - (t_1 + t_2)\| < \varepsilon$$

4. Calculate center-paths using these center-point

A point ordering algorithm is used for this task. Some center points are ordered to form a center path while others may need to be discarded. The idea of center paths is very close to the that of *Voronoi Diagrams* [13] but it is more appropriate in the AI part of the welding process.

A center point can be completely described by two points of the perimeter of the region. Since the perimeter is represented by an ordered list of image points, two integer indices, say l and u , indicating the position of the respective points in the perimeter list can be used to describe each center point. Without loss of generality, we assume that $0 \leq l < u$. Using these indices, the coordinates of a center point can be calculated as:

$$p_{center} = \frac{1}{2} (p_{perimeter}[l] + p_{perimeter}[u])$$

This representation of center points, helps us sort the central points in order to construct the central paths of the region. Below we will provide some definitions that will facilitate the rest of the investigation.

Let us consider two ordered sets of central points, say $A_1 = \{(l_{11}, u_{11}), \dots, (l_{1n}, u_{1n})\}$ and $A_2 = \{(l_{21}, u_{21}), \dots, (l_{2m}, u_{2m})\}$. Their union is the ordered set:

$$A_1 \cup A_2 = \{(l_{11}, u_{11}), \dots, (l_{1n}, u_{1n}), (l_{21}, u_{21}), \dots, (l_{2m}, u_{2m})\}$$

We say that the ordered set A is a *simple path* of a region iff:

1. $\forall i = 1..n, (l_i, u_i)$ describes a center point of the region
2. $\forall i = 1..n-1, l_i < l_{i+1}$
3. $\forall i = 1..n-1, u_i > u_{i+1}$

Finally, let us define the space of a simple path $P = \{(l_1, u_1), \dots, (l_n, u_n)\}$ as the following set:

$$Sp(P) = [l_1, l_n] \cup [u_n, u_1]$$

Now we can define the term *global path* of the region as a set of its simple paths. Let us consider the ordered sets of center points $P_i, i = 1..k$. The set $RN = \{P_i, i = 1..k\}$ is a global path of a region R iff:

1. Every center point of R , belongs to exactly one P_i
2. $\forall i = 1..k, P_i$ is a valid simple path of R
3. $\forall i, j \in \mathbb{N}$ and $1 \leq i < j \leq k, Sp(P_i) \cap Sp(P_j) = \emptyset$

The set RN is an *independent global path* of region R , iff:

1. RN is a valid global path of R
2. $\forall i, j \in \mathbb{N}$ and $1 \leq i < j \leq k, RN - \{P_i, P_j\} + \{P_i \cup P_j\}$ is not a valid global path of R

It is easy to prove that there can be only one independent global path and it has the least number of elements compared to every other global path of the region.

Because of the simplicity of the welding area, the independent global path can have one or at most two elements. In the latter case, the paths are easily joined. In our implementation, condition 3 of the global path definition may not hold due to the quantization noise. To overcome this “problem”, some center points need to be dropped so that the violation no longer exists.

5. Calculate center-trajectories using the paths calculated above

This is necessary since we not only need *positions* but also *orientations* for each point so as to effectively drive the robot mounted gun along the center-path. At this stage, the extension of the center path so as to include the starting and ending points of the welding gun, which are placed on the region boundary. Moreover, a normalization of the distribution of the center points over the center paths may be in

order, so as to adapt the path to the motion capabilities of the robot arm and also to the needs of the on- or off-line control loop of the welding process parameters.

A demonstration of the above steps on a real camera image after the noise has been filtered is given below.

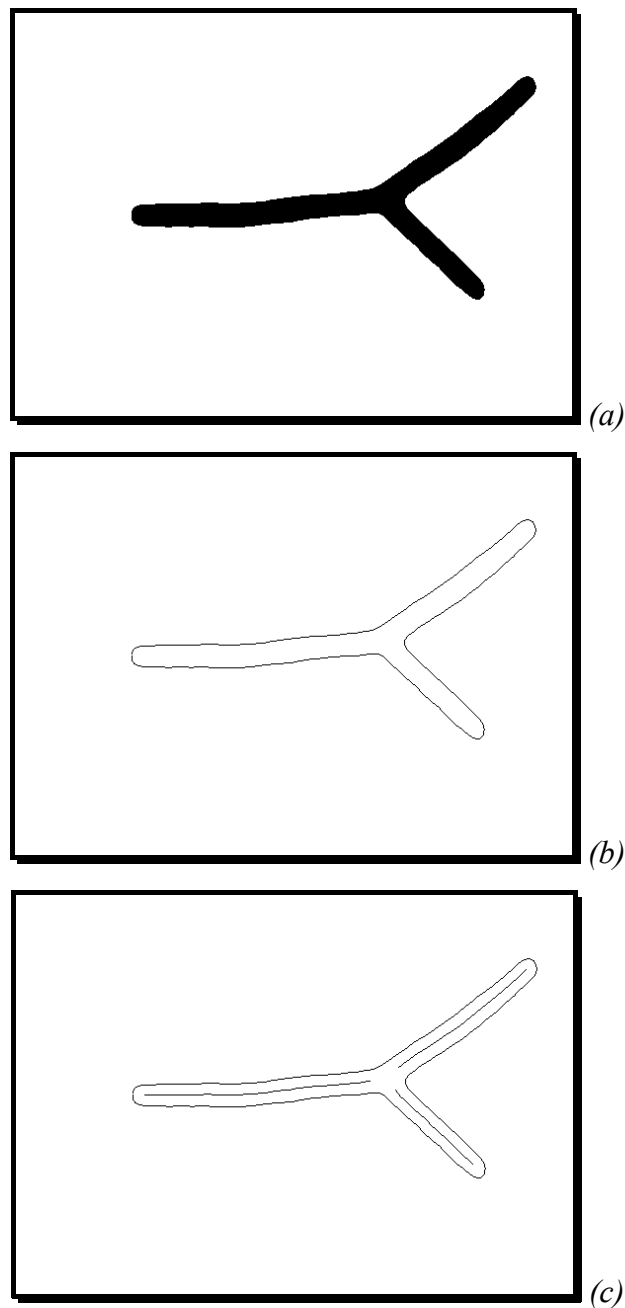


Figure 5: (a) *Extracting the object*, (b) *extracting the perimeter*, (c) *finding the center paths*

It is important to note that image-to-reference coordinate system (CS) transformations are involved in the above algorithm as shown in Fig. 6. This involves the following transformations:

- *From the image to the camera*

This is actually the inverse perspective transformation where the world coordinates (x,y,z) need to be extracted from the image coordinates (x,y) . This is an ill-defined problem since the number of solutions is infinite. The additional information required is usually provided by external sensors that measure the distance from the camera to the image plane (i.e. its elevation), say λ . In our implementation, the position of the camera during the rough scanning phase is chosen to be far enough from the plane where the welding area lies and it is the same for all the tests. This is acceptable since the role of that phase is only to formulate a rough path for the fine scanning phase to follow.

The *inverse perspective transformation* is given by:

$${}_{camera}\mathbf{T}^{image} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & f & \frac{f\lambda}{f-\lambda} \\ 0 & 0 & 0 & \frac{f}{f-\lambda} \end{bmatrix}$$

- *From the camera to the robot's tool center point*

This transformation, say ${}_{tool}\mathbf{T}^{camera}$, is known a priori and fixed.

- *From the tool center point to the reference*

This transformation, say \mathbf{T}^{tool} , is calculated via the robot kinematics parameters.

- *From pixel coordinates to the image plane coordinates*

If every pixel is of size $\Delta x \times \Delta y$ in the image plane and we have a resolution $m \times n$, then this transformation is given by:

$${}_{image}\mathbf{T}^{pixel} = \begin{bmatrix} -\Delta x & 0 & 0 & m\frac{\Delta x}{2} \\ 0 & -\Delta y & 0 & n\frac{\Delta y}{2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The overall transformation that will provide the world coordinates of an image point (pixel) is obtained by multiplying the transformations described:

$$\mathbf{T} = \mathbf{T}_{tool}^{tool} \mathbf{T}_{camera}^{camera} \mathbf{T}_{image}^{image} \mathbf{T}_{pixel}^{pixel}$$

$$\mathbf{p}_{world} = \mathbf{T} \cdot \mathbf{p}_{pixel}$$

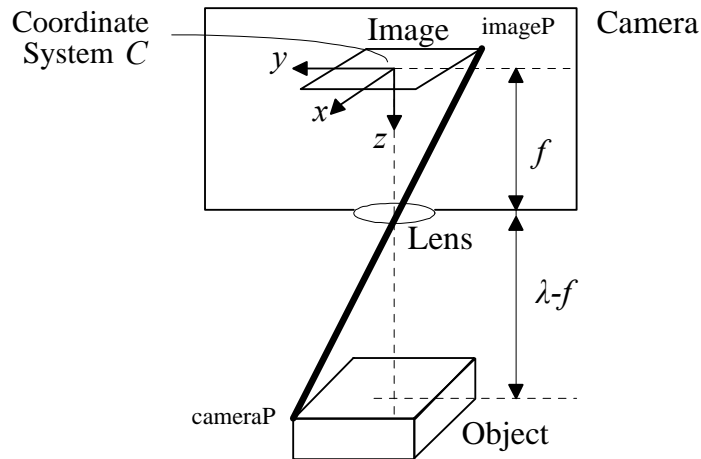


Figure 6: *The various coordinate systems*

IV. Fine Scanning

At the final stage, the robot is driven above the starting position at an appropriate elevation and starts performing the actual fine scanning of the joint area. During this phase, accurate data for the crucial model parameters and variables to be used during the welding process are collected. Such data are in this case the actual gap length which will have effect on the elevation of the gun. Using more sophisticated sensor equipment as, for example, a laser camera, parameters of the 3D model of the welding area may be extracted [1]. This may be of important help since the amount of filler metal to be deposited could be more precisely calculated.

For example a butt V-groove joint can be modeled as shown in figure 7.

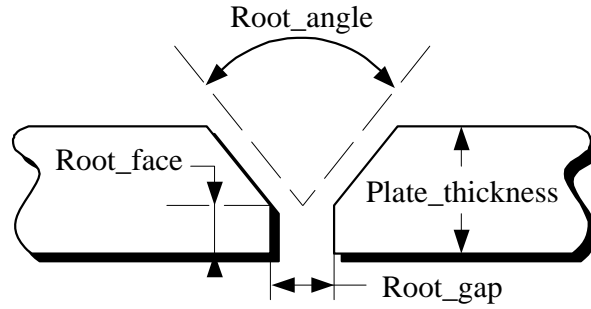


Figure 7: Geometric parameters of a butt V-groove joint

It is clear that all the important parameters of this model may be measured by a laser camera during the fine scanning phase. In any case, model variations along the joint are mainly introduced during the plate pre-processing phase and are not usually expected to dramatically vary. So for the needs of this investigation, random noise was introduced to the model parameters in order to compensate for such variations.

3. Using the 3D Model

What has been obtained after these preliminary phases are the parameters of the 3D model prior to the beginning of the welding process itself. Some of them are used directly on-line to place the welding gun at the right x- and y-coordinates above the joint while others will be used to calculate the required amount of filler metal and by this the elevation of the welding gun (z-coordinate).

A simplified expression for this amount is:

$$A = \frac{1}{2}(b - g)(h + t - f) + g(t + h)$$

Other parameters may also be used for different situations or different models.

Having the 3D model of the joint area, the largest part of the welding process may be pre-programmed and the actual on-line feedback control loop may, thus, be simplified a lot.

Moreover it is possible to control the waving of the welding gun, which is necessary when the joint gap becomes too large.

4. Simulation Results

For the simulation, the system consisted of an RTX robot manipulator and a JVC camera, both controlled by a personal computer (PC).

The RTX robot is a simple P-5R robot arm which may be controlled by a PC through a serial link and a specialized IPC protocol.

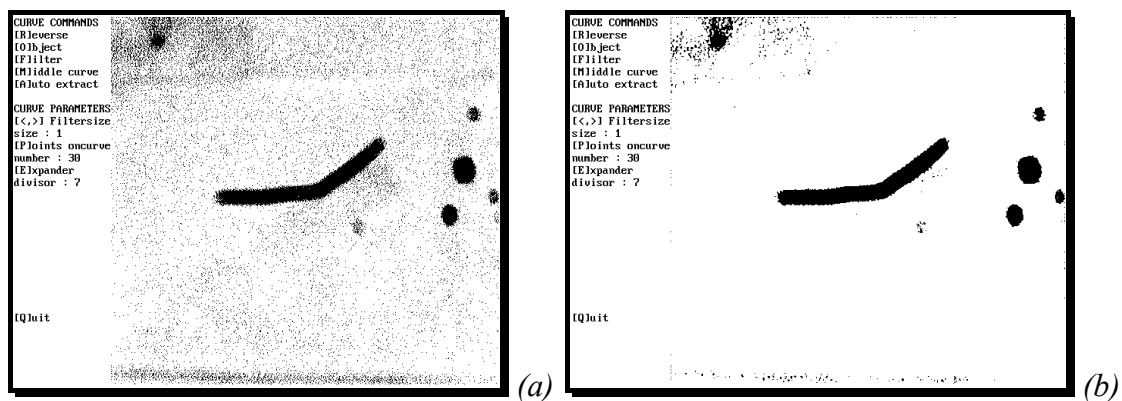
The JVC camera is a simple CCD monochrome camera providing resolution 512×480 pixels. It has the ability to communicate with a PC through an appropriate hardware control card and to adjust its black-to-white ratio, threshold, etc. through software.

High contrast samples were used to represent the joint area. Random noise in a predefined interval was used for the model parameters instead of a laser camera. Based on this, a 3D model of the joint was constructed and a 3D trajectory was calculated.

The system also provided the ability to control the speed of the welding gun along the trajectory. But since the speed is one of the primary control variables for welding, and the welding phenomenon itself was not addressed, simple heuristic rules were used for it. Figure 8 shows the various steps of the image processing.

After finding the center-trajectory, a fine scanning phase follows, and the joint parameters are accurately measured. For the ones that are not measured, random noise is introduced. Finally, the 3D model of the joint is produced and the welding process is simulated. Figure 9 shows the 3D model of joint (different than the one shown in Fig. 8).

Several variables of the welding process depend on the 3D model of the joint area. Most of them can be off-line programmed. In the simulation such variables as the gun elevation, speed, and waving are calculated for the entire process. Their typical values are shown in figure 10.



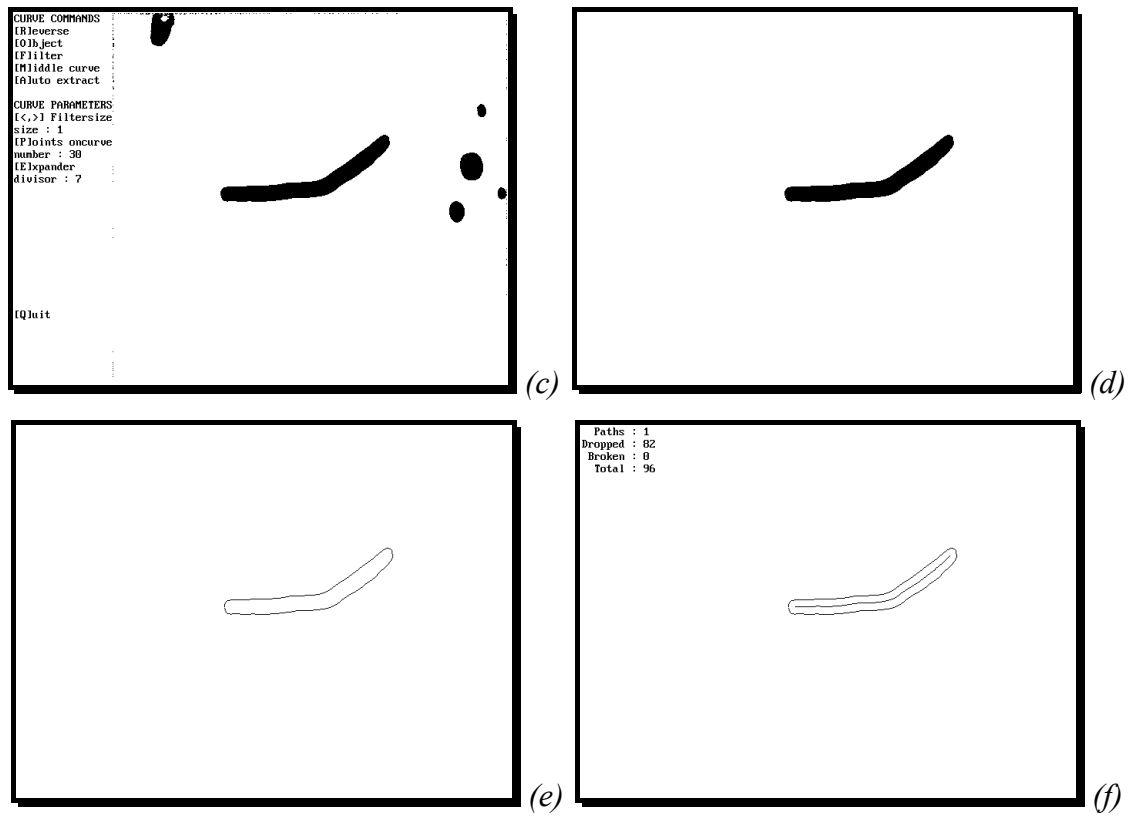


Figure 8: (a) The camera image, (b) Cleaning the salt 'n' pepper noise, (c) Using additional filters, (d) Extracting the object of interest, (e) Calculating its perimeter, (f) Finding the center-path.

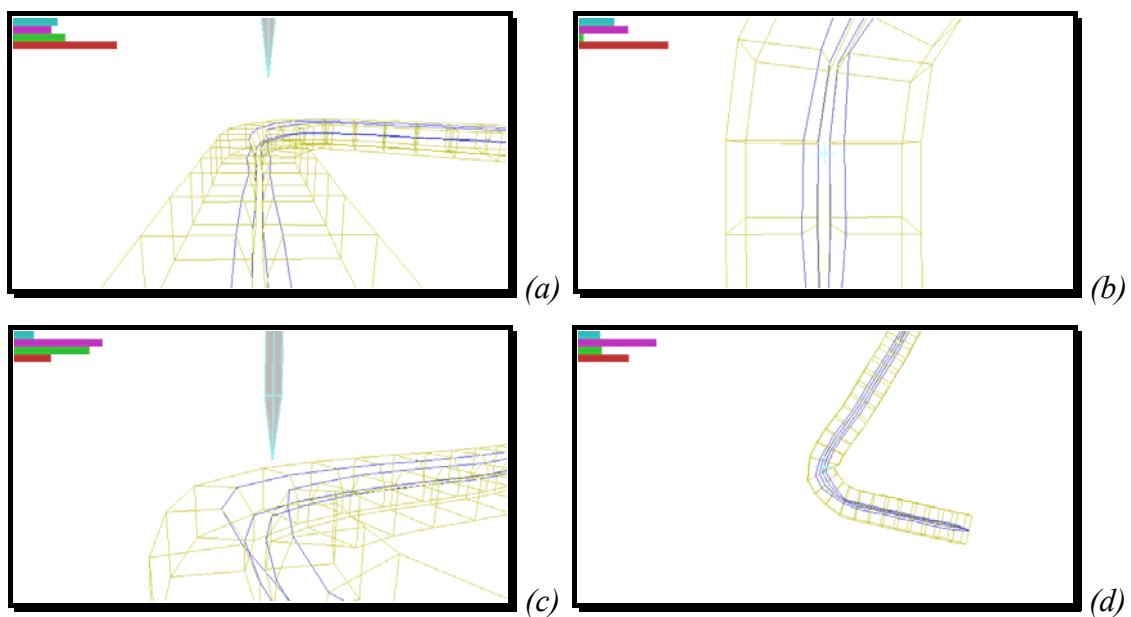


Figure 9: Various views of the 3D joint model during the simulated welding process.

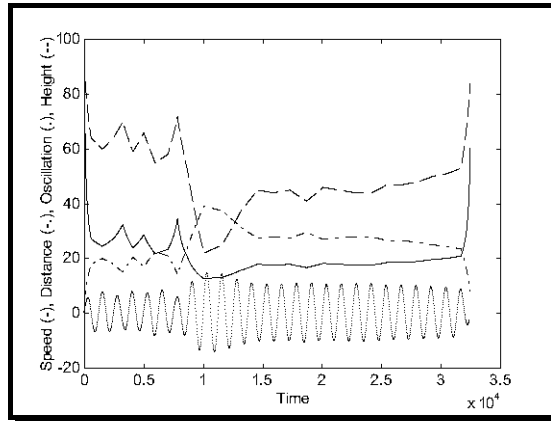


Figure 10: Some parameters calculated prior to the beginning of the process
(the units of the time axis are arbitrary)

Conclusions

The system presented in this paper addresses the problem of path planning for a robot mounted welding gun by the use of image processing algorithms and tools. Well known algorithms have been extended and specialized in order to meet the constraints and characteristics of the specific problem as well as to efficiently interact to each other. The result is an efficient system that can function with minimum or no user intervention and can be used for either simulating or monitoring the path planning of the gun in a welding process.

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