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A System for Measurement and Control of Weld Pool Geometry in Automatic Arc Welding

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A system for measurement and control of weld pool geometry in automatic arc welding
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Summary

In automatic arc welding systems a sensor can be used to control the quality of the weld. Several types of sensors are eligible for this purpose. The commercially available sensors and sensors in development are based on various phenomena and offer different possibilities.

In arc welding, the shape and dimensions of the pool depend on the state of the process and might be used in weld quality control.

For gas metal arc (GMA) welding a system has been developed which observes the pool by registering the radiation emitted by the pool with a solid state camera (CCD). The arc does not have to be diminished or to be interrupted to view the pool. Optical filtering effectively reduces the excessive intensity of arc radiation relative to the intensity of the radiation from the pool.

Images in which the contour of the weld pool can be recognized are captured in welding of low-alloy steel products. Weld pool observation is feasible in the presence of the arc in the diptransfer, globular transfer and spray transfer regimes.

A computer is used to process the captured images. Software has been developed to analyze the geometry of the pool. Existing pool measurement systems are all based on thresholding of the image. It appeared that thresholding does not satisfactorily unveil the real contour of the pool in the images captured. Therefore, in this project the image analysis is based on edge detection.

The system is intended for control of the weld quality by adjustment of the torch position (usually called seam tracking) and adjustment of the welding parameters.

The system has been tested with a limited number of experiments. The case of seam tracking errors has not been considered, because several sensor systems (mostly less complex than for weld pool measurements) already are commercially available for the seam tracking function. The results of the experiments show potential for application of the system in automatic welding.
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Chapter 1
Introduction

Welding is an important joining technique that is used on a large scale in industry. For different reasons, there is a push for mechanization and automation of the welding operations. However, process automation usually requires more, and more precise knowledge of general process behaviour and the actual process state than is needed for manual operation.

In many respects welding is still more a craft than a science. With manual welding the welder, faced with a particular task, first chooses the nominal welding conditions and parameters on the basis of general experience, partly documented in handbooks and other publications. Then, during the process, he reacts correctively to incidental deviations and disturbances guided by his visual, auditory and mechanical perceptions, and by his personal experience. Thus a weld is produced at the desired location, and weld defects are prevented in a way that is not readily accessible for scientific modelling.

In the basic form of welding automation, a mechanism manipulates the torch (welding head). The torch movements and weld parameter settings will be the same for all products of the batch. In this case all corrective actions are blocked. One consequence of this is that all products must be supplied in exactly the same position. In practice, however, the parts of products are always manufactured with a finite accuracy. The dimensions of product parts are therefore always specified with a tolerance.

Automatic welding in batch manufacturing is used successfully for products with narrow tolerances on parts production and positioning. But the tolerances in manufacturing are mostly larger than can be allowed in mechanized welding. In those applications it may be very expensive to narrow the tolerances. For the automation of the welding task, a system is desired that can react adaptively to the variations normally occurring in product dimensions. This adaptation must make it possible to accomplish the desired weld quality with an automatic system without substantial constraints on other production processes. Sensors offer the opportunity to achieve this goal. The sensor must observe whether a deviation from the nominal dimension or position occurs and measure it. With this information, the welding system can adapt to the deviation.

Arc welding with an industrial robot is a well known example of automatic welding. Industrial robots for arc welding mostly use the GMA welding process\(^1\). Arc welding robots used in industrial applications achieve increased productivity and quality. These robots still function mostly without welding sensor. It is expected that the number of applications will increase when the robots can be equipped with more intelligence. This means that

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\(^1\) The GMA (Gas Metal Arc) welding process will be described in section 1.1.
useful sensor information must be available and used. Robots equipped with sensors are called robots of the third generation.

Different sensing principles have been developed for arc welding applications. However, the type of information that becomes available differs from the traditional feedback mechanisms of the manual welder. Therefore new knowledge has to be built up to make full use of the potentials. It is the lack of this knowledge which causes the opportunities offered by information technology to be only scarcely used in welding.

This thesis describes a system developed for measurement of the weld pool geometry during the GMA welding process. It differs from most existing sensor systems in that the state of the welding process is determined rather than the variation in welding circumstances. This makes it possible to react to process disturbances other than the geometric variations as well. We will indicate how this type of measurements can contribute to controlling the quality of the weld.

The system developed comprises a video camera, pointing at the welding spot. A dedicated computer is used to analyze the images captured with the camera and determines whether and how the process could be adjusted to achieve the process state that can lead to an acceptable weld quality.

1.1 Welding technology

This section is intended for the reader who is not familiar with welding technology.

Welding is a joining technique producing a continuous metallic joint between parts, in which the joint has approximately the same material properties as the parts joined.

In welding, the parts to be joined are locally heated, so that they melt at the welding spot. The liquid metal from the parts merges in what we call the *weld pool* which forms the weld after solidification.

Often a filler metal is added which melts also and merges into the pool. The melting and solidification often take place in a (semi-)continuous process: The heat source (welding head or torch) is moved over the line along which a weld must be produced. Melting takes place immediately ahead of and under the welding torch and solidification takes place simultaneously at the rear side.

Spot welding is an example of a discontinuous process: The heat source is held at a fixed position, where a weld is produced. There, all the material of

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1 In literature, occasionally the term *melt* or *weld puddle* is used instead of the more commonly used 'weld pool'.
a particular weld is melted and solidified afterwards. In a (semi-)continuous welding process, a weld is formed along a line. This usually is the intersection line of two more or less sheet like parts of the workpiece. The edges of the parts to be welded form what is called the seam. Different types of seams can be distinguished, depending on the cross sectional geometry of the seam. Some of these are given in figure 1.1. The seam geometry is obtained by an appropriate preparation of the edges of the parts. The amount of heat produced per unit of length of the weld is called the heat input. This is used in metallurgical evaluation of the welding process. The metallurgical aspects of welding are irrelevant for this thesis and are therefore not discussed.

Welding processes
In welding technology many processes can be distinguished, all with specific areas of application in industry due to their specific benefits and limitations. In this chapter we shall mention some different processes and explain in detail the one we selected for our experiments. We confine ourselves to the processes that are important for this thesis. In the processes most frequently encountered in industry, the heat is supplied by an electric arc. We call these arc welding processes. The arc is usually present between an electrode and the workpiece, which are therefore electrically connected to the welding power source. Other welding processes are for instance resistance welding, friction welding, laser welding, electron beam welding and oxyacetylene welding. One of these, resistance welding, is widely known for its application in the production of car bodies. In this application robots have been introduced into industry in large numbers.

Widely used arc welding processes are:
- Shielded metal arc welding (SMAW). This process uses a shielded metal rod as an electrode which is consumed during welding. Vapours and slag formed out of the shield material protect the process from the air.
- Gas tungsten arc welding (GTA welding or GTAW). This process uses a welding torch with a non consumable tungsten electrode under protection of argon or helium gas. Often a wire (not connected as an electrode) is
added separately as filler material.

- **Plasma arc welding.** This process can be seen as a modification of the GTAW process. An arc is maintained between two electrodes in the welding torch and a plasma jet is blown out of the torch.

- **Gas metal arc welding** (GMA welding or GMAW). This process uses a metal welding wire as a consumable electrode. The wire is supplied to the torch mechanically during welding. CO₂ and argon are often used as the shielding gas.

- **Flux cored arc welding** (FCAW). This process is very similar to GMA welding, but uses a flux cored wire as the consumable electrode. Some flux types make the gas protection superfluous.

- **Submerged arc welding** (SAW). This process uses a consumable wire electrode that melts under the protection of a separately supplied flux granulate.

### 1.1.1 GMA welding

The GMA welding process is used in the work described in this thesis. To understand its characteristics, we will now discuss some phenomena that appear in this process.

GMA welding is a (semi-)continuous process. An electric arc is present between a wire sticking out of the torch and the workpiece. The wire is connected with the positive pole of a DC-power source via the contact tube in the torch (figure 1.2).

The main parameters that can be varied during welding to control the GMA process are the wire feed rate, the voltage, the welding speed and the torch to workpiece distance. Pre-chosen fixed parameters are, amongst others, the wire diameter and composition, the torch orientation, the weaving motion (oscillation transverse to the direction of welding) and the gas composition.

The main parameters determine the current which to a large extent determines the internal process behaviour and weld properties. Traditionally, the welding conditions are mostly specified by current and voltage rather than by wire feed rate and voltage.
1.1.2 Melting of the workpiece

The melting of the workpiece material takes place mainly at the front side of the pool due to arc heating (ALLUM and QUINTINO 1985b). In addition, some workpiece material is melted due to heat transferred via the pool. Under normal welding conditions, the arc is located between the wire and the pool front. Cathode spots appear on the workpiece surface in the vicinity of the pool border, where an oxide and other layers are still present. Oxide and other inhomogeneities or impurities have a lower emission energy for the electrons than the pure metal (ESSERS and v. GOMPEL 1984). The oxide layer disappears, forming slag, which has a slightly lower melting temperature than the metal.

The depth of the melting front in the workpiece is called the penetration depth, or, for short, the penetration. One speaks of full penetration when the weld penetrates the full thickness of the workpiece.

It was shown (see for instance ALLUM and QUINTINO 1985a) that the penetration is correlated with the welding current and slightly less with the travel speed. The welding voltage has an insignificant influence on the penetration. It only influences the arc length, the temperature of the pool and the width of the penetration area.

When the welding current is relatively high, the melting of the workpiece is boosted by two effects. The first one is that the molten material is slightly blown away by the arc plasma, which facilitates direct arc heating of the workpiece. The other one is that the flow of droplets that are projected with a certain velocity into the pool, generate a flow within the pool which locally causes a deep penetration in the centre of the weld (ALLUM and QUINTINO 1985b).

Frequently, the torch is weaved over the width of the seam during welding to get a smooth distribution of heat. This aims at obtaining penetration all over the seam to get a good attachment between the weld and the workpiece.

1.1.3 Melting of the wire

Figure 1.2 is a drawing of a GMA welding torch. The wire sticking out of the torch is both electrode and welding consumable. The wire is supplied mechanically to make the process continuous. It is electrically connected to the power source via the contact tube in the torch. Under steady state conditions the wire melts at the rate it is supplied. This steady state is the result of a form of self-regulation, which is achieved by using a (nearly) constant-voltage power source.

The heat required to melt the wire is contributed by Joule heating in the wire extension, heat transported from the arc by electrons, and the absorption energy of electrons entering the wire electrode (ALLUM and QUINTINO 1985b, WASZINK and van den HEUVEL 1982). The Joule heating depends
on the welding current and the wire extension length (WASZINK and van den HEUVEL 1979), that is the distance between the contact tube and the arc, see figure 1.2. Thus current depends not only on the wire feed rate, but also on the wire extension length.

1.1.4 Material transfer to the workpiece

The flow of material from the wire to the weld pool takes place in droplets. Three types of forces play a role in the transfer of material (FARWER 1985, ESSERS and v. GOMPEL 1984):

- surface tension of the liquid metal retaining a droplet onto the wire,
- gravity,
- electromagnetic forces which repel a droplet from the wire and facilitate the detachment of a droplet through the pinch effect.

In the transfer of material one can distinguish different regimes, at different welding conditions:

- Diptransfer or short arc. This occurs in welding with relatively low values of the wire feed rate and voltage. The current settles at a relatively low value and the arc is relatively short. The drop at the end of the wire grows until it makes contact with the pool surface. This interrupts the arc. Within a few milliseconds, the drop is pulled into the pool, mainly due to surface tension. At the short circuit the voltage drops and the current rises with a slope determined by the inductance of the source and the (reduced) resistance, see figure 1.3. When the contact between the pool and the wire is broken, the voltage rises sharply due to the inductance of the source causing reignition of the arc. Meanwhile,

\[ V(t) \]

\[ i(t) \]

**Figure 1.3**

Electrical model of diptransfer welding.
the current stabilizes at the normal value.
Generally speaking the pool is mechanically excited by this process in such a way that the pool surface swings to the wire where it pulls off the droplet as it swings back again. The drop detachment is facilitated by the dynamics of the weld pool.
The deposition rate, pool dimensions and penetration are relatively low. Diptransfer welding is often used for welding thin sheet material and for the root run (first pass) in a multi-pass weld, where the pool must be kept in position by surface tension and the heat input must be low.

- **Globular transfer.** This occurs also in welding with a relatively low value of the wire feed rate, but with the voltage set at a higher value than for diptransfer welding. The higher voltage causes a longer arc, that is not interrupted by short circuits. The drops adhere much longer to the wire tip than in diptransfer welding. They may grow as large as 4-6 times the wire diameter. Gravity is the main force causing detachment. Therefore the torch must be pointing down.
Globular transfer usually is avoided in GMA welding because it takes place in a more irregular manner than diptransfer welding and consequently also the weld surface is more irregular.
Globular welding produces a wider penetration area than diptransfer welding.

- **Spray transfer.** This occurs when the welding current exceeds a certain value. The transition value depends mainly on the wire diameter and the gas composition. The droplets are pulled from the wire mainly due to electromagnetic forces (ESSERS and v. GOMPEL 1984). This force is so strong that the droplets are detached before they attain the diameter of the wire. The weld pool dimensions will be relatively large, because the wire feed rate and the voltage are preset at relatively high values.
Spray transfer welding is a quiet process mode with a high deposition rate and a deep penetration.

- **Pulsed transfer.** This occurs when the power is supplied by an electronically controlled pulsed current source, instead of a constant-voltage power source as used in conventional GMA welding. The current has a relatively low base value with pulses of high current. Each pulse causes a detachment of a drop in a way as occurring in spray transfer welding. A regulator in the source is used to ensure that the wire melts at the rate it is supplied and that just one drop detaches with each pulse.
Pulsed transfer welding is useful for applications which require a relatively low deposition rate and a good penetration. Pulsed transfer welding makes it possible to weld in position\(^1\) with low (average) current. The process takes place in a much more quiet and controlled

\(^1\) The term *in position* indicates that the torch is not pointing down. This is for instance the case in welding in a vertical wall.
fashion than globular transfer welding.

1.1.5  Arc pressure

In GMA welding, the pool surface is slightly depressed under the arc. There are two mechanisms that cause this. The first is the pressure of the plasma blowing on the pool. Under the electrode the arc widens and hence the current paths diverge. The Lorentz force working on the charge carriers has a direction perpendicular to the lines of the electric field and points to the centre line of the arc. This makes the plasma pressure in the centre of the arc to be higher than the surrounding atmosphere and the plasma to be blown onto the pool (LIN and EAGAR 1985). The second mechanism is the impulse of the spray of droplets that are impelled into the pool also by the Lorentz force (ESSERS and WALTER 1981). Both mechanisms become significant in spray transfer welding.

1.1.6  Quality of a weld

Quality, as defined in ISO 8402, is 'the totality of features and characteristics of a product that bear on its ability to satisfy stated needs'. If a structure fails to satisfy a stated need by failing before its design life is reached, then it is the quality of the structure which is inadequate. So the quality of a weld is good when it does not fail the stated needs. Various defects can be a source for failure. Major weld defects are (see figure 1.4.) :

a. Lack of fusion at the junction to the workpiece parts.

b. Insufficient penetration at the root of the weld.

c. Excessive penetration at the root (too much weld metal bulging at the back face of the weld).

d. Porosity: the inclusion of gas bubbles in the weld.

e. Inclusions of other kind, e.g. slag.

f. Bad contacting angle between workpiece and weld.

g. Undercut, the part of the crater created

Figure 1.4

Major weld defects :
a. Lack of fusion.
b. Insufficient penetration.
c. Excessive penetration.
d. Porosity. e. Inclusions.
f. Bad contacting angle (weld convexity). g. Undercut.
h. Cracks.

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by arc heating of the seam, that is not filled with the weld.

h  Cracks in or near the weld.
i  Structural changes in the base material in the heat affected zone near the weld.

The liquid metal of the pool contains gas forming constituents, such as N, H, and O (generated by dissociation of $\text{H}_2\text{O}$, $\text{N}_2$ and $\text{CO}_2$), which are less soluble in the solidified metal and form bubbles which must disappear before solidification. Porosity occurs when this fails. Causes can be: inadequate gas protection and excessive travel speed.

The last two defects are caused by the chemical composition of the base and the filler material rather than by the welding procedure.

It depends on the application, which possible weld defects can play a role and must be avoided. In critical applications, the weld quality is controlled by well defined welding procedures and post welding inspections.

### 1.1.7 Influence of the wire feed rate

In this and the following sections the influences of some parameters on the GMA welding process are discussed. Figure 1.5 shows a relation diagram with the parameters discussed.

![Relation diagram for some welding parameters of the GMA process.](image)

The wire feed rate not only determines the amount of filler metal deposited, but also has influence on the penetration and the material transfer regime.

The penetration strongly depends on the current, while the current depends on the wire feed rate and the wire extension length. As a result, the pene-
tration strongly depends on the wire feed rate assuming the wire extension to be constant.
The influence of the current on the material transfer regime was discussed in section 1.1.4.

1.1.8 Influence of the travel speed

The travel speed and the wire feed rate should not be set independently. The desired weld geometry requires a predefined quantity of filler metal per unit of seam length (POMASKA 1983). One cause of undercut can for instance be that too little filler material is deposited in a seam. Undercut is a weld defect, because it weakens the joint and because it is a possible source for lack of fusion in a filling run of a multi-pass weld.

Enlarging the travel speed without altering the wire feed rate will under normal conditions result in a light reduction of the penetration (ALLUM and QUINTINO 1985a). When however the wire feed rate is increased in proportion, the penetration will increase, because the wire feed rate has more influence on the penetration than the travel speed.

At a very low value of the travel speed roll-over may occur. The pool flows between the arc and the workpiece. This causes the arc to be no longer at the front of the pool, but on it. The pool shields the workpiece from direct arc heating. When this occurs, the penetration is very low and lack of fusion may occur. In addition, the temperature of the pool is relatively high, which has a negative influence on the metallurgical properties of the weld. Roll-over occurs at a travel speed below 1.5 - 2 mm/s (POMASKA 1983)

1.1.9 Influence of the torch to workpiece distance

The torch to workpiece distance gives a good indication of the wire extension length, because the arc length is always very short compared with the wire extension length.

The torch to workpiece distance has an influence on the welding current and thus on penetration. The welder uses this effect to regulate the penetration at a constant wire feed rate. Increasing the torch to workpiece distance will cause a decrease of the welding current, which makes the penetration decrease too (ALLUM and QUINTINO 1985a, ESSERS and WALTER 1981, POMASKA 1983), because the penetration strongly depends on the current.
1.1.10 Influence of the voltage

The setting of the source voltage determines whether a short or a long arc forms. With a long arc (high voltage) much heat is put into the pool, because the droplets remain a long time in the arc, and much radiation is supplied to the pool. Through the high temperature of the pool the weld receives a more smooth and wide surface. The radiation to the workpiece increases too. As the centre of the heat source lies slightly higher, the crater in the workpiece will be wider, especially in groove shaped seams.

The drops absorb gas forming constituents during their flight through the arc. They may absorb so much, when the arc is long due to a high voltage, that porosity arises.

The voltage cannot be chosen freely but must be within a range that matches the wire feed rate as it has influence on the material transfer.

1.1.11 Influence of the gas composition

Argon is frequently used as the protective gas in GMA welding. It flows out of the torch and protects the liquid metal against N and H (generated by dissociation of N$_2$ and H$_2$O). The material transfer is rather quiet when pure argon is used. The weld pool is relatively cool and viscous. Often the welding gas is argon mixed with CO$_2$ and O$_2$ (e.g. 15% CO$_2$, or 18% CO$_2$ and 2% O$_2$). The gas additions are oxidizers and bind preferentially with the wire material additions Mn, Si and C, forming slag that is visible on the weld. The gas additions have an influence on the surface tension and make the pool warmer and less viscous.

Sometimes pure CO$_2$ is used as the welding gas, because this is cheaper than argon. The material transfer is more agitated in this gas and more spatters are produced. Short circuits occur even at high values of the current.

1.2 Mechanization and automation in arc welding

We use the term mechanization for the partial or complete replacement of manual work by a piece of equipment or machine. Several stages in mechanization can be recognized in arc welding.

SMAW is the least mechanized of the arc welding processes. The stick electrode movement, replacement of the electrodes and process control are all performed by the welder. Meanwhile, this is the most versatile form of welding. Corrective actions are made when the position of the seam deviates from the nominal position, when the shape of the seam changes, or when the state of the process could lead to weld defects.
The term partially mechanized welding is used for the processes in which the filler metal is supplied mechanically, as in manual GMA welding. The deposition rate (of filler material) is in general, higher than in SMAW.

In fully mechanized welding, the torch movement relative to the seam is realized by mechanical manipulation, in addition to the mechanical supply of the filler material. A welder acts as supervisor. The mechanical manipulation of the torch leads to a more smooth movement than in manual manipulation, which leaves the weld surface more regular and constant. With fully mechanized welding, higher deposition rates can be achieved than with manual welding, because more robust and heavy welding heads and a higher welding current can be applied. All these factors reduce the production costs of the welds.

We speak of automatic welding when the welding tasks are completed without human interference. In automatic welding the torch is moved over the seam of a workpiece and the welding parameters are set for each weld according to a predefined programme. Welding experience is utilized only for the generation of that programme. Arc welding with an industrial robot is an example of automatic welding.

In a further stage of automation, the generation of programmes is attained automatically. This is achieved by using geometric information about the product from a CAD system and technological information from a welding expert system. This development is in a laboratory stage, see for instance BURKE et al. (1987).

Mechanization and automation in arc welding not only bring down the welding costs, but also place greater demands on the preparation of the parts to be welded. The corrective actions, which make the manual welding so versatile, are not viable. Therefore conditions are created in which the corrective actions are not necessary.

Where in manual welding the torch is guided along the seam, the torch is moved along a preprogrammed path in automatic welding. This implies that the seam must coincide with the programmed path within the tolerances of the welding process. In practice this means that the workpiece parts must be manufactured and positioned within narrow tolerances. The shape of the seam must be within narrow tolerances too. Variations in gap width for instance require adaptation of the welding parameters.

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1 Different definitions are used for the term automation. In Germany, one speaks for instance of automatic welding, when the welding task and the transport of products to and from the welding place is realized without human interference (EICHHORN 1985). In computer science, production automation has a different meaning. It is used for the introduction of information technology in production processes.

2 The term programme is used for the sequence of instructions that prescribe the movements and actions to be carried out in welding a particular product.
Some seam types place more moderate demands on the positioning of the torch and the shape of the seam than others. Those seam types are preferred in automatic welding, which leads to design for manufacturing (DFM) rules for products that must be welded automatically. Other DFM rules aim at minimizing the thermal deformation during welding. Mechanization also brings about the necessity to use robust jigs in which the seams have a good accessibility and the parts can be positioned very accurately. As these jigs are rather expensive, mechanized and automated welding is applied mainly in the manufacturing of large series of products.

1.3 Sensors for automatic welding

Sensors can be used in automatic welding to enhance the versatility of the system. Different types of motivation can be distinguished for the use of a sensor in an automatic welding system:

- Enabling automatic welding of products for which it is expensive or impossible to manufacture the parts with narrow tolerances.
- Realizing a better weld quality.
- Realizing a higher welding speed, because of a more accurate positioning of the torch in the seam.
- Allowing less accurate preprogramming.

A wide variety of aspects determine the quality of a joint. It depends strongly on the type of joint and material to be welded which aspects are critical. A general solution does not exist for automatic process control (JONES and STARKE 1985). As a result, only partial solutions have been proposed and presented in literature.

In this section we give a survey of the state of the art and potentials of these sensors. We limit the survey to sensors for arc welding processes and use the following definition:

A sensor for arc welding processes is an instrument that can be a part of a fully mechanized welding system, and can transform information on the variable welding conditions of the process (position or shape of the seam), or the state of the process into a form that can be used by the system (electrical signal).

Sensors can be used for:

- Torch movement control:
  - finding the position of the beginning of a weld,
  - recognizing the end,
  - following the seam (seam tracking).
- Welding process control (process parameter optimization):
  - adjustments in response to geometrical variations in the workpiece,
  - adjustments in response to other process disturbances.

In applications not all these control functions are required simultaneously.
A brief overview of the main principles of operation of sensors for arc welding can be found in MADIGAN (1987) and DILTHEY (1989). More detailed overviews are given in DETRICHE (1988) and MATSUNAWA et al. (1991). However, little attention is given in these overviews to the measurements for process control.

Various measurements are performed in practice to realize control functions. The variables that are determined have a small deviation from their nominal value. For instance, the positional variations that occur in practice never exceed a few millimetres.

The localization of the beginning of a seam can be realized with a switch as the sensing element: The sensor is moved towards the workpiece until it signals that the workpiece is reached. In doing so, a position is sensed in the direction of the motion, which gives a reference for the position of a seam or workpiece. The three dimensional position of a workpiece can be determined with a few measurement sequences in different directions. The location of the seam can be derived from this, as the geometry of the workpiece is usually known.

The localization of the beginning of a seam within a search volume, can be determined more directly with a profile sensor. This is a sensor system that determines the surface profile in a plane perpendicular to the axis of the seam (the principle of operation is explained later). The system can recognize the seam in the profile. The sensor must be moved perpendicular to the plane of measurement. The localization is accomplished by moving the sensor in the direction of the seam.

The localization of the end of a seam can be determined with a switch in the same way as the beginning. With a profile sensor the recognition of the seam end can take place during the welding operation. For seam tracking it is desired to determine the seam position in two directions: the height, and the lateral position (direction perpendicular to the height and the direction of movement). Sometimes seam tracking is realized by maintaining a constant distance to two workpiece surfaces that are parallel to the seam. This requires two distance measurements, see figure 1.6.

For weld parameter control in response to variations in the workpiece, a sensor must determine the shape of the seam. Useful measurements are for instance the gap

![Figure 1.6](image-url)

Seam tracking with two distance sensors.

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1 It is usually not necessary to adjust the torch orientation in seam tracking. The torch inclination can if necessary be derived from the sequence of height measurements.
width, the volume of the seam that must be filled, and the seam width. These measurements can be used in feed forward control to regulate the weld quality. Such a controller requires the knowledge how to set the welding parameters for each possible condition. A theoretical model of the welding process for such an application does not exist. Therefore, pragmatic approaches are used in practical realizations. The knowledge is acquired from a series of test welds for a given application, and stored in a data base. The data is not valid for other applications, because various known and unknown influences are incorporated in them. (For instance even the type of welding source used has an influence on the weld result.)

For weld parameter control in response to other process disturbances, a sensor can be used that determines the state of the welding process. Examples of this are measurements of the penetration, the dilution\(^1\), the pool geometry, and the arc length. When a feature is measured that has a close and known relationship with weld defects, the quality can be regulated with feedback control. The controller avoids the occurrence of the weld defects. This requires no exact process model.

Different types of sensors are commercially available for automatic welding systems. Some others are in development. Among these very different principles of operation can be found, all with specific benefits and limitations.

For applications, it is not important how the sensor works, but what the possibilities and limitations are. It is therefore useful to classify the sensors based on what can be controlled with them. However, many sensor systems determine, or have the potential to determine more than one variable. Those sensor systems can be used for different control functions, which makes the just mentioned base of classification unpracticable.

We review here the state of the art and potential of the main principles of measurement that are used or proposed for arc welding applications. We do this on the basis of the arrangement given in figure 1.7.

We classify the sensors for arc welding processes based on the place where the measurement takes place: before (or aside of) the welding spot, at the welding spot, or behind the welding spot. Further, concerning sensors that measure before the welding spot, we distinguish between those that make contact with the workpiece, and those that operate contactless. Sensors that measure at or behind the welding spot are all contactless. Among the sensors that do not measure at the welding spot, there may be sensors that work off-line with respect to the welding process (sometimes called two-pass sensors). This is not important for the principle of operation, and is therefore not taken into account here.

\(^{1}\) The term dilution indicates the ratio of filler metal to base metal in the weld.
1.3.1 Sensors for arc welding that operate before or aside of the welding spot

The arrangement of the principles of operation of sensors for arc welding.

Figure 1.7
The arrangement of the principles of operation of sensors for arc welding.

The location "before the welding spot" refers to the position or shape of the unwelded seam. Other sensors are mounted aside of the torch, determining the position of a workpiece surface that is parallel to the seam that must be welded. This can be used for instance in guiding the torch in fillet welds (figure 1.6).

Tactile sensing is the oldest principle used in automatic arc welding. A flexibly mounted stylus or wheel is pulled through a seam groove, see figure 1.8. The position of the seam is determined by sensing the stylus (or wheel) position, see for instance FABER and LINDENAU (1985). This principle can be used for seam tracking of groove shaped seams. For some sensors based on this principle tack welds are not allowed.

Another form of tactile sensing is in use for determining the position of the beginning and/or the end of the seam that must be welded: The torch is moved towards the workpiece until it makes electrical contact with the workpiece (switch function), see figure 1.9 (see for instance CULLEN 1988). Most welding robot systems are nowadays available with this sensing
function as an option. Two versions of this principle are in use: measuring with the wire (GMA), and with the shield gas nozzle as the sensing electrode.

An (extraordinary) example of a sensor system having contact with the workpiece is reported by CARLSON and JOHNSON (1988). An ultrasonic sensor is moved over the workpiece surface that sends ultrasound pulses into the workpiece and measures the reflections. From the reflection characteristics it is determined whether the penetration at the bottom side of the pool is positive. No other information can be derived with this principle. One could alternatively say that the system determines a feature of the pool that belongs to the welding spot. Therefore, this principle could also be placed in the group measuring at the welding spot.

Sensors having no contact with the workpiece are the counterpart of the tactile sensors. We first review those measuring before (or aside of) the welding spot.

Inductive sensors can be used in measuring a distance to a surface. More useful are the inductive sensors that determine the height, as well as the lateral position of the sensor relative to the seam. They are used in practical applications for seam tracking, see for instance GOLDBERG (1985). Tack welds may cause measurement disturbances.

The inductive principle is also used in an attempt to determine the seam shape and position simultaneously, with a linear array of eddy current sensors, see PLACKO et al. (1985).

Capacitive sensors can perform nearly the same measurements as the inductive ones, but are hardly used in welding applications.

Ultrasonic sensors can be used to determine a distance by time of flight measurement. This principle has the disadvantage that the measurement is sensitive amongst others to the temperature and flow of the medium (air).
experimental application is reported by MAQUEIRA et al. (1987). They used a single ultrasonic transducer in tracking a seam in a two-dimensional space. The transducer emits sound pulses in a direction at 45° from the horizontal. Seam types can be located that produce an echo in the direction of the transducer. This is the case for lap joints and butt joints with a V-shaped preparation.

The radiation emitted by the workpiece just ahead of the pool, can be used to determine whether the torch is still centred correctly over the seam. Malpositioning of the torch will cause a non-symmetrical heating of the workpiece parts, see figure 1.10. CHIN et al. (1983) used an infrared camera to determine the temperature distribution in GTAW. The asymmetry ahead of the pool can be recognized.

This can also be detected with an infrared line scan across the seam or with a two point measurement (HUBER and ILLEGEMS 1984). The method is expected to be useful for I-shaped seams without gap in sheet metal. No applications are reported.

Infrared thermography can also be a source of information on the penetration, see for instance KHAN et al. (1986), or CHEN, W. and CHIN (1990).

Optical sensing is used in various ways. All systems that operate ahead of the torch, determine the position and/or the shape of the seam. The main differences lie in the source of light that is used.

The arc radiation can be used as the light source, see for instance BROWNE and FALKOWSKI (1983), BONVALET et al. (1985), or VAISBAND et al. (1971). The lateral position of the seam centre under the sensor is determined. The same measurement is realized by lighting the workpiece with a strong source (STARKE 1987). The latter reference mentions measurement of the gap width as well.

The height can be measured with the principle of optical triangulation. This principle is illustrated in figure 1.11: A light beam is emitted to the workpiece at a fixed distance from an image sensor. The sensor (a line camera) determines where the beam hits the surface of the workpiece. The light beam is in the plane in which the camera views. The principle is used in a commercially available sensor system for seam finding, see STHEN and FORSANDER (1983).

When the principle of optical triangulation is extended in the third dimension, the principle of sensing a surface profile is obtained: a light stripe is projected on the workpiece (over the seam) and the height profile of the
stripe is sensed with a camera that views the stripe under an angle. This principle is visualized in figure 1.12. Sensors that use this principle are called (optical) profile sensors. They are used for seam tracking and seam finding in industrial applications. Furthermore, they offer the possibility to adjust the welding process parameters based on measurement of parameters like gap width (KUHNE 1987, OOMEN and VERBEEK 1983), seam volume, and seam width (KOUWENBERG and KLAASSEN 1985, VERDON et al. 1981). In some applications this additional information is used effectively. Research and development are aiming at the knowledge that is necessary to make full use of this information in a handsome way.

Figure 1.11
The principle of optical triangulation.

Figure 1.12
The principle of operation of an optical profile sensor.

1.3.2 Sensors for arc welding that operate at the welding spot

Sensors that operate at the welding spot are all contactless, because the welding spot is an adverse environment. The most widely used principle in this group is the arc sensor. It is based on the principle that the electrical resistance of the arc and electrode stick out depends on the torch to workpiece distance. It is used in GMA welding. The torch is weaving (oscillation transverse to the direction of welding) over the seam groove, see figure 1.13. From the variations in the electrical parameters current and voltage caused by the weaving it is determined which seam wall is the nearest to the centre of weaving motion. With this information, the torch can be centred over the seam during welding. The best results are found in spray transfer welding. In diptransfer welding the measurement is obstructed by the occurrence of short circuits. Most industrial robots for welding applications can be delivered with this sensing function as an option. Systems are in development that give good
results in diaperture transfer welding as well. Other developments based on this principle, aim at sensing the volume that must be filled, or the width of the seam.

The same principle is used in a system, where an electro-magnet is mounted on the torch. This enables measurement without introducing the weaving motion. The arc is deflected for short periods (less than 1 ms) towards the sidewalls of the seam alternately using a strong electromagnetic field. The distance from the centre of weaving to the seam walls is measured during the deflections. This principle is not widely used.

Another system based on the same principle is using two separate wires a small distance a side instead of one (EICHHORN and DREWS 1975). The difference in distance to the workpiece is determined. The system can be used in SAW or GMA welding, for centring the torch over the seam.

A rather simple optical principle is used by DEAM and DREW (1990). A sensor measures the intensity of the radiation coming from the arc in GTAW. With this measurement the arc length is determined.

Another optical measurement is reported by CHEN, X.Q. and LUCAS (1990). In narrow gap GTAW, the arc is deflected towards the sidewalls by an electromagnet. At the moments of deflection, an image of the arc region is captured using a CCD area camera. From the images, the arc length, i.e. distance from the electrode to the sidewall, is determined. The measurement is used in a laboratory experiment for centring the torch.

The frequency of the pool resonance can be used as a source of information on whether full penetration is present in GTAW. The frequency depends on the mode of vibration, see figure 1.14. In case of incomplete penetration, the vibration is established by surface waves on the pool. When the weld penetrates the full thickness of the workpiece, the pool has a free surface at the back. In this case, the vibration is established by up and down movement of the whole pool volume, which occurs at a significantly lower frequency than with incomplete penetration. Two versions of this sensing principle exist. One system determines the variations in arc radiation due to the arc length variations that come with the pool resonance, using an optical transducer (SALTER and DEAM 1988). The other determines the variations of the arc length from the electrical characteristics (XIAO and den OUDEN 1990). Both systems invoke the oscillation of the pool by injecting a short pulse of high current. The first system is ending its laboratory phase.

Another measurement principle is used in centring the torch in GMA welding in welding materials with different chemical compositions. The pool radiation is analyzed spectroscopically and from this, the torch position is determined.

Figure 1.13
The arc sensor centers the torch when weaving over the seam.
Spectroscopical analysis is also claimed to be useful in determining if the pool material is well mixed with the base material of the workpiece (STAHLER GmbH 1985). It is not known if the principle is in use in practical applications.

Another principle used to determine the penetration in a laboratory experiment is reported in DORNFEld et al. (1982). The intensity of the radiation that is emitted at the back side of a plate is sensed with an infrared detector. The penetration depth is kept constant using the measurement. In the experiments the GMA welding process is used. Arc radiation is not transmitted to the detector, because in the experiments a bead on plate weld is produced.

SUZUKI and HARDT (1987) report a system for controlling the heat at the back of the weld. They measured the width of the back bead (by optical means) in a full penetration weld.

A vision technique with the camera pointed at the welding process is used in POTTHOFF et al. (1977) to measure the key hole dimension. This measurement is used in the control of the penetration in the root run of a multi-pass weld.

Measurement of the pool geometry and position, subject of this thesis, is another principle used in sensors for arc welding. It is well established that the weld pool geometry is influenced by changes in joint geometry, welding process parameters and internal defects. Therefore, different types of features can be derived from the geometry simultaneously and used in separate control functions. These functions are seam tracking and welding process control.

All weld pool sensor systems capture the geometry with a camera system (optical). Some differences are found in the way the image of the pool is formed. These differences are pointed out in Chapter 2, where the image capturing of our system is explained.

Seam tracking is the only geometric function that can be realized with pool measurements, because information is only available when the pool is present. An example of a measurement for seam tracking is reported by INOUE (1980a). An image is captured in which the silhouette of the not yet molten seam is visible against the arc crater. The experiments apply to GMA welding of a T-butt joint with a relatively high current (400A). The high current causes a deep crater in the workpiece. Another example is the measurement of the lateral position of the leading extension of the pool in

Figure 1.14
The pool resonance mode in the case of:

a. incomplete penetration,
b. full penetration.
GMA diptransfer welding as described in NIEPOLD (1983). The potential of the sensor system is better exploited when the geometrical information is not only used for seam tracking but also for process control. Most systems described in literature for the last function confine themselves to measurement of the pool width. See for instance: VROMAN and BRANDT (1976), RICHARDSON et al. (1982) and BONVALET et al. (1983) for GTA welding and INOUE (1980b), BÈGIN and BOILLOT (1983) and YAMAMOTO et al. et al. (1988) for GMA welding. Width measurements are used to regulate the heat input by adjusting the travel speed, wire feed rate (GMA), or current (GTA).

Some publications mention measurements for process control other than the pool width.

OHSHIMA and YAMAMOTO (1987) reported the measurement of the length of the pool in the image (distance from the torch cap (gas cup) to the pool front). The measurement was not used in a control function.

BRUEMMER and NIEPOLD (1987) measured the length of the leading extension in the image (distance from the electrode tip to the pool front) in GMA welding. The measurement was used in conjunction with the pool width in estimating the penetration in a bead on plate weld.

INOUE (1980a) and NIEPOLD and BRÜMMER (1984) measured the width of the leading pool extension and identified this as the gap width of the seam in a T-butt joint. Niepold and Brümmer used the measurement in adjusting the weaving motion amplitude.

NADEAU et al. (1988) measured the depth of the leading pool extension by viewing the pool at an angle of 15° relative to the seam axis. The measured depth is found to be representative for the penetration depth. This measurement is used in a system for automatic GMA pipe welding, see NADEAU et al. (1990).

Most weld pool sensing systems are in the laboratory phase except the coaxial vision principle used for GTAW, which is commercially available, see for instance SWEET (1984).

For the sake of completeness we mention the publication of ROKHLIN and GUU (1990), where a system for on-line radiographic sensing is described. This principle has the potential of directly sensing the weld defects. However, this measurement uses heavy equipment, and automatic on-line interpretation of the images is a complex task.

1.3.3 Sensors for arc welding that operate behind the welding spot

Sensors that work behind the welding spot inspect the welding result. Little information about such measurements is found in literature. KARASTOJANOV and NACHEV (1985) mention a sensor that measures the
workpiece profile by optical triangulation on a circle around the torch. The sensor rotates around the torch. With that sensor the weld could be inspected. AGAPAKIS et al. (1985) describe a system for 3-D inspection of the weld with projection of laser stripes over the weld.

1.4 Objective of this thesis

In automatic welding, information is desirable for both geometrical and process control. The objective of this thesis is to describe the development of a sensor system for such control by means of measurement of the weld pool geometry. This sensor system operates at the welding spot.

We have seen in section 1.3 that various systems can be used to realize geometrical control. Systems for process control are mostly in an early phase of development. Three sensing principles have the potential to provide information for both process and geometrical control. These are:

- Optical profile sensing.
- Weld pool geometry measurement.
- Temperature distribution measurement with an infrared camera.

Optical profile measurements provide information for feed forward control of the welding process. This requires a model that incorporates the specific conditions of the welding application. In this model all uncontrolled process variables must be considered. The model has to be determined for each new application.

Both weld pool geometry measurements and temperature distribution measurements are expected to provide information that is closely related with the quality aspects of the formed weld. It is therefore expected that a control system based on these measurements can adapt the process not only to variations in the seam geometry, but also to variations in other parameters such as the workpiece thickness and workpiece temperature. Further analysis shows that this results in some kind of mixture between feedback and feed forward control, see section 4.1.

The development of solid state cameras made it possible to observe the pool geometry with a small and light camera, which therefore can easily be mounted on a robot end effector without overloading that robot. Cameras for imaging the temperature distribution are much bigger and also more expensive.

This thesis aims at:

- developing a system that can measure the pool geometry,
- contributing to the knowledge of how to interpret the pool geometry and how to use the measurements in a control system.
The work consists of three main subjects.
Chapter 2 deals with the problem of how to acquire images of the pool from which the geometry can be determined.
Chapter 3 describes in detail how geometric features are derived from the images in our weld pool measurement system.
Chapter 4 finally, covers the identification of image features that can be used for control purposes.
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Chapter 2
Image Acquisition

2.1 Introduction

This chapter describes the acquisition of images from which the geometry of the weld pool is determined. The interpretation and processing of the images are reported in the next chapters.

The welding scene is projected on an imaging device (camera) that forms an image of the weld pool and its surroundings. According to welders both the front side and the rear side of the weld pool contain information of the process. On the rear side, however, it is not easy to recognize where the liquid to solid transition occurs, because the temperature gradient there is much smaller than at the front side, as explained in the next section.

In this project the camera is mounted in front of the torch (in the welding direction), see figure 2.1. To have a good view of the pool, the torch is turned pointing forward, which means a restriction of the torch inclination to negative angles.

The camera mounted in front of the torch can be an obstacle when accessing partially concealed seams in complex workpieces. In those applications the use of fibre optics might be useful.

In the image the pool must be distinguished from the workpiece and the arc. Generally speaking, arc glare is a problem for getting a clear image of the pool. The approaches to overcome this problem can be categorized as (1) those using the reflective properties of the pool, (2) those taking images during arc interruptions and (3) those using selective optical filtering.

(1) The reflective properties of the pool can be used effectively as the pool is always glossy, without any diffuse reflection, whereas the workpiece always gives some diffuse reflection, although its surface can vary from rusty to machined.

Ter AVEST et al. (1978) described a system for telemanipulated welding in an
adverse environment. The pool is made visible by halogen spot lights. The image, captured with a colour TV camera, shows the torch, arc and surrounding parts of the workpiece. Determining the shape of the pool from such an image with a vision system will be time consuming, because the only difference between pool and workpiece lies in their texture. Similar systems are reported in different publications (STREET 1986; LYONS and MIDDLETON 1984; KIEFER 1982; POTHIER and BRISEBOIS 1982; WELDING DESIGN AND FABRICATION 1986). None of these are intended for automatic recognition of weld pool features.

RICHARDSON et al. (1982) reported another approach for observing the pool in GTA welding by using a viewing system in which the optical axis coincides with the weld torch and the electrode axis. The arc is hidden by the electrode and the image is formed by reflections of arc light coming from the pool and workpiece. The edge of the pool is visible as a discontinuity in the brightness because some diffuse reflection is coming from the workpiece. This system cannot be used in GMA welding, because the electrode and power supply elements within the torch are bigger for this process, and the pool surface is more irregular, reflecting more arc radiation to the camera.

ALLEMEIER and BANNISTER (1987) described a system that observes the pool, by illuminating it with a pulsed nitrogen laser, forming an array of diffuse light sources that are reflected to a camera. The pool surface is determined by the deformation of the pattern. The system offers the opportunity to study the curvature (arc depression) of the pool surface.

(2) Arc interruptions can be useful periods for observing the pool. Here the captured images are formed by the radiation emitted from the pool.

NIEPOLD (1983) described a system that uses the natural periods of arc interruption in diptransfer GMA welding to capture images of the pool. It uses a camera with a mechanical shutter, that opens at the electronically detected short circuits.

Another system was reported by RIDER (1983), in which short interruptions (1 - 2 ms) of current are introduced in GTA welding for image capture. The arc may be removed because interruptions of a few milliseconds are supposed not to have a big influence on most arc welding applications.

OHSHIMA and YAMAMOTO (1987) reported a system in which short periods of very low current are introduced in pulsed GMA welding.

(3) Selective filtering is another approach in observing the pool. It can be used to view the radiation emitted by the pool in the presence of an arc as the arc produces most of its radiated energy in another part of the spectrum than the pool.

BEGIN and BOILLOT (1983) reported a system that uses an array of infrared sensors made of PbS sensitive to radiation from 2 to 2.5 \( \mu \text{m} \).

CHIN et al. (1983) reported a system that uses a camera sensitive to radiation from 8 to 12 \( \mu \text{m} \) to view the thermal distribution in the workpiece and pool during GTA welding of carbon steel. Similar experiments were reported by BANGS (1987). The pool edge is an isotherm in the thermographic image.
Infrared cameras usually register incident radiation differences rather than absolute temperatures. Unfortunately, this makes it complicated to distinguish the pool isotherm by thresholding the image with an absolute value\(^1\). An alternative method of determining the pool contour from the images is edge detection. We will see in the next section that a shorter wavelength of observation produces a sharper pool edge.

LILLQUIST (1983) claimed that the spectral range of observation must be somewhere between 3 and 14 \(\mu\)m to get a clear image of the pool for electric arc welding processes.

As will be explained in the next section the spectral range of observation chosen is a compromise between image contrast and camera dimensions. In our system we chose for selective filtering, transmitting a wavelength band somewhere between 1 and 1.5 \(\mu\)m with the following expectations and arguments (discussed in the next sections):

- For GMA welding of carbon steel, the arc radiation will be sufficiently suppressed to get an image from which the pool edges can be determined automatically.
- A camera that is sensitive to radiation in this range of wavelength can be selected that is sufficiently small and light to be mounted on a torch holder in an automatic welding system.
- The interpretation and automatic processing of reflective images is more complicated than the processing of images formed by pool radiation.
- Filtering is less complicated than synchronizing with arc interruptions and makes the camera system independent of the welding power source.

### 2.2 Optical filtering

The camera must provide an image of the weld scene without additional illumination. As we are interested in the shape and dimensions of the pool, it may partially be hidden by the arc; however, its edges must be recognizable. The dynamic range of a vision system is restricted. Commonly used grey scale systems use 256 values. If, without further provisions, the camera aperture would be adjusted to the emittance of the arc, radiation emitted by the pool would be below the threshold of the camera. Therefore filtering is necessary to bring down the ratio of arc to pool intensity in the images to a level at which it is possible to distinguish the pool from the dark workpiece.

To achieve this filtering we use an interference filter, an optical narrow band pass filter. This section deals with the selection of the central wavelength of the filter. In addition a camera type is selected sensitive to the transmitted radiation.

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\(^1\) The image processing techniques thresholding and edge detection are explained in chapter 3.
To select the filter, there are three aspects of importance regarding its centre wavelength:

- the ratio of arc to pool emission,
- the contrast between pool and workpiece,
- the response of the camera.

Let us examine the first aspect of importance. Figure 2.2 gives qualitatively the emittance of arc and pool as a function of the wavelength. The emittance is obtained by multiplying the spectral emittance of a black body given by Planck's law (equation [2.1]) with the emissivity. In the figure the emissivities of the arc and pool which are not very well known are taken to be independent of the wavelength. The emissivity of the arc (which is not opaque) is supposed to be an order of magnitude smaller than that of the pool. Further the arc

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1. The *spectral emittance* is the radiant flux per unit area at a specified wavelength emitted by a body.

2. The *emissivity* is the ratio of emitted radiant flux per unit area of a sample to that of a black body radiator at the same temperature and under the same conditions.
temperature is estimated at 4000 K. This is a conservative value, since measured values of welding arc temperatures normally fall between 5000 and 30,000 K (LANCASTER 1986). Here it must be noted that the higher values are found using the GTA welding process. The pool surface temperature is estimated at 1800 K, about the melting temperature of steel. The pool surface directly under the arc is slightly warmer due to arc heating. KRAUS (1989) measured a maximum surface temperature varying from 2050 to 2570 K (for different values of current and travel speed) for the GTA welding process. For the GMA welding process lower temperatures can be expected as flow and convection within the pool are stimulated by the metal transfer. Near the borders of the pool, the temperature will be approximately at the melting point. This region must be recognised.

\[
M_{e\lambda} = \frac{c_1 \lambda^{-5}}{e^{\frac{c_2}{\lambda T}} - 1}
\]

where

\[
\lambda \quad \text{wavelength in meters}
\]
\[
T \quad \text{temperature in Kelvin}
\]
\[
c_1 = 3.741 \times 10^{-16} \text{ W m}^-2 \text{ K}^-1
\]
\[
c_2 = 1.4388 \times 10^{-2} \text{ m K}^{-1}
\]

From figure 2.2 it can be concluded that the wavelength of observation must be as long as possible to obtain the best ratio of arc to pool emittance, see also RIDER (1983).

Spectroscopic studies of the arc emission show that spectral lines may be important. Different studies of this effect show different results, but have one aspect in common: major spectral lines occur at wavelengths below 0.8 \( \mu \)m (SHAW 1975; SLINEY et al. 1982; NOZAKI and HIGO 1980).

The second aspect of importance is the contrast between pool and workpiece in the image. It must be as large as possible to allow fast and accurate signal processing. The temperature of the melt is about 1800 K. The workpiece is much colder. It can be calculated with a model for heat transport that the temperature gradient in the workpiece at the front side and immediately adjacent to the pool measures at normal welding conditions a few hundred K/mm (200 - 300), see for instance RYKALIN (1957), or MÜLLER (1968). The temperature distribution on the pool surface is more smooth due to convection within the pool. Ignoring reflections of arc light and supposing the same emissivity for both workpiece and pool, we can examine the pool-to-workpiece contrast.

The contrast between pool and workpiece is a function of the temperature difference. For the emittance gradient at a selected wavelength we can write:

\[
\frac{dM_{e\lambda}}{dx} = \frac{\partial M_{e\lambda}}{\partial T} \frac{dT}{dx}
\]

With Planck's law (equation [2.1]) we find:

\[
\frac{\partial M_{e\lambda}}{\partial T} \approx M_{e\lambda} \frac{c_2}{\lambda T^2}
\]

when \( \lambda T < 3100 \mu \text{m K} \)
Hence,\[
\frac{dM_{\lambda}}{M_{\lambda}} = \frac{c^2}{\lambda T} \frac{dT}{T}
\]  \[2.4\]

This shows that to have a maximum workpiece-to-pool contrast the wavelength of observation must be as short as possible. The range of 8 to 15 \(\mu m\) which corresponds to a very low arc to pool emittance ratio is certainly too long as observations have shown (van den BIGGELAAR 1984).

The third aspect of importance is the response of the camera in the pass-band of the filter. There is a broad range of cameras commercially available for observation in the visible and infrared spectrum. Some of them are listed in table 2.1. Generally speaking, cost, dimensions and weight all increase with the wavelength for which the camera is sensitive, except the solid state camera\(^1\).

We prefer the use of a solid state camera because it is small, has sufficient response in the near infrared and is insensitive to magnetic fields.

The first two aspects are contradictory. A compromise must be found between them in selecting the central wavelength of the filter suitable for all conditions encountered during GMA welding. As several factors such as arc temperature and arc emissivity are not well known, precise application of the theory is not possible. However the theory gives insight in the trends. The selection was done empirically.

An experimental arrangement was made with a welding torch placed in a fixture above a rotating workpiece. The workpiece consisted of tubes (Ø200 x 150 x 10 mm) that were placed on a welding manipulator. This arrangement allowed a camera to be mounted on a standard tripod.

Welding experiments were carried out to determine whether it was possible to observe the weld pool with a solid state camera, and if positive to select the central wavelength of filtering. A camera with a CID (Charge Injection Device) sensing chip was used in the first experiments. The CID principle is known to have good anti-blooming behaviour. Therefore the camera may locally be saturated by arc radiation, without degrading the rest of the image. Different types of welds were made such as root runs of a V-butt joint, filler runs, and bead on plate welds with the GMA-process, using a 1 mm thick solid wire. The current was 180 - 250 A and the voltage 20 - 28 V. Optical narrow band pass filters with centre wavelengths ranging from 0.74 \(\mu m\) to 1.489 \(\mu m\) were used.

\[1\] A solid state camera is a camera which has a chip as the sensing device.
As the wavelength of observation increased, the dimensions of the bright region in the images in which the arc resides decreased. For shorter wavelengths, the bright region was so large that parts of the pool edges were covered. For the filters with centre wavelengths of 1.188 µm, 1.392 µm and 1.489 µm the edges of the pool were always visible in the images. The best images were captured at the longest wavelength. A further increase of the wavelength is not possible with silicon based solid state cameras. For longer wavelengths compact cameras that can be mounted on a robot wrist are currently not available.

The experiments were repeated using a camera with a CCD (Charge Coupled Device) sensing chip (CCD-camera). Its anti-blooming performance proved to be sufficient, as the resulting images showed no big differences with those of the CID-camera. A CCD-camera is cheaper and more commonly used than a CID-camera.

A CCD-camera is used in all further experiments.

2.3 The nature of the images

Figure 2.3 shows some examples of images captured with a CCD-camera and a band pass filter with the centre wavelength of 1.392 µm. In this image the pool is visible as a grey object contrasting with the dark workpiece. The pool is partially hidden by a white region, in which the arc resides. The arc itself is not visible as a sharp object as would be the case when observing in the visible part of the spectrum.

The camera produces a video signal according to the CCIR standard and the integration time between readouts of an image is 20 ms. Due to this, fast phenomena such as movements of the arc and droplet transfer effects are not visible. However, this is not the main reason why the image of the arc is not distinct. The wavelength of observation is relatively long, which means that the arc has not a sharp contrast with the hot air surrounding it. In addition, the arc is a partly transparent object having finite dimensions. The radiation reaching the camera forming the centre of the arc image, is emitted by a larger volume of arc plasma than that coming from the outer region.

Some arc light may be reflected by the workpiece, depending on the orientation and condition of the surface. This results in regions of increased intensity in the workpiece. These reflections mainly appear in the vicinity of locations where the arc region extends to near the pool edges. At those places the pool surface is heated above the melting point. Therefore the transition from pool to workpiece appears at a higher intensity level.

During GMA welding, slag is sometimes produced. Due to surface tension effects, it can be found near the contours of the pool in narrow regions. As the emissivity of these regions exceeds that of the pool, they appear as light regions in the image, enhancing the contrast between pool and workpiece. The slag accumulates at the rear side of the arc where it leaves droplets from time to time.
Figure 2.3
Examples of weld pool images captured with the CCD-camera and a band pass filter with centre wavelength of 1.392 μm.


that can be found on the borders of the solidified weld. The accumulated slag appears in the image as a dancing region of higher intensity.

The presence of oxide on the workpiece causes the formation of more slag, but a skin of oxide on the workpiece will melt and form small glowing droplets just before the pool front due to the arc heating, because its melting point is lower than that of steel. Due to the higher emissivity these droplets have nearly the same intensity as the pool. This is deceptive for the recognition of the pool edge. In Chapter 4 it will be discussed how to distinguish the pool from the more irregular slag.

Spatters that leave the welding region have the same temperature as the pool, giving them the same intensity in the image. When they leave the region of gas protection, oxidation takes place and the intensity increases. These spatters are sometimes visible as light stripes because they move during image caption. The majority of the spatters however do not disturb the image because they are out of focus.

The torch has a fixed position in the image because the camera is mounted on it. The shield gas nozzle and contact tube are dark objects that sometimes contrast with their background. The wire sticking out of the torch is an object of importance, because its variable extension length influences the electrical characteristic of the process. The wire is also a dark object, and its tip always contrasts strongly with the arc region and the pool.

The image acquired with the camera differs from what a welder sees through a welding glass. For instance, a welder can see the workpiece and knows where
to move the torch. He also sees a more sharply confined arc region. The reasons for these differences are:

- the human eye has a much better dynamical response than a camera,
- the human eye cannot see anything in the near infrared,
- a welder can see depth,
- a welder often looks at the process from the side,
- a welder reacts to differences in colour.

This results in the fact that some features that are used by welders cannot be registered with a camera directly, for instance:

- the melting of the workpiece,
- the wetting of the workpiece by the pool,
- the gap width,
- the length of the arc.

We must remember, however, that a welder needs other information than an automatic welding system. For instance, realizing the desired travel speed needs his constant attention, for which he uses visual information. A welding machine, on the contrary, can realize a desired travel speed without weld pool information.

To test whether the captured images contain enough information to control the process we asked a welder to position the torch during welding based on what he could see on a monitor only. Therefore we expanded the arrangement mentioned in the previous section with a horizontal and a vertical translation unit for positioning the torch. A workpiece was fixed with its cylinder axis at an angle with the manipulator’s rotation axis, so corrective actions were necessary to achieve a correct weld.

The result was that the positioning of the torch was very easy and accurate, because the image on the monitor was much bigger than the real welding scene.

Until now a description has been given of an individual image captured with the camera. Registrations of subsequent images, during welding under stationary conditions, have been made to analyze the movements of the pool. Visual observation shows clearly that the shape and dimensions of the pool are subject to various local and temporal variations. Although

Figure 2.4
Registration of the leading edge of the pool in diptransfer welding of a fillet weld. Consecutive contours occupy the same region in the camera image. In this figure they have been shifted according to the travel distance to make them individually discernible.
the torch is moved with a constant velocity over the workpiece, the pool moves somewhat like a raindrop over a window pane. The progression of the pool front edge is erratic. The movement is strongly influenced by pool surface tension, while the wetting angle between pool and workpiece shows local variations. The weld pool is pushed by the supply of material from the electrode and is pulled by newly molten workpiece surface. Hindrances for a constant movement of the pool are:

- irregularities of the workpiece,
- cold or hot spatters on the workpiece,
- fluctuations of the arc and metal transfer,
- oscillations of the pool surface.

In figure 2.4 the agitation of the pool front is visualised. The pool front edges of consecutive pool images (constant interval of 20 ms) are given. From the registrations the following can be concluded:

- Most agitation can be found on the front side of the pool.
- The unrest of the pool front is related with the stability of the arc, but it is not a convenient source of information about the state of the process.
- Local and temporal variations are not of interest in this study, but hinder the measurements in the image processing stage.

As the integration time of the camera is fixed at 20 ms, it is not possible to register faster movements of the pool. During the time interval between two images, changes occur. We can recognize shape transitions that last longer than one integration time. The fast changes cannot have a large influence on the quality of the weld because the passing time of the pool over any point of the workpiece is about one second. However, they give rise to image blur.

As the shape of the pool can change in the interval between the two fields of one complete video frame, the fields are treated as separate images. Averaging of images, realized for instance by using a camera with a large integration time, can be used to get rid of the variations. However, it gives a blurred image, from which the averaged pool contour cannot be derived, as pool, arc and possible reflections from the workpiece form a vague image and can no longer be distinguished.

### 2.4 Practical tests

The registration of weld pool images was first tested for diptransfer welding of 2 mm sheet metal. In this situation current and voltage are relatively low, resulting in a short arc of limited intensity and frequent interruptions by direct contact between electrode and pool. In the images the arc region is rather small. It is possible to detect the edges of the pool, although the pool dimensions are rather small too.

When the voltage is increased, the process characteristics shift to globular transfer, whereby the arc length and intensity increase. In the images a larger arc region can be recognised. Because the arc length accretion occurs at the top
end, detection of the pool edges remains possible. When the welding current is increased too (and a thicker workpiece is used) the process characteristics change to spray transfer. In the resulting images, the arc occupies a very large and intense region, but the pool dimensions are large as well. As a result of this, the outlines of the pool can be recognised completely. It was also observed that the pool moves more smoothly over the workpiece than with diptransfer welding.

A preliminary study has also been made of pulsed transfer arc welding. Although this has not been tested systematically, it appeared that the images have a very large and relatively intense arc region. At the same time the pool dimensions are relatively small. Recognition of the weld pool is not practicable, because sometimes parts of the contour are hidden by the arc.

2.5 Applicability of the adopted principle

Although the sensor system has been developed and tested for GMA welding of low alloy steel products, the applicability with respect to other materials and other processes will be briefly discussed in this section.

Besides GMA welding of low alloy steel products, important applications with respect to welding automation in industry are:

- **GMA welding of aluminium products.** For this material we cannot expect to recognise the weld pool shape by its own radiation with our camera, because the melting temperature of aluminium is about 1200 K and emission from the pool is shifted to longer wavelengths. In addition, in comparison with low alloy steel, the emissivity is at least 4 times lower and the reflection coefficient is much higher. The thermal conductivity of aluminium is 3-5 times that of steel. Therefore, in spite of the lower melting temperature, the arc power (and with it the luminosity) must be more intense to keep the weld pool molten.

- **GTA welding.** The use of a vision system was tested for the production of stainless steel coffee containers (BODERIE 1986). The seams in the 1 mm thick plates were square butt joints without gap and were welded without filler material. The welding scene was observed with the same camera and filters as with the GMA experiments. In the resulting images the glowing electrode tip is visible. However, it was not simple to recognize the weld pool because:
  - the emissivity of stainless steel is lower than that of carbon steel, while the reflection coefficient is much higher,
  - the arc light of the GTA process is more intense than with GMA welding,
  - the weld pool for the 1 mm plates was very small and therefore completely hidden by the arc.

In this particular application process control was not necessary but geometric information was needed. When viewing the scene from the front,
the seam could be detected as a dark line in the reflection of arc light on the glossy workpiece. The position of the line relative to the electrode was determined for tracking control.

As the images give a clear view of the electrode, this principle can be used to determine the geometry of the electrode tip during welding.

- **Submerged arc welding.** In this process the welding scene is covered so visual information cannot be captured concerning the welding process.
- **Plasma welding.** The arc intensity with this process is very high compared with GMA welding, whereas the pool size is relatively small. We suppose that pool measurements are impossible with the chosen equipment, but we did no tests to check this.
- **Laser welding.** The power density is some orders of magnitude greater than with the GMA welding process. As the laser provides its energy at one wavelength, it should not be difficult to filter it out and get a clear view of the weld scene. The behaviour of the pool is dominated by other effects than for GMA welding. This process has not been investigated.

In GMA welding some new developments can be observed at this moment. Of these we mention:

- In imitation of the superior metallurgical effects of coated electrodes, flux-cored wire is being introduced for GMA welding. The additives in the wire cause changes in the arc behaviour, as more material has to be transferred to the workpiece, but this is no dramatic change. Furthermore, the pool is partially covered by slag. Recognition of the weld pool will probably be difficult. On the other hand the behaviour of the slag can be observed, for as has already been stated in the case with solid wires, slag produces more radiation than the pool. This is not expected to be different for filler wires.
- **Pulsed arc welding.** It has already been mentioned that continuous pool measurements may become difficult with pulsed arc welding. However, good results were reported by OHSHIMA and YAMAMOTO (1987), using a camera with an electronic shutter that was controlled to capture images during the low current periods, see section 2.1.
- **New gas mixtures,** aiming at producing less spatter, smoke, or certain smoke contaminants like ozone, are commercially available. A different arc behaviour and intensity could be expected from these. We expect that the intensity will be hardly affected. When less spatters are produced, one may assume that the material transfer takes place more quietly, resulting in a more smoothly moving pool. This would be advantageous for the method treated in this thesis.
References


Chapter 3
Image Analysis

The main task of image analysis is deriving the relevant features from images captured with the camera. The nature of the images has already been described in Chapter 2. The current chapter presents how the geometry of the pool is derived from the images. As it is not yet known what the relevant features are, the image analysis results in a general description of the pool geometry. We suppose the description to be sufficiently information-preserving. The image analysis is used in Chapter 4 for the identification of some features that might be relevant for controlling the welding process.

In this chapter, the algorithm selected is discussed first, then the hardware configuration is presented and an alternative for the configuration is explored. Finally, an overview of the system is presented.

The terms used in image analysis and pattern recognition are partly overlapping and sometimes confusing. Therefore the terms used in this thesis are briefly explained in the appendix to this chapter.

3.1 Introduction

For our investigations a general purpose digital image processing system is available on which the analysis of the weld pool images is executed. Unlike in most vision applications for arc welding described in publications, this is not a binary but a grey-level processing system. In order to enable processing, the video images are digitized in that system. Individual images can be stored in a block of memory called frame buffer. The image is already provided in lines by the camera (according to the CCIR standard), so the sampling of the (sequentially received) lines performs spatial quantization into picture elements (pixels). It can be achieved that a pixel represents a square part of the image, by choosing the sampling frequency such that the horizontal distance between two samples on an image-line is equal to the vertical distance between two lines of the image. Generally speaking, this is not the case. In the system that we use, like in many other commercially available systems, the sampling frequency is 10 MHz, which is twice the bandwidth of a video signal that meets the CCIR standard. This also implies that the pixels are not 'square', but rectangular.

The brightness which is proportional to the irradiance received by the image sensor is quantized into grey-levels. Since it is difficult to measure brightness with great accuracy, the hardware system discriminates grey-levels 0 to 255 requiring just 8 bits. The camera aperture and electrical gain are chosen so as to project the brightest pixel in weld pool images onto grey-level 255. Hence, the brightness is normalized. The brightness in a single image can be represented
by a two-dimensional function $I(x,y)$, where the $x$-axis is taken in the horizontal direction (direction of the video lines) and the $y$-axis is the vertical in the image. The origin is the upper left corner of the image\(^1\) (see figure 3.1).

A significant constraint in the image analysis is that the measurements must be available fast enough to be used in a feedback loop.

### 3.2 The algorithm for image analysis

This section describes how the algorithm for image analysis was selected. Figure 3.2 presents the interrelations of methods and techniques mentioned in this section.

Image analysis of weld pool images is performed in three steps:

- **segmentation**, the process that divides the image into regions (pool, wire); image enhancement by filtering is incorporated in this step,
- **shape analysis**, the generation of a data structure that describes the regions in the image,
- **description**, the extraction of the relevant features from the data structure.

The description step yields the values of the relevant image features. These values are used by the subsequent process where the successive results are evaluated. This process is usually called scene analysis, and is not comprised in image analysis.

Template matching is a technique complementary to the steps mentioned above. This technique determines the position of an object with a known shape in an image by determining the maximum of the calculated cross-correlation function between the image and a template. In the analysis of weld pool images this technique cannot be used because we are interested in the shape as well as the position of the weld pool, so a family of templates would be necessary, which is not practicable.

The shape of the wire is not variable, so template matching could be used in determining the position of the wire tip in the images. However, for reasons of coherence, the same technique is used to determine the position of the wire tip.

\[\text{Figure 3.1} \quad \text{An image is a two-dimensional brightness function } I(x,y).\]

---

\(^1\) In vision systems the origin usually is defined in the upper left corner of the image, because a video signal starts there describing an image line by line.
Figure 3.2

Overview of methods and techniques mentioned in this chapter.

In the image as to determine the shape and position of the pool.
3.2.1 Segmentation

In weld pool images the information we are interested in is contained in the form and dimensions of the pool and the position of the wire tip. The segmentation operation identifies segments that are defined as areas of constant characteristics, such as brightness, reflectivity, texture etc. The method of segmentation must be chosen such that the segments coincide with the objects in the scene that must be analyzed: the pool and its surroundings (whereby the wire is treated as belonging to the surroundings).

We consider four methods of segmentation:
- global thresholding,
- local thresholding,
- edge-detection using a rotationally invariant differential operator,
- edge-detection using directional differential operators.

Segmentation methods that use the texture or the colour of image segments are not relevant for the analysis of the weld pool images, and are therefore disregarded.

Global thresholding is the simplest and fastest of the segmentation methods and assumes that the regions in the image have non-overlapping brightness distributions. This means that the edges between the regions can be found at a uniform brightness value. This is not the case for weld pool images, where puddle emission and arc light reflections in the workpiece are subject to local and temporal variations, see Chapter 2. So this method cannot be used, because it leads to assigning reflecting areas of the workpiece to the pool segment and rejecting low intensity parts of the pool.

Local thresholding is a method in which pixels are classified as object or as background by comparing their brightness with a threshold value function, rather than with a fixed (global) threshold value. The threshold value function is calculated at each position in the image, based on the brightness values in a restricted neighbourhood.

This method is known to work well in some applications with images having a non uniform illumination. The threshold function is based on an estimation of the illumination obtained by low-pass like filtering the image. For our application, the threshold value function must be recalculated for each image, because the disturbing reflections show temporal variations. The problem that makes this method unusable for weld pool images is the fact that it is not possible to estimate the reflections with simple operators, because the reflections are often adjacent to the pool.

Edge detection is a different method in segmentation. In this method the image is scanned searching for the points that lie on the edge between two segments. When the segments differ in brightness, the transition in brightness that occurs at the edge can be detected using a differential operator. This must be combined with a smoothing operation to reduce the influence of noise, see section 3.2.1.2.

The natural definition of brightness edges is the location of the points where the second directional derivative along the brightness gradient \( \frac{\partial^2 I}{\partial n^2} \) has zero-
crossings. The operator \( \frac{\partial^2}{\partial n^2} \) is rotationally invariant. It is nonlinear\(^1\); hence, the order of the operations of filtering and differentiation are non-commutative. A disadvantage of the operator is that it is undefined where the amplitude of the gradient of the brightness is zero.

Another rotationally invariant differential operator is the Laplacian (\( \nabla^2 \)), which is widely used for its computational convenience. It is also a second order differential operator. MARR and HILDRETH (1980) argued that the Laplacian must be combined with a two dimensional Gaussian smoothing filter. This method gives correct localisation of straight edges; however, it may give incorrect results around corners, caused by the smoothing operation. BERZINS (1984) analyzed this effect in detail. The Laplacian of a Gaussian filter was approximated by Marr and Hildreth with a difference of two Gaussians (DOG) operator, which is rotationally symmetric too. The DOG operator is obtained by subtracting two concentric Gaussian functions. The best approximation of the Laplacian of a Gaussian is obtained with the variance of one function being 1.6 times that of the other. This operator is easy to implement in hardware.

Edge detection with directional differential operators, as used by CANNY (1983), is an alternative for the rotationally invariant differential operators. The brightness is differentiated in fixed directions and edges are found on the local extrema (in the direction of differentiation) of the first derivative (coinciding with zero-crossings of the second derivative). The use of just two directional derivatives is sufficient to detect all edges detected by rotationally invariant differential operators (TORRE and POGGIO 1986). The incorrect localisations around corners will not occur when the required smoothing of the image is limited to the direction of the differentiation. A correct implementation of the individual operators should therefore be only one pixel wide.

An important aspect in edge detection is that relevant edges must be discriminated from spurious ones, which are caused by minor brightness differences within one segment. In figure 3.3 it can be seen for the horizontal direction in a weld pool image that zero-crossings of the second derivative not only occur between the segments of interest. The relevant edges correspond with the pronounced extrema of the first derivative.

In the method using directional operators, the discrimination can be realized by thresholding the magnitude of the first derivative. In the example given in BERTERO et al. (1988) it can be seen that this is an effective tool for discriminating between relevant edges and spurious ones.

When using a rotationally invariant differential operator, the discrimination can be accomplished by evaluating the amplitude of the first derivative in the direction of the gradient, which is of course the gradient itself. The rotationally invariant differential methods have the disadvantage that an approximation of the first derivative must be calculated separately when the discrimination is desired.

---

\(^1\) An operator A is linear if for any scalars \( \alpha \) and \( \beta \) it can be proven that:
\[
A(\alpha f_1 + \beta f_2) = \alpha A f_1 + \beta A f_2
\]
where \( f_1 \) and \( f_2 \) are (brightness)functions.

55
The adopted segmentation method
An algorithm for the segmentation of weld pool images has been designed by VERVUURT (1989).
In the analysis we have chosen for detecting edges with two directional operators having a dimension of $l \times n$ pixels. This involves less computations than using an $n \times n$ pixel wide rotationally invariant differential operator. In addition, the detection of the maxima is less complex than the detection of the zero-crossings. Experiments confirmed that a good discrimination between pool edges and spurious edges is found by thresholding the first derivative, with little additional computational effort.

With a horizontal detector it is possible to detect the near-vertical contour parts in the image, i.e. the left and right edges of the pool and the left and right boundary of the extending wire. With a vertical detector, the near-horizontal contour parts are detected, i.e. the front of the pool and the tip of the wire. Sometimes, a dent appears in the contour of the pool caused by a droplet on the workpiece. This causes the chain of points detected with one of the directional operators to be interrupted. The other operator may produce the information to complete the chain.

In order to gain processing time, it is desirable to apply an operator only to the region where we can expect edges to be detected. Our hardware supports limiting an image processing operation to a rectangular area of interest, with a proportionate gain of processing time.

As we apply two different directional operators, we can choose areas of interest, depending on the dominant direction of the edge to be detected. Although the areas may be partially overlapping, the sum of the image areas that must be processed will not be twice as large as the area to be processed when using a rotationally symmetric operator.

As already stated in Chapter 2, the two rasters of a complete video frame must be analyzed separately, because they are captured with a time lag of 20 ms.

![Figure 3.3](image)

**Figure 3.3**

a. Brightness function on one line in a weld pool image $I(x)$.
b. First derivative (of the filtered data) $dI(x)/dx$.
c. Second derivative $d^2I(x)/dx^2$.
d. Absolute value of the first derivative.
e. Rising parts of the thresholded peaks.
f. Detected edge points.
between them. Especially at locations where the pool has moved within 20 ms, the interleaved lines of a complete frame form an image that appears as a mixing of two images. For the detection of edges in the vertical direction in a complete frame this would mean that two pool edges could be detected in one column, whereby the detection of an edge in one raster is influenced by effects within the other raster, which is of course not acceptable.

Summarizing, we can say that with this method edges are detected and located at points where:

- the derivative in horizontal or vertical direction exceeds a certain threshold,
- the derivative has a local extremum.

From a set of test images from the feasibility tests of Chapter 2 a threshold value was derived with which 90% of the pixels on the pool edge in predefined regions of the image were detected as an edge point. With this threshold value spurious edge points were detected to. Most of these were found inside the pool and are caused by the edge of the arc. In order to select the pool edges (and that of the wire) only, we can add a third condition for the relevant edges:

- the original image intensity at the edges is always below a certain value.

This condition has been built into our detection algorithm by introducing an intensity mapping whereby the pixel intensity above a certain level is compressed. This also reduces the first derivatives of transitions that occur at high brightness, which makes them less frequently fulfil the first condition. The non-linear transformation should not influence the detection of the pool edges, so the brightness level of the nonlinearity must be so high that it occurs always far enough inside the pool contours to be outside the reach of the finite impulse response filter detecting the pool edge.

Figure 3.4 gives the result of the edge detection sketched above performed in the horizontal direction on the weld pool image given in figure 3.1.

### 3.2.1.1 Edge detection and optimal filtering

In the edge detection process derivatives are used. It is well known that differentiation enhances the high frequency components of a signal. In images the high spatial frequency components are mainly due to noise contributions. This can cause detection of spurious edges and locating edges at a wrong position. We want to minimize this effect.
Of course much attention must be paid to the image formation process in order to obtain images with a favourable signal to noise ratio. As in many other processes noise is unavoidable in machine vision. It is introduced by the sensor (we use a CCD camera as mentioned) and the sampling process in the vision computer.

BERTERO et al. (1988) showed that differentiation of image data is too much sensitive to noise and that the image must be smoothed to regularize the problem. They found with the theory of Tikhonov that the optimal filtering is obtained by convolving\(^1\) the image data with a filter which is (a) a cubic spline, and (b) similar to a Gaussian.

The width of the filter is a parameter that must be chosen in accordance with the characteristics of the transition that must be detected. When a linear differential operator is used, it can effectively be combined with the filtering step by convolving the image with the differentiated filtering function. In the next section we pursue this matter further.

Good results can be achieved with nonlinear filters. Generally speaking, they involve more computations than linear filters. Therefore we will not go into this further.

### 3.2.1.2 The transitions in weld pool images

In this section we look at the transitions in practical images. We verify the assumption that the pool edge coincides with the maximum in the image intensity gradient and in addition determine pragmatically a value for the standard deviation of the Gaussian filter. The edge we want to locate in the physical world is the transition from solid to liquid metal. This is a step change. As mentioned in Chapter 2 it can be calculated with a model for heat transport in the workpiece that the temperature gradient in the workpiece at the front side and immediately adjacent to the pool measures at normal welding conditions a few hundred K/mm (200-300), while the pool surface has a much smoother temperature distribution due to convection within the pool. This leads to a nearly stepwise transition of the emission in the bandwidth of observation at the pool.

---

\(^1\) The result is the convolution of the brightness function in an image \(I(x,y)\) and a filter function \(f(x,y)\):

\[
I(x,y) * f(x,y) = \int \int I(x-u,y-v) \times f(x,y) \ dudv \\
\]

In digital vision systems images are often convolved with an operator \(f\) having finite dimensions. In this case the infinite integral becomes a finite sum. The output \(O\) can be expressed as:

\[
O(x,y) = \sum_{i=1}^{n} \sum_{j=1}^{m} I(x-i,y-j) \times f(i,j)
\]
A series of images at different welding conditions were captured to study the intensity profile at the pool to workpiece transition. Thereby lines as well as columns were analyzed. The transition is always blurred over several pixels. In order to investigate the blurring process the difference of intensity between subsequent pixels was observed. The edge is visible as a peak in the difference signal and it was found that this peak is symmetrical over the stretch of the transition. Fast fourier transformations of the peaks showed that the blurring process can well be estimated by a Gaussian filter. In figure 3.5 the similarity between a measured transition and a Gaussian filtered step function is visualized.

Figure 3.5
Comparison of the measured data and a Step-Gauss convolution.

The observed blurring of the edge is caused by:
• movements of the pool within the integration time of the camera,
• unsharpness of the optical system,
• cross-talk in the image sensor of the camera due to operating it in the near-infrared,
• limited bandwidth of the video signal and sampling process.

As a result of these phenomena the edge will be blurred symmetrically, which justifies the identification of the pool edge with the points of maximum brightness gradient.

The next thing we want to know is the standard deviation $\sigma$ of the blurring in the edges. The above mentioned phenomena have different effects in horizontal and vertical direction. Moreover we must not forget that the pixels of our image are not square. Therefore we determined different estimates of $\sigma$ for the horizontal and vertical directions. The best fitting Gauss-step convolution was determined with the minimal quadratic approach.

In the analyzed images the $\sigma$ for the horizontal direction ranged from 1.4 to 4 pixels, with an average of 2 pixels. In the vertical direction the average value for $\sigma$ was also 2 pixels. The $\sigma$ of the transition from welding wire to pool or arc in horizontal direction measures 1.7 pixels and shows less variation than that of the pool edge.

The arc produces an edge too but it has already been mentioned in Chapter 2 that this transition is much more vague so its typical $\sigma$ must be much bigger than that of the pool or wire. This $\sigma$ has not been determined.
The standard deviation of the filtering function $\sigma_{\text{filter}}$, that must be chosen, must be large enough to suppress the influence of noise effectively. However, it must not be larger than the $\sigma$ of the transition, because this would lead to a detector with a support that is so wide that brightness differences in the pool or workpiece can influence the location of the detected edge point.

Global thresholding of the first derivative is used to make a distinction between weld pool edges and edges due to reflections, weld spatter and noise. The threshold value determines the number of pool edges and the number of false edges detected. Analysis showed that the steepness of weld pool edges varies in time and place. Therefore, a high threshold value will not only suppress spurious edges, but also some pool edges.

We believe that local thresholding of the first derivative with a fixed threshold value function for all images could give better results, because the disturbing reflections and spatter mainly occur in regions of the image where pool edges are relatively sharp. However, this is not implemented on our vision system, because it would mean extra processing time.

The performance of a filter can be judged by registering the detected edges within a rectangular part of an image in which on each horizontal line there is just one transition from workpiece to pool. Supposing that the transition on a line is detected when one or more edge points are found on that line, the threshold value is adjusted so that a predefined number of edge points are detected on the pool contour. The noise ratio, here defined as the ratio of spurious edge points to the total number of detected edge points, characterizes the performance of the filter in that part of the image. The sketched way of evaluating a filter has been executed for a number of test images and for filters with various $\sigma$ values, with the condition to detect 75% or 90% of the pool contour.

We found the best results with $\sigma_{\text{filter}} = 1.5$ pixels. The threshold value that gives a specified number of edges in a user defined test region of the image, depends on the welding conditions.

### 3.2.1.3 Suppression of spurious edges

**Arc suppression**

In weld pool images edges are often detected within the pool, in the transition region from the pool to the arc. There the first derivative of the brightness has maxima of about the same magnitude as at the edge of the pool. However, the brightness is higher than at the pool border. As the first derivative of the brightness offers no possibilities for discriminating between pool edges and spurious ones, we want to use the image brightness.

We therefore introduced a non-linear mapping of the brightness of each pixel prior to filtering and edge detection, see figure 3.6. The image brightness transfer function coefficient is reduced with a factor 4 in so far as the brightness
exceeds a fixed reference value. The effect is that no edges are detected in the area with a brightness beyond the reference value. The reference value must be high enough to ensure that the non-linear effect of the mapping is only affecting the area inside the pool, and is not interfering with the detection of the pool edge. The mapping may cause the appearance of spurious edges at points with the brightness of the reference value.

The results of this non-linear mapping are that in weld pool images the number of spurious edges inside the pool is reduced. However, in images of high brightness (welded with a high voltage) a line of edge points is detected inside the pool at the brightness of the reference value, and in images of low brightness (welded with a low voltage) the mapping has little effect.

Contrast edge detection
Another problem in analyzing weld pool images is that no edge points are detected in dark parts of the pool contour. It appeared that this obstructs recognition of the pool contour of welds made with a very low value of the voltage, see section 4.2.2. In other images this occurs at the front and at the sides above the end of the wire.

The problem is caused by the fact that the first derivative of the brightness is low in dark parts of the pool contour. Decreasing the threshold value for edges is no solution to the problem because this increases the number of spurious edge points.

A solution to the problem is found in contrast based edge detection, described by JOHNSON (1990). In contrast edge detection, edges at higher brightness must have a higher first derivative of the brightness. This is achieved by thresholding contrast gradient instead of the brightness gradient. The contrast gradient is obtained by weighting the first derivative of the brightness with the original brightness.

Three variants of contrast edge detection in weld pool images are evaluated by van der GIESSEN (1991). These are based on what we defined as:

- 'linear contrast gradient' $\Gamma_{\text{lin}}$, with a parameter d to regulate the suppression, see equation [3.1],
- 'average value contrast gradient' $\Gamma_{\text{avg}}$, suppressing spurious edge points outside the pool as well, see equation [3.2],
- 'quadratic contrast gradient' $\Gamma_{\text{sq}}$, with reduced suppressing effect, see equation [3.3].

In these equations x is the direction of derivation of the horizontal edge detector.

Figure 3.6
Non-linear mapping for suppressing edges inside the pool.
The parameter \(d\) regulates the suppression of edge points at high brightness \(I(x,y)\):
- \(d \gg I(x,y)\) yields the conventional gradient,
- \(0 < d < I(x,y)\) yields an intermediate effect,
- \(d = 0\) yields the contrast gradient and
- \(d < 0\) yields an improved contrast gradient.

The linear contrast gradient is selected for implementation. It showed a better performance in most pool images of the evaluation than the conventional edge detection with the above mentioned non-linear mapping. Van der Giessen showed that when parameter \(d\) is given the value 5 (full scale brightness has a value of 255) good results are obtained.

It can be derived that:

\[
\Gamma_{lin} = \frac{\partial I(x,y)}{I(x,y)+d} \quad [3.4]
\]

Equation [3.4] shows that the linear contrast gradient is the gradient of the logarithm of the brightness function. The contrast method is implemented as a logarithmic mapping of the image brightness followed by the already described conventional edge detection. The mapping is shown graphically in figure 3.7. Quantization errors and noise in dark parts of the image are amplified by the contrast method. The small positive value of the parameter \(d\) reduces the sensitivity of the method to noise in dark image areas.

Simulations of the contrast edge detector on the model of the pool edge (the step Gauss convolution) showed that the contrast method detects the edge at a location shifted 1.3 to 3.7 pixels towards the outside of the pool compared with the conventional edge detection.
3.2.2 Shape analysis

Shape analysis is the generation of a data structure that describes the regions in the image (pool and wire), based on the results of the segmentation process. The data structure must contain information on all relevant aspects of the pool shape. Local disturbances of the pool shape caused by spatter, noise, and the irregular movement of the pool over the workpiece (see Chapter 2), are not supposed to be of interest and must therefore be smoothed in the data structure. The structure must also bridge gaps in the contour that may have been left by the process of edge detection.

We chose for describing the contour with three polynomials, one for the pool front and one for each side. The rear side of the pool cannot be described because edge detection is not successful there due to poor contrast between the pool and the (hot) weld. The polynomials are approximations of the pool contour parts. The approximations each are valid in a certain area only. The front of the pool is described with a 4th-degree polynomial and the sides are described with 2nd-degree polynomials, see figure 3.8. Adding more terms to the polynomials gave no visual improvement in most weld pool images. The additional terms were nearly zero. In addition to the polynomials, the position of the end of the wire in the image is determined.

The polynomial parameters completed with the wire end position form a data structure which is considered to be sufficiently differentiating between weld pool shapes of significance.

The selection of a method of shape analysis is determined by the criteria:
- the accuracy with which the features can be extracted from the result,
- the influence of disturbances on the determined features,
- the processing time.
The hardware supports a first step in shape analysis: the coordinates of the pixels that fulfil predefined conditions can be collected in a data structure, where they are placed in the order in which they occur scanning pixels from left to right, beginning with the uppermost line. Thus a list is produced for each direction of detection, containing the positions of pixels that are on the edge of the pool, or wire, or are a spurious edge point. (We have explained in section 3.2.1.1 that the edge detection is performed in two directions separately.)

The approximating polynomials are determined by the least squares method. This method would fail if the spurious edge points were not eliminated from the input. Thus a list of points belonging to the pool contour must be extracted from the list of points delivered by the edge detector. This is performed by contour tracing. Contour tracing also delivers the points on the edge of the extending wire.

Projection is a statistical method that can be an alternative for contour tracing and polynomial approximation with the least squares method. It demands less computations than contour tracing. In this method, the edge points detected with the horizontal operator for instance, can be analyzed by histogramming the x-coordinates, which can be seen as projecting the edge points on a horizontal line. In the histogram, maxima are formed by the edge on the right and left side of the pool, so the distance between them is the width of the pool. The position of the maxima can be distinguished although spurious edge points can cause noise in the histogram. This method is very efficient for determining the width and horizontal position as well as the front position of the pool. For the other measurements (like curvature or dent depth) it is not applicable and therefore not used in this research.

Other statistical methods usual in image analysis, like figure of merit computation of all combinations of edge points or template matching of edge points, require much more computation than the tracing and approximation method to attain the same accuracy and are therefore not taken into account.

### 3.2.2.1 Contour tracing

Contour tracing is the building of structures of pixels on contours in the image. Here we want to recognize the edge of the pool and that of the wire. In the list of pixels identified by the horizontal edge detector, four contour segments are of interest: the left and right side of the pool and the left and right side of the wire. From the other list, the front of the pool and the tip of the wire must be recognized.

With the set of edge points we build data structures, which we call traces and which are sequences of points on a contour in the image of the pool. BLACK et al. (1981), described a contour tracing algorithm with the following cycle:
1. predict the direction and distance to the next point on the contour,
2. scan for new candidates,
3. select the new point from the candidates,
4. add the new point to the trace and
5. go to 1.

Following this method, all traces in the image are found sequentially. Because the edge points are available in the order a raster of an image is scanned, it is more suitable for our images to use a variant of contour tracing, known as a raster scan algorithm (see for instance CAPSON, 1984), in which traces are built in parallel, by adding each edge point to an existing or a new trace. The performance of the algorithm depends on the criteria used in the acceptance of a new point of a trace. In our images processed with a directional derivative, there are gaps in the contour of the pool having different causes, like for instance the presence of an obstructing cold drop on the workpiece, a flying hot drop in the image, or a location where the edge is too much blurred to be detected. The edge points at both ends of such a gap should be recognized as belonging to the same contour. By using a simple criterion for acceptance, where the distance between the last trace element and the candidate point must be below a critical value, the gaps will not be bridged correctly.

**Tracing by branch selection**

KURVERS (1989) designed an algorithm for contour tracing in weld pool images. For bridging gaps the algorithm uses a criterion based on the direction of the contour at both sides of the gap as well as the width of the gap. This is made possible by splitting the tracing into stages:

- In the first stage the edge points are assembled into traces having no gaps, using a tracing algorithm with a simple acceptance criterion for the edge points.
- In the next stage, traces are linked whereby a figure of merit is calculated that indicates the likelihood of the link.
- In the last stage the branches of linked traces are evaluated and one linked trace is selected for each contour part to be recognized.

We call this method 'tracing by branch selection'.

The criterion in the first stage is accepting a new point when it is in the vicinity of the last trace point, and the y-coordinate is not less than that of the last trace point. This implies that only more or less vertically oriented traces can be built. This is useful for the set of edge points detected with the horizontal detector. The same algorithm can be used for the edge of the pool front, when the image is rotated by 90°.

The figure of merit that indicates the likelihood of a link, must depend on:

- the distance between the traces,
- the direction of the traces at both sides of the connecting line,
- the direction of the connecting line.
In the evaluation of branches, a new figure of merit must be calculated that depends on:
- the total length,
- the curvature,
- the figures of merit of the gaps,
- the position.

In order to calculate these figures of merit, estimates of the direction and curvature of traces are desired. Polynomial approximation of all traces is a robust method to realize this; however, it involves a tremendous computational effort. Therefore we chose for a more simple approach of trial and error in designing figures of merit with which we can select the correct traces.

The tracing by branch selection gave very good results for some test images, however appeared not to be robust against spurious edge points in other images. Therefore an alternative method was purchased.

**Recurrent tracing**

Until now analysis of individual weld pool images was discussed. In practical situations a series of successive images has been analyzed. The weld pool shape in two successive images will not differ very much. This knowledge is used by van DOMMELEN (1990) in another approach to contour tracing. We call this recurrent tracing.

The analysis is based on expected polynomials that are determined by the polynomial approximations of the pool (see section 3.2.2.2) of the previously analyzed image. Now a trace is built with edge points that are near the expected polynomial of the side that is to be traced. Next, each trace is approximated with a polynomial. Finally expected polynomials for the next image are determined by averaging the actual expected polynomials and the actual approximations. The averaging uses a weight factor of 0.3 for the approximation and one of 0.7 for the actual expectation. This prevents stray off of the polynomial parameters of the temporary changing pool.

The recurrent tracing gave better results than tracing by branch selection.

For the analysis of the first image, expected polynomials must be determined by another method.

For off-line analysis, manual adjustment of initial polynomials is used.

For automatic analysis, the Hough transformation is implemented, see section 3.2.2.3.

### 3.2.2.2 Approximation with the least squares method

Van DOMMELEN (1990) also designed an algorithm for approximation of traces with polynomials by the least squares method. The traces of the sides of the pool are approximated with 2nd-degree polynomials. For this simple polynomials are used: \( x(y) = a_0 + a_1 y + a_2 y^2 \).

The trace of the pool front is approximated with a 4th-degree polynomial:
y(x) = b_0 + b_1x + b_2x^2 + b_3x^3 + b_4x^4.
The polynomials have an infinite domain. However, the approximations refer only to a finite domain in the neighbourhood of the wire end. No limits of the domains have been determined. However, we can roughly say that the approximations refer to areas limited by the lines through the end of the wire that form angles of 45° with the image axes.

### 3.2.2.3 Shape analysis with the Hough transformation

In the automatic analysis of the first image of a series the recurrent tracing method is not applicable because initial values of the expected polynomials are not available. Van der Giessen described an algorithm for shape analysis of weld pool images based on the Hough transformation. The algorithm is used to analyze the first image of a series to determine the initial values for recurrent tracing.

The Hough transformation is a method of determining the values of parameters of a function that fits an image. The method is often applied with functions with two parameters. It is frequently used for the detection of straight lines in an image. However, the method is also suited for functions with more parameters. It can even accommodate shapes that are not described by a function. We use it to determine the polynomial parameters.

The method transforms the shape recognition problem into a (local) maximum detection problem in the parameter space, see for instance DUDA and HART (1972).

The Hough transformation maps only the edge points of an image. The transformation can therefore use the list of edge points delivered by the hardware. These points are mapped into the space of polynomial parameters, where they each represent a hyper-plane of parameter combinations of all polynomials through the edge point in the image. The edge point votes for each of these combinations by incrementing all points on the hyper-plane. As a result, after processing the list of points, the maximum in the parameter space is the most probable parameter combination.

The parameter space used is restricted to parameter combinations describing shapes in the image that are potential approximations. The number of computations is proportional with \( n^{k-1} \), where \( n \) = the number of parameter values evaluated and \( k \) = the number of the polynomial parameters. This makes the method slow for determining the 4th-degree approximation of the pool front. Therefore, a 2nd degree polynomial is determined as the initial front approximation used as expected polynomial, which gives satisfactory results. For the sides of the pool, 2nd degree polynomials are determined as the initial approximations.

Some fast implementations are found in literature, all based on the idea of several low resolution iterations narrowing the parameter domain each time, sometimes referred to as zooming. See for instance, LI et al. (1986),
ILLINGWORTH and KITTLER (1987), or BERGER and KHOSLA (1990). We used the adaptive Hough transformation described by Illingworth and Kittler. The transformation gave satisfactory results, especially in combination with contrast edge detection. The accuracy of the approximation process in the regions where the polynomials approximate the pool is $\pm 2$ pixels. This is inferior to the least squares method, where sub-pixel accuracy can be obtained. The processing time for the approximation process with the Hough transformation is about 200 ms for the side polynomials of the pool and an average weld pool image. The tracing and least squares approximation take about 160 ms for this. In both cases the processing is executed on a SUN 3-140 computer. The Hough transformation method therefore is very acceptable to capture automatically the parameters of the initial polynomials.

3.2.3 Description

The polynomials and the position of the wire end in the image form a data structure that contains 13 parameters. The task of the description process is to derive the relevant features from the data structure. These features must be defined such that they describe the significant shape properties that can be used to discriminate various relevant welding conditions. The definition of image features and their interpretation is subject of Chapter 4. In section 3.2.2 it was stated that the approximation with polynomials is considered to be sufficiently differentiating between weld pool shapes of significance. Yet this statement is to be verified in Chapter 4.

3.3 Hardware

Three hardware systems have been used in the analysis of weld pool images:
- a digital system for the development and prototyping of weld pool image analysis and the analysis of experimental results,
- a digital system used for further support of image analysis development and for image capture in the experiments of Chapter 4,
- a system built to explore the potential of analogue electronics.

3.3.1 The development system

For the development and prototyping of weld pool image analysis a digital image processing system was selected in 1987 from the systems obtainable at that time. The following considerations were taken into account:
• Speed: in order to enable feedback in the case of path control, we set a processing time for the measurements of 100 ms as an aspired value. Systems that consist of a standard computer supplied with a framegrabber and framestore only are not considered here, because only a small part of an image can be analyzed when all processing is executed by the host computer. So, a system that incorporates dedicated (vision) processing hardware is required.

• It must be a general purpose system, because it is meant for the development of measurements. So, it must be possible to create and alter the algorithm of processing images, and implement new measurements on the images, during the development of the weld pool sensing system.

• We want to use rather than develop a vision system, so a commercially available system is preferred over systems based on array-processors or transputers, as the latter demand more effort for software development.

• Price of the system.

• A system that can be expanded with modules for which the need appears during the developments is favoured.

• Grey-level processing is necessary, because a binary system cannot recognize the weld pool correctly.

• The number of pixels per image must be at least 256 in both horizontal and vertical direction.

• Processing of individual rasters of the video signal must be supported, see Chapter 2 and section 3.2.1.1.

A system was selected that consists of processing modules configured in a pipeline. The modules operate in parallel on an image. Image data is sent to the first module in the pipeline and each module receives data, performs operations on it and passes the result to the next module, see figure 3.9. The system is

![Diagram of processing system](image)

ADI = analog/digital interface; FB = frame buffer; HF = histogram/Feature extractor; ALU = pipeline processor; RTC = real-time convolver.

Figure 3.9
The processing boards and buses for image data of the development system. The width of the buses (8 or 16 bit) is indicated.
based on a VMEbus. Some data lines on the P2-connector of the VMEbus are reserved for the exchange of image data. The system is controlled by a host computer. A library of image processing routines supporting the modules facilitates the development of image processing software.

The modules in our system are:

- **Analog/Digital Interface (ADI).** This module provides the interfacing to the camera and a monitor. It contains the A/D and D/A conversions, different timing functions and look-up tables. The A/D converter samples the lines of the video signal with 10 MHz, recognizing 256 grey-levels. Of each line 512 pixels and of each field of a video frame, 256 lines are digitized. The dimensions of a complete digitized image are therefore 512 x 512 pixels of 8 bit.

- **Frame Buffer (FB).** This module contains 1 megabyte of memory for storage of image data, organized as two 512 x 512 x 8-bit frame stores and a 512 x 512 x 16-bit store for processing results.

- **Real-Time Convolver (RTC).** This module is designed for performing convolutions at video rate on image data with a 4 x 4 or 16 x 1 pixel operator. The 16-bit result is passed on to the next board.

- **Pipeline Processor (ALU).** This module can perform operations on individual pixels of one or two images.

- **Histogram/Feature extractor (HF).** This module passes image data without changing them so that they can be stored in the FB-board. Meanwhile it computes a histogram of the image data or it can put the coordinates of the points with predefined features in a list.

Software for weld pool analysis was developed in the high-level language C and using the library. In this programme one can choose between on-line processing of the images coming from the camera and off-line processing of one or more previously captured and digitally stored (in a file) images. The processing of image data is similar for both cases.

The hardware modules are programmed to perform the segmentation and the first step in the shape analysis. The other processing stages are executed on the host computer.

The detection of edges with the horizontal detector is performed by this system in two passes through the pipeline.

In the first pass, one raster of an image coming from the camera is digitized by the ADI, in the case of on-line processing. The same board performs the intensity mapping introduced to reduce the arc intensity by passing a look-up table. In the case of off-line processing, image data stored in a file is transported to the FB and passed through a similar look-up table before processing. The RTC performs the smoothing and differentiation and makes the result absolute to enable equal treatment of positive and negative edges by the ALU. The result of this for one image line is visualized in figure 3.3.d. The ALU produces a
binary image by making those pixels white that have a grey-value (output of RTC) that is greater than or equal to that of the previous pixel and exceed a threshold. This result is visualized in figure 3.3.e. The HF has no function in this pass and the result is placed in an image buffer of the FB.

In the second pass, the camera input is disabled and the just stored image is processed. The RTC is used to determine the difference between subsequent pixel values. The result is not made absolute in this pass. The white to black transition produces a high output value. The ALU identifies the negative transitions, which coincide with the extrema of the first derivative, see figure 3.3.f. The HF is now used to perform the first stage in shape analysis: The coordinates of all points that are recognized as an edge, are put in a list.

In the case of on-line processing, the operation of the boards is synchronized with the video signal of the camera. As the modules in the pipeline operate at video rate, each pass takes nearly 20 ms for the processing of one video raster. During the raster-sync time of the video signal, no processing takes place and the registers that control the operation of the modules can be altered by the host computer. This time is too short to transfer the list produced by the HF to the host computer, so the cycle-time for the processing by the vision sub-system is at least 60 ms (3 video rasters).

The detection of edges with the vertical detector takes at least four passes through the pipeline. This is caused by the facts that the RTC operates with an operator that cannot be more than 4 pixels high and the ALU can compare horizontally neighbouring pixels only.

It is therefore more attractive to rotate the image 90° to analyze the pool front. This can be achieved in various ways.

One option is to use a second camera that is rotated by 90°. The image processing system can be programmed to analyze the images from both cameras alternately.

Another option is to use a part of the image area that reaches to the camera to view an optically rotated image of the pool front. This option detects the horizontal and vertical edges simultaneously in the two passes through the pipeline.

A third option is to store the image in a buffer before transforming it and to make a rotated copy of the front part of the pool in a part of the image not occupied by the pool. This option requires an extra pass for the intermediate storage of an image and processing time for the rotation depending on the area to be rotated. The hardware does not support rotation directly, therefore it is an operation that is executed at a relatively slow speed.

For the off-line analysis described in Chapter 4, we chose for separate analysis of the rotated and unrotated image. In the analysis of the pool front, the image is rotated in the FB.
3.3.2 Auxiliary digital hardware

A digital system has been used for further support of image analysis development and for image capture in the experiments of Chapter 4. This system is a PC-based vision system (Matrox type MVP-AT/NP) with 8-bit ADC and a 1MB frame store. This frame store can hold just 4 complete frames of a video signal. (A complete frame is stored in 512x512 pixels of 1 byte).

In the experiments of Chapter 4 it was desirable to register as much consecutive weld pool images as possible to study the behaviour of the pool during welding. By digitizing only a part of the image field (168x128 pixels), the information of 48 consecutive images is recorded in the frame store. After the filling of the frame store, the information is transferred to a file on disk, containing one series of 48 raster images. Since the video signal contains 50 raster images per second, this represents 0.96 s image information. The transfer to disk takes about 8 s. The file can be transferred to the development system for off-line analysis.

3.3.3 Analogue electronics

In the previous section we reviewed the hardware used to analyze the weld pool images. The edge detection is performed by an image processing sub-system and the more elaborate operations of contour tracing and description are executed on the host computer. Although the operations in the edge detection are rather simple, the sub-system contains considerable computational power, because the images incorporate a considerable number of pixels, whereas a limited processing time is desired.

For an industrial application a system with less complexity (and cost) is desirable.

REIJNDERS (1987) studied whether analogue electronic circuits could be used in analyzing weld pool images. These circuits operate in real-time on the (analogue) video signal coming from the camera, before the digitizing of the images.

A system, based on those circuits, was developed. Thereby images captured from drawings containing black to white and black to grey transitions were used to obtain a stationary input signal. In addition a video tape recorder was used to work with recorded weld pool images.

As the use of the video tape medium slightly degrades the quality of the images, which complicates the edge detection, the system was tested in an experimental welding situation at different welding conditions. The results were good enough to recognize the left and right boundaries of the pool and wire, see figure 3.10. It must be noted that the detection is limited to the transitions in the horizontal lines of the video signal and that the realization of the system suffers from some shortcomings which leads for instance to the presence of 'echo edge points' behind the detected points on the contour. These aspects are explained later in
Figure 3.10
Weld pool images processed with the analog system. Left: Bead-on-plate. Right: V-groove. The stripe in this image is caused by a spatter in the flight.

Figure 3.11
Block diagram of the system with analogue circuits.

this section.
The system with analogue circuits is given schematically in figure 3.11. The video signal coming from the camera is input to the system. The system detects the brightness changes in the lines of the video signal, which are the transitions from pool to workpiece and from pool to wire. The output of the system is a video signal containing highlighted points at the locations where a transition is detected. This signal can be made visible on a monitor. For diagnostic purposes, it is also made possible to visualize the intermediate results $u$, $u'$ and $u''$, as well as the signal $u$ mixed with the highlighted points.
The system is expanded with a digital interface, to provide a computer with compressed information of an image. For each detected edge point, the position
in the image is determined and expressed with an x and y-coordinate, that are stored in a block of memory. The list of coordinates in the memory are made accessible for a computer, where it is used as input for contour tracing and description.

The detection of the transitions in images is based on the conditions mentioned in section 3.2.1.1:

- The absolute value of the first derivative must exceed a certain threshold.
- The first derivative has a local maximum, which means that the second derivative has a zero-crossing.
- The image brightness is below a certain value.

The horizontal differentiation in the spatial domain in an image is equivalent with the differentiation of the video signal in the time domain. Two differentiators are in the system to produce the first and second horizontal directional derivative of an image. The differentiation in the vertical spatial direction cannot be realized easily with an analogue circuit. Therefore, the detection is restricted to transitions on horizontal lines.

The transitions are recognized by the edge detector circuit. This circuit uses two comparators to signal that the derivative of the image brightness exceeds a certain threshold (the first condition mentioned above). One comparator tests for the positive values and the other for the negative values. Another comparator can be used to signal the sign of the second derivative. Now a pulse is produced by a logic circuit when the first two conditions mentioned above are met, indicating that an edge point is recognized (the signal 'ed').

The third condition is explored by a non-linear transformation before the differentiation. The image brightness is lowered by the transformation when it exceeds a level that is expected to occur only within the contour of the weld pool. The transformation characteristic is given in figure 3.12. As a result of this transformation the first derivative of transitions that occur at a high brightness level in the image, are lowered. These transitions can be found within the pool contour and are caused by the arc. The ultimate goal of the transformation is to let these transitions not be detected as an edge point.

The incoming video signal contains not only image information but also line and raster sync pulses. These pulses are transformed by the differentiation and cause the undesired detection of edge points. In order to reject these edge points a window signal is generated indicating when the video signal presents video information. This is done by a sync separator that isolates the sync pulses from the video signal. These pulses are used to generate the window signal and to restore sync.
pulses to the output video signal.

The video clamp circuit restores the DC-component of the input video signal that is supplied via a coax cable. The input and output have a 75 Ohm impedance which is common practice for these video circuits.

The differentiators are the most critical elements in the system. It has already been mentioned in section 3.2.1.2. that differentiation must be combined with (low-pass) filtering the image to limit the influence of noise. The optimal filter has a symmetrical impulse response and is very similar to a Gauss function. However, a more simple first order low-pass filter (which has a non symmetrical impulse response) is used in the experimental realization. The filter may shift the input in time depending on the form of the signal, which leads to an uncertainty in the position of the result on a video line. The breakpoint of the filter is chosen at 10 MHz which makes the time shift of the order of 15 ns (a video line has a duration of 52 \( \mu s \)). The realized differentiator produces a first derivative that can be used by the edge detector. The second derivative, however, suffers to much from noise influences to be used by the detector.

When the detected edge points are visualized on a monitor, it can be observed that sometimes two edge points are detected with a short and more or less constant distance between them on a video line. The second point is not caused by a transient in the input signal, but is due to an imperfection of the circuits. We call the extra detected points 'echo edge points'. It has not yet been determined whether these are caused by damped oscillations of the differentiator or cross-talk between parts of the system. The use of a filter with a symmetrical impulse response is recommended for improvement of the system.

Although the present implementation is not perfect, it did allow us to demonstrate the feasibility of the analogue method.

### 3.4 The system

We resume here the system for analysis of weld pool images as developed. The hardware is the development system described in section 3.3.1. Figure 3.13 presents a block diagram of the software for off-line analysis. For on-line analysis, the same sequence of processing blocks can be chosen except for the time consuming rotation of the image. An alternative for the rotation must be chosen from the solutions presented in section 3.3.1:

- using two cameras, one of which is rotated 90°,
- rotate a part of the image optically,
- restrict the processing to edge detection in one direction only.
Figure 3.13
Flow chart of weld pool image analysis routine.
Appendix 3.A  Terms used in image analysis

In image analysis and pattern recognition a lot of methods have been developed. Unfortunately there is no standardisation of the terms used for them. Therefore it happens that different methods are depicted with the same name in literature, or that different names are used for the same method. The terms used in this thesis are described below. Some of them are based on the survey of methods collected by MANTAS (1987).

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image analysis</td>
<td>A major area studying image descriptions which are expressed in the form of relational structures which represent relationships between and the properties of image parts.</td>
</tr>
<tr>
<td>Template matching</td>
<td>Estimation of the position in an image of an object (or a part of an object) with a known shape. This is done by calculating where a predefined pattern (template) matches best with the brightness function of a captured image. This occurs at the maximum in the cross-correlation function between image and template.</td>
</tr>
<tr>
<td>Segmentation</td>
<td>The process that divides the image into regions by clustering and classification of pixels.</td>
</tr>
<tr>
<td>Thresholding</td>
<td>The transformation of a grey-level image into a binary image by assigning unity to pixels where the intensity is greater than a threshold value and zero where it is not (or vice versa).</td>
</tr>
<tr>
<td>Edge detection</td>
<td>The operation to detect and locate the boundaries between image regions (segments) with different brightness. The ultimate goal is the characterization of intensity changes in the image in terms of the physical processes that originated them (TORRE and POGGIO, 1986). Unlike in this thesis, some authors consider edge detection not as a segmentation method, but as complementary to it, (see for instance HORN, 1986).</td>
</tr>
<tr>
<td>Edge point</td>
<td>Pixel location where an edge has been detected.</td>
</tr>
<tr>
<td>Shape analysis</td>
<td>The generation of a data structure that describes the geometry of the regions in the image obtained by segmentation.</td>
</tr>
<tr>
<td>Contour tracing</td>
<td>The collection of a sequence of neighbouring points of a contour in the image.</td>
</tr>
<tr>
<td>Trace</td>
<td>Chain of neighbouring edge points.</td>
</tr>
<tr>
<td>Raster scan</td>
<td>Variant of contour tracing, whereby, in stead of 'walking' along the contours, an image is scanned 'raster wise' for points on a contour, that are subsequently assigned to traces (contour parts).</td>
</tr>
<tr>
<td>Description</td>
<td>The extraction of relevant features of the object from the data structure.</td>
</tr>
<tr>
<td>Scene analysis</td>
<td>Processing of the subsequent results of image analysis.</td>
</tr>
</tbody>
</table>
References


4.1 Introduction

The development of the weld pool sensor is based on the assumption that useful information of the welding process can be derived from the actual shape of the pool.

In a preliminary experiment we had established the fact that the full image as captured by the camera and presented on a monitor in real-time, contains sufficient information to enable a welder to control the process. Following BANGS (1987) and others, we have made the further assumption that much of the relevant information is contained in the shape of the pool, as represented by the set of edge points. However, the dimensionality of this set is far too high to make it immediately useful. Hence, further data reduction is required. The approximation with low order polynomials leaves us with a set of 13 parameters, but this is just an intermediate step, and it may not even be sufficiently information-preserving. Therefore, we are confronted with the question: What specific features should we extract from our data set (either the full contour, or the approximated one) that might be used for controlling the welding process?

The welding process is complex and can be represented as a black box with inputs and outputs (figure 4.1). The primary output is the weld quality, defined by common practice and standards, as applicable to a specific job. The most straightforward method of controlling the weld quality would be by measuring the quality on-line. Unfortunately, the quality of the weld cannot be directly measured on-line. It is not expected that quality measurement is possible from the pool geometry either. However, the pool measurements are valuable when disturbances can be detected and identified that cannot be measured otherwise.

For every reasonable set of job specifications it is possible to specify a set of values for the controllable process parameters, the nominal set, which in the absence of disturbances, guarantees the emergence of a good quality weld. We assume that under these conditions the weld pool shape is represented by
a set of geometric features (yet to be defined), that we will call the reference set.

Disturbances of the nominal process conditions can arrive in various ways, and they will affect the process outputs, weld quality and weld pool geometry, in various ways. Basically 3 types of disturbances can be distinguished:

1. Disturbances that have an effect on both pool geometry and weld quality.
2. Disturbances that have an effect on pool geometry, but not on weld quality.
3. Disturbances that have an effect on weld quality, but not on pool geometry.

Disturbances that have no effect on either pool geometry or weld quality are ignored. They do not influence the process and are therefore not an input parameter in our model.

We formulate the following assumptions:

• Given the settings of the controlled parameters, it is possible to identify disturbances of both class 1 and 2 from the deviation of the pool geometry from its reference value.

• Once a disturbance has been identified it is possible to specify new settings for the controlled parameters, that will restore the weld quality to its design value (feed forward control). Generally, with this new set a different reference pool geometry will be associated. In some cases, the nature of the disturbance may be such that it suffices to restore the pool to its previous reference shape in order to reestablish the desired weld quality. This would correspond with pure feedback control.

The geometric features that we are looking for should preferably be sensitive to disturbances of type 1, but be insensitive to disturbances of type 2.

In the literature on weld pool measurements no systematic analysis of the pool geometry is found. Only some obviously interesting features are mentioned. These are the width, used for adjustment of the wire feed rate or the travel speed, the relative position of the leading pool extension (1-seam), used to centre the torch over the seam, and the length of the pool extension (which could be interpreted as a depth measurement) is used to control the penetration of the root pass of a V-groove weld. See section 1.3.2 for references.

There is a body of literature on the physics of welding, that addresses the geometry of the weld pool, see for instance LANCASTER (1986), or FRANSE et al. (1984). However, these sources consider mainly the shape of the cross-section of the weld bead and not the shape of the free surface of the pool.

Interviewing experienced welders is not very informative either. One problem is that a welder cannot indicate exactly which visual features play a role. Another problem is that the camera does not generate the same kind of image as the human eye perceives, as noted in Chapter 2.

In the searching for relevant image features and their meaning two
complementary methods are used.
Deduction is one method. Suggestions for relevant image features are derived from the variation in the pool geometry that may occur. The set of possible pool shapes are obtained from the various conditions of the welding process that may occur. Particularly conditions affecting the weld quality are important. Section 4.2 presents the formation of different weld defects. The factors playing a role in the defect formation and their influence on the pool geometry are discussed. This produces the suggestions for features.
Induction is the other method. Section 4.3 presents a practical exploration searching in a systematic way for geometry features for one particular seam type. A complete study would be beyond the scope of this thesis.
Section 4.4 presents some experimental explorations of defects that did not occur in the experiments presented in section 4.3.
Finally section 4.5 presents suggestions for using the system in control loops. These suggestions are based on the results of the previous sections.

4.2 The appearance of weld defects

This section presents the deductive approach in search of the relevant features by discussing the formation of weld defects. This yields suggestions for the geometry of the pool associated with process conditions that may cause defects. Special attention is given to recognition of disturbances. Incidentally the recognition of (the formation of) a weld defect is discussed, for a control algorithm based on defect recognition is less complex than control based on recognition of disturbances.
This section addresses the weld defects, presented in Chapter 1 (figure 1.4), extended with defects that occur by malpositioning the torch over the workpiece.

Penetration defects:
- Lack of fusion at the junction between the weld and the workpiece parts.
  This defect is always caused by the fact that the workpiece surface is locally heated insufficiently to melt. The pool has covered that location without being able to make a real metallic contact with the base metal. Three situations may cause lack of fusion: The heat input is insufficient, the heat flow to the workpiece is shielded by the pool, or the seam has an unsuitable shape.
  The pool can give an indication of the amount of heat input, because the width of the crater produced by the arc is approximately the width of the pool. So we can see whether a weld of the desired width is produced. The width must be in proportion with the amount of deposited weld metal per unit of length.
  When the pool shields the workpiece from direct arc heating as it flows under the arc over the workpiece (roll-over), the pool extension length
(distance between the wire tip and the pool front) will become large. So this length indicates the risk of roll-over. This can be the case when welding downward in a vertical seam.

It is not possible to forecast in general terms whether the pool geometry gets a specific characteristic feature when the seam geometry is such that the arc heat cannot be distributed uniformly.

- Insufficient penetration at the root of the weld.
  This may occur in a full penetration weld, as in the root pass of a butt joint. This defect occurs when the heat is not able to reach the back of the workpiece. The workpiece remains unmolten at the back, which causes the pool not to reach the back side of the workpiece. Causes can be: the gap in a butt joint is too small, or the pool fills the seam and causes the arc to be higher in the seam. The pool extension length is large in both cases.

In remote controlled GTA welding of the root pass of a butt joint it was found that the shape of the rear of the pool can indicate whether full penetration exists or not (BELLEKOM 1988). In the case of full penetration, the rear boundary of the pool develops a characteristic sharp V-shape. In the case of incomplete penetration, the shape is more round, because the cooling of the weld comes also from the back, see figure 4.2. Unfortunately, the principle of weld pool imaging adopted here results in little contrast between the pool and the weld, which makes recognition by rear edge detection impossible, see Chapter 2.

- Excessive penetration at the root.
  This is also a defect that may occur in a full penetration weld. When too much heat is supplied to the bottom of the seam (root), the pool back face becomes very wide. This causes the surface tension, that usually must keep the pool in place, to become overtaxed. The weld back protrudes excessively under the workpiece surface, or worse, the arc may burn through the workpiece. This defect can occur when the gap between the workpiece parts is too wide, or when the heat input is too high. The pool and the arc sink deep into the seam. The distance between the wire end and the pool front diminishes, and the pool

![Figure 4.2](https://example.com/figure42.png)

*Figure 4.2 Top view of the weld pool shape found in remote controlled GTA welding.*
extension becomes narrow.
Lack of fusion is a defect that occurred in the experiments with fillet welds. The practical recognition will be discussed in section 4.4. The penetration at the root of a V-groove joint is studied in the experiments presented in section 4.5.

Fill-up defects:
- Undercut.
The arc heats the workpiece forming a crater with liquid metal. Undercut (figure 4.3) is formed where the volume of the molten metal is insufficient to fill the crater. In that case, a part of the crater surface is covered with a residue of molten base material. As the residue has a small heat capacity, it solidifies immediately after the torch has passed. Figure 4.3 gives the top view of the pool for this situation. Undercut thus causes a sudden reduction of the pool width just behind the torch centre, which was already recognized in images of remote controlled GTA welding (BELLEKOM 1988).

In a model ignoring surface tension effects, undercut appears when the amount of material deposited per unit of seam length is insufficient to fill the crater volume by a weld with a flat surface. This is the case when the voltage is too high, which makes the pool width large.

- Too large contacting angle between the workpiece and the weld, often combined with weld surface convexity.
This defect may occur when the seam has an incorrect profile, or when the amount of filler metal is not in proportion with the width of the crater. The latter can be recognized in the same manner as undercut, except that the crater is too small in this case. The profile of the workpiece cannot be determined from the pool geometry. However, it may be possible that certain seam profile properties leading to the too large contacting angle cause a typical feature of the pool contour.
In the experiments with fillet welds both undercut and a too large contacting angle occurred. The practical recognition will be discussed in section 4.4.
Tracking defects:
- Unequal leg length.

When welding in groove shaped seams, the torch must usually be centred above the seam to obtain a correct weld result. In this case the pool geometry is more or less symmetrical with respect to the plane defined by the electrode axis and the seam direction. As the image is captured by the camera from the front side, the pool geometry in the image is symmetrical with respect to the electrode axis. Malpositioning of the torch (not centred) causes the pool to be non-symmetrical. An example of such a pool shape is given in figure 4.4.

A feature that indicates the degree of non-symmetry is desired for centring the torch. When a leading extension protrudes from the pool front, the centre of this extension can be identified as the seam centre line. In this case, the torch displacement relative to the seam centre can be measured directly, see figure 4.5. This usually is the case in an open I-seam, and sometimes in a V-seam. This type of measurement is described in INOUE (1980) and NIEPOLD (1983).

In producing a fillet weld, there is usually no protruding extension. Therefore, the seam centre cannot be located. BÉGIN et al. (1983) measured the position of the wire relative to the pool side boundaries as

![Figure 4.4](image)

*Example of a non-symmetrical weld pool caused by a malpositioning of the torch. (Edge points found with horizontal edge detection).*

![Figure 4.5](image)

*The protruding extension of the pool in an I-seam can indicate a lateral torch displacement.*

![Figure 4.6](image)

*Measurement of the asymmetry by determining the position of the wire relative to the pool side boundaries.*
an indication for the torch misalignment, see figure 4.6.

Torch misalignment will produce unequal penetration of the workpiece parts. Hence, the weld obtains unequal leg lengths, see figure 4.7. This hinders estimation of the misalignment by measuring the position of the wire end relative to the pool side boundaries.

The torch misalignment could be determined if it were possible to measure the distances between the wire end (point W in figure 4.8) and both side surfaces of the seam (which are supposed not to be in a flat plane). Of course, this cannot be measured because the perpendicular projections of W on the surfaces usually are inside the pool. We propose to measure the distances WF and WG instead, to get an indication of the torch misalignment. This will give a better estimation of the horizontal distances than WA and WB, because the difference in horizontal (lateral) direction between A and F is larger than that between B and G, when the torch is displaced from the seam centre in the direction of A.

- Deviation of the torch to workpiece distance.
  This deviation is in itself not a weld defect, but affects the penetration. A deviation of this distance causes about the same deviation of the wire extension

Figure 4.7
Torch misalignment causes unequal leg lengths of the weld.

Figure 4.8
Definitions of some points on the polynomials describing the pool contour.
T End of the contact tube.
W End of the wire stick out.
A, B Left and right most points of the pool.
C Lowest point of the pool.
H Intersection of the front polynomial with a vertical line through W.
J, K Intersection of the side polynomials with a horizontal line through W.
F, G Intersection of the side polynomials with lines through W making an angle of 60° with the vertical axis.
length (ignoring dynamical effects). As the end of the wire is visible and
the contact tube has a fixed position in the image which can be calibrated
prior to welding, the wire extension length can be measured directly.
Tracking defects have not been studied in the experiments carried out.

**Metallurgical defects:**
- Structural changes in the base material in the heat affected zone near the
  weld.
  The geometry of the front of solidification, combined with the (usually
  known) travel speed, can be informative because it gives an indication of
  the speed of solidification. At a given travel speed, a long pool means a
  relatively slow solidification. This may cause large metal crystals to
  form, which has a negative influence on the metallurgical properties.
  However, as already mentioned, it is not possible to detect the rear
  boundary of the pool with our system.
- Cracks in or near the weld.
  These defects are caused by metallurgical problems. The pool
  measurements are not expected to supply useful information for solving
  those kinds of problems.
Metallurgical effects have not been studied in the experiments carried out.

**Other defects:**
- Spatter.
  Spatters generated during the welding process cannot be detected with the
  system, because they move too fast, see Chapter 2. Furthermore, most
  spatters are out of focus when they fly in the field of view. Therefore,
  the system cannot be used for estimating the amount of spatter produced.
- Porosity.
  This defect is usually due to an incorrect gas protection. In the images,
  the emergence of gas bubbles from the pool surface cannot be
  recognized. The weld pool geometry is not expected to change in a
  particular way when porosity occurs.
- Inclusions of other kinds, e.g. slag.
  The weld pool geometry is not expected to be useful for recognizing the
  occurrence of this defect.
Spatter, porosity and inclusions have not been studied in the experiments
carried out.
4.3 Experiments with fillet welds

After the deductive discussion of section 4.2 this section presents the inductive exploration of the prospects of the pool measurement system. Experiments were conducted to unveil relevant features and their interpretation.

Welding is a complex technology in which many parameters and factors play a role. It is not feasible in the course of this study to test the sensor system for the complete range of conditions encountered in practical welding jobs. We restrict the exploration to a spot check. Only one specific type of weld was used in the experiments. We selected a fillet weld as the object of investigation because this is the most frequently used type of weld in (semi-)mechanized and automated welding.

We produced welds with different settings of the input parameters. Only a few input parameters were varied, making good as well as defective welds. All other input parameters were unchanged during the experiments.

The experiments incorporated variations of:
- voltage,
- wire feed rate,
- travel speed,
- gap width.

The experiments consisted of three series. The gap width between the parts of the workpiece was set to 0 mm in the first series of experiments, to 1 mm in the next, and to 2 mm in the last series.

The ratio of wire feed rate to travel speed was held constant for each series of experiments, to attain a constant deposition of metal per unit of length of the weld.

The experiments aimed at determining the steady state response. Therefore, each weld was made with a fixed set of input parameters.

In the experiments only a few types of defects occurred, namely lack of fusion, a too large contacting angle and undercut. We did not introduce tracking errors, for several sensors for arc welding exist for the tracking function, whereas the strength of the pool measurement method must become apparent in its potential for preventing other defects.

4.3.1 Experimental set-up

The workpiece and equipment used

The experiments were conducted on an existing test facility, see figure 4.9. It comprises a horizontal table and a carriage with a horizontal axis of motion. On the carriage a support is mounted holding the GMA torch and the camera. The support allows manual adjustment of the torch and camera
Figure 4.9
Overall picture of the test facility with carriage movement (1), torch position adjustment (2) and camera position and orientation adjustment (3).

The movement of the torch along the seam is realized by the electric drive of the carriage. The travel speed can be set between 0 and 0.038 m/s. The accuracy is ± 0.0002 m/s. The torch is moved over a workpiece with a constant speed, without superimposed weaving motion.

A workpiece fixture for T-joints was available which has a length of 500 mm, see figure 4.10. The fixture was designed for workpieces of up to 10 mm thick sheet metal. It is mounted on the table and aligned in such a way that the axis of the seam and of the carriage are parallel.

We chose for a fillet weld of a T-joint in 4 mm steel, which we obtained by placing strips of 500x50x4 mm in the fixture. The strips are made of commonly used mild steel (Fe360). Prior to welding dust and oil are removed from the strips as these might become visible in the image at the border of the pool potentially hindering recognition of the pool contour. An experiment with dust and oil was not performed.

The torch and camera are mounted in such a way that the torch axis and the camera optical axis are in the plane through the seam axis bisecting the angle between the workpiece surfaces.
forming the seam. The torch is pointing forward, making an angle of $75^\circ$ with the seam axis. The camera is pointing backward, viewing the pool from the front. Its orientation is such that the torch axis is projected on the vertical axis of the camera. The camera and torch axes form an angle of $55^\circ$. To give a free view on the pool, the gas nozzle of the torch is shortened, so the contact tube is protruding 3 mm out of the nozzle.

The optical system and video digitizing are such that at the welding spot in the direction perpendicular to the plane of the torch and camera, 10 mm is projected onto 215 pixels. 10 mm in the direction of the seam axis is projected onto 131 pixels. The torch position is checked for each workpiece, keeping tracking errors minimal.

The distance between the contact tube and the intersection line of the workpiece surfaces forming the seam is set at 17 mm. During the experiments it appeared that this torch to workpiece distance is too short for welds produced with a voltage of above 24 V. Therefore for some workpieces the distance was raised to about 20 mm.

A conventional GMA welding power supply unit was used (Philips type PZ 2325/31), allowing three major regimes of material transfer (dip, globular and spray transfer) and excluding pulsed arc welding.

We used a copper clad solid welding wire: Ø 1,0 mm quality SG2.

The shielding gas used is a mixture of 85 % Ar and 15% CO$_2$, and was supplied during welding with a rate of 10 l/min.

**Recordings**

The images were processed off-line for two reasons:

- The shape of the pool shows temporal fluctuations. As the melt solidify cycle time of the welding process used is of the order of 1 s, it is not likely that phenomena of short duration have a strong influence on the process. However, in the course of this study it is desirable to analyze consecutive images, which is not feasible by using the image analysis system on-line.

- We do not yet know whether the analysis presented in Chapter 3 is sufficiently information preserving. Off-line analysis leaves the possibility of using other analysis methods.

Preceding experiments learned us that analogue recording (VCR) of images introduces noise, which makes processing difficult. Therefore digital registration of image data was adopted. The registration of images was performed by the auxiliary digital hardware described in section 3.3.2.

It was decided to store only a rectangular part of the image in which the wire-end, pool front and side edges are visible. This allows us to store a pixel is a picture element of the digitized image and represents not necessarily a square part of the scene, see Chapter 3.

---

1 A pixel is a picture element of the digitized image and represents not necessarily a square part of the scene, see Chapter 3.
maximum of image information within the frame store dimension. Furthermore, it was decided not to give the rectangle a fixed position relative to the torch, because this would enlarge the required rectangle dimension, and reduce the number of rectangles that fits in the frame store. The position of the rectangle had to be adjusted several times between two workpieces to ensure that all relevant image details were stored. This makes it impossible to reconstruct the position of the weld pool relative to the torch from the stored images. The repositioning of the rectangle in the image for instance was performed each time the experimental facility was dismantled and rebuilt.

The recorded part of the image field measures 168x128 pixels, which allows the information of 48 consecutive images to be recorded in the frame store. After the filling of the frame store, the information is transferred to a file on disk, containing one series of 48 raster images. Since the video signal contains 50 raster images per second, this represents 0.96 s image information. The transfer to disk takes about 8 s.

Of each weld two or three of these series of 48 images have been recorded, beginning about 2.5 s after starting the welding process. (When the travel speed was low enough a third series could be captured before reaching the end of the workpiece.) In addition, for each image series of each weld a record has been made containing:

- the running number of the weld,
- a letter A, B, or C indicating the image series,
- the gap width,
- the setting of the travel speed,
- the setting of the wire feed rate,
- the measured and averaged voltage,
- the measured and averaged current.

The welding current was determined by measuring the voltage over a shunt (300 A = 100 mV). The welding voltage was measured over the clamps of the power source. The voltages have been recorded with digital voltage meters (DVM) that were interfaced to the PC. An RC-filter (with time constant of 0.22 s, R=1k, C=220µF) was placed at the input of the DVMs, as we are interested in the steady state response only, see figure 4.11. The voltage was recorded at the beginning and at the end of each image series. The two values thus obtained are averaged.

The travel speed was indicated on a digital display.

A wire feed rate measuring device was placed on the wire going to the wire feeder. Both travel speed and wire feed rate have been monitored manually during welding.
Operating the system
Adjusting the travel speed and wire feed rate is time consuming, whereas changing the voltage is very simple. Therefore setting the travel speed and wire feed rate was done once for a set of welds made with different voltages. The voltage was increased and decreased until a defective weld was created. All operating parameters for the first weld (number 0) were set to a value to obtain a good weld quality. This was done by an experienced welder. The values are adopted as the nominal settings. All unmanipulated parameters were kept constant as well as possible for the rest of the experiments. The welder also set the parameters for the first weld in a workpiece with a gap (number 50).
The ranges of the welding conditions employed in the experiments are given in table 4.1. The actual conditions of the welds are listed in appendix 4.A.

<table>
<thead>
<tr>
<th></th>
<th>0 mm gap</th>
<th>1 mm gap</th>
<th>2 mm gap</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>11.9 - 26.1</td>
<td>14.2 - 28.5</td>
<td>13.9 - 26.9</td>
<td>V</td>
</tr>
<tr>
<td>Travel Speed</td>
<td>0.36 - 1.71</td>
<td>0.36 - 1.49</td>
<td>0.36 - 1.03</td>
<td>m/min</td>
</tr>
<tr>
<td>Wire Feed Rate</td>
<td>2.5 - 12.0</td>
<td>3.4 - 14.0</td>
<td>4.2 - 12.0</td>
<td>m/min</td>
</tr>
<tr>
<td>Current</td>
<td>74 - 296</td>
<td>107 - 295</td>
<td>120 - 249</td>
<td>A</td>
</tr>
</tbody>
</table>

Table 4.1
The range of the welding conditions in the experiments. The conditions of all workpieces are listed in Appendix 4.A.

Determining the quality
An expert welder classified the workpieces by visual inspection. The workpieces are classified as good, questionable or unacceptable. Of those with an unacceptable quality the type of defect was recorded. A limited number of workpieces are selected of which optical macrographs are made.

Image analysis
The image registrations are analyzed off-line on the digital image processing system. The image processing is described in detail in Chapter 3. Here we summarize briefly the three steps:

1 An optical macrograph makes the penetration and cross-sectional area of the weld visible. It is obtained by making a cross-section of the workpiece perpendicular to the weld, polishing the cross-section and finally etching it. In a macrograph, the region in the base material adjacent to the weld, where the structure has changed, has acquired a different brightness by this treatment.
• **Segmentation**, the process that divides the image into regions. This is performed by scanning the image twice with an edge detection algorithm, once along horizontal lines and again along vertical lines. They locate intensity transitions across a more or less vertical and a horizontal pool boundary respectively.

• **Shape analysis**, the generation of a data structure that describes the regions in the image. This process is performed by a contour tracing algorithm. Points isolated by the horizontal edge detector merge into structures that describe the left and right part of the pool contour and the two sides of the wire silhouette. Structures describing the wire end and the front of the pool are built by using the points located by the vertical edge detector.

• **Description**, the extraction of the relevant features from the data structures. Spatter and other irregular phenomena at the border of the pool making the contour rugged are considered unimportant in our experiments. Therefore description is performed by approximation of the contour parts by a smooth function with enough degrees of freedom to represent all relevant aspects of the pool shape. The approximation filters out small irregularities and bridges gaps in the contour. The approximating functions each are valid in a restricted part of the image. Polynomials are used as the approximating functions.

The features thus determined are:
- the position of the wire end,
- the front boundary of the pool,
- the left and right side boundaries.

The position of the wire end is determined from the (horizontal) wire end structure by averaging the coordinates of the pixels in that structure. This gives an acceptable estimate of the desired position.

The pool front contains several interesting shape aspects, like the lowest position of the pool in the image, the lateral position of the leading extension, and the type of curvature (to discriminate between a sharp protruding extension and a wide flat front). Under certain conditions a dent can be observed in the pool front line, which was recognized as a potentially important feature, see section 4.3.4. We chose a 4th-degree polynomial as the approximating function of the pool front.

The side boundary approximations must have a good fit at the outer left and right portions of the contour, as well as a good fit near the arc region, which is in the video lines just below the wire end. We found good results with a 2nd-degree polynomial. We also experimented with a 4th-degree polynomial for several images. The improvement obtained by the extra terms was negligible.

Averaged features are computed for each series of images by averaging each of the polynomial coefficients. With this, an average shape of the pool can be reconstructed for each image series. An example of this is given in figure 4.12.
Figure 4.12
The average shape of the pool. The 'U' indicates the position of the wire end. The number is the weld number.

Figure 4.13
The contour parts of the pool are expressed in polar coordinates. The difference between the pool shape and the nominal shape is defined as: $R(\varphi) - R_0(\varphi)$.

We are interested in the differences in the pool geometry between the experiments. Therefore a graphic presentation is constructed that shows the differences between the average pool geometry of an experiment and a nominal weld pool shape. The averaged shape of the pool of image series 0A is defined as the nominal weld pool. The three parts of the pool contour are expressed in polar coordinates taking the position of the wire end as the origin, see figure 4.13. In a figure the difference of the radii is given as a function of the angle $\varphi$. The difference is positive where the pool is larger than the nominal pool. An example of this figure is given in figure 4.14.

Figure 4.14
The differences between the average polynomials of a workpiece and those of the nominal weld pool shape (positive when larger). The number indicated (39) is the weld number.
4.3.2 Results

Workpieces without gap (root opening)
The workpieces without gap are welded with the ratio of wire feed rate to travel speed set at 7 : 1. Setting up a material balance shows that under these conditions the design throat thickness 'a' (see figure 4.15) of the weld will be 2.345 mm, when the weld is flat and when there is no loss of material from spatter. This is close to the ideal value of the design throat thickness for the selected workpiece which is 0.6 times the plate thickness, or $0.6 \times 4 = 2.4$ mm.

One weld, no. 35, suffered from an unintended tracking error and is therefore abolished.

In figure 4.16 the results obtained with workpieces without gap are plotted. In that figure the attached quality classification is given. Two boundaries are delineated.

Beyond the upper boundary, the welds are rejected because of undercut. At lower values of the travel speed (below 1.2 m/min) this occurs first at the left side of the weld (as seen from the camera position), which is the upper side with respect to the gravity direction.

Below the lower boundary, the welds are rejected because the surface of the weld is convex, which indicates lack of fusion, or a too large contacting angle.

Although the experiments were set up to recognize an upper limit for the travel speed, no such limit was encountered. In the experiments, the travel speed is limited by the length of the workpiece and the wish to record at least two image series of each weld. A defect that could limit the travel speed is a 'humped bead', reported in LANCASTER (1986, pp.296 - 298).

As the welds with an acceptable quality group into a distinct area in figure 4.16, it seems that no unknown factors have a disturbing influence on the experiments.

The optical macrographs made in addition to the visual classification, and gave information on the penetration into the workpieces. The welds selected to produce macrographs from are: 44, 36, 30, 00, 08, 16 and 24 to express the influence of increasing travel speed, 45, 112, 113 and 18 to express the influence of a high voltage and 47, 34, 33 and 22 to express the influence of a low voltage. The macrographs are shown in figure 4.17. They confirm the common experience that penetration depth increases with increasing wire feed.
The weld quality as a function of the operating parameters.

- acceptable quality, o undercut,
- questionable quality, -
- unacceptable quality, x convex surface.

rate and proportionally increased travel speed. Therefore the welds with a convex surface, have only lack of fusion when the travel speed is low. At a high travel speed the welds with a convex surface are classified as having an unacceptable quality because they have a too large contacting angle. The macrograph of weld 22, which is made with a low voltage and a high travel speed, shows that the penetration depth is sufficient.

We can also learn from the macrographs that increasing the voltage widens the penetration, but makes this not much deeper. This is because a higher voltage causes the arc to be longer. The centre of the arc is located higher above the seam and the arc heat is distributed over a larger area.

Figure 4.18 displays some pool images of workpieces without gap.

Image analysis was not successful for all image series of the welds. For some welds it was not possible to construct a reliable approximation of the pool because in the images too few points were detected by the edge detector. This was especially the case for welds made with a low value of the voltage.
Figure 4.17a
Optical macrographs of workpieces without gap. The workpieces of which macrographs are given here, have a different travel speed, but are all classified as having an acceptable quality.
Figure 4.17b
Optical macrographs of workpieces without gap.
The welds made with a high voltage are given on the left.
The welds made with a low voltage are given on the right.
Some pool images of workpieces with gap = 0 mm.

Quite unexpectedly it appeared that processing of these images was obstructed because the brightness of the pool near the border was substantially lower than in the nominal weld pool image. This phenomenon can be explained by supposing the pool liquid at the front and side boundary to be supercooled by some dozens of degrees Celsius. This seems reasonable at the extremely low values of the voltage used in those welds. It should be pointed out that a partial explanation is found in the fact that the melt has a solidification range rather than a solidification point. Another possible mechanism for the observed phenomenon is that the arc is not active at the pool front so that oxide layers contact the pool and have some chemical interactions with the pool that lower either the emission coefficient or the melting temperature of the pool. The observed phenomenon has not been further investigated in this study.

Sometimes image analysis was not successful in individual images of one series. Those images were not taken into account in the averaging within an image series.

The averaged shapes of the pools of welds for which image analysis was successful are given in figure 4.19. Figure 4.20 gives for the same welds the differences between the polynomials approximating the averaged pool shape and those of the nominal pool shape.

The averaged shapes and geometry differences show the influence of the voltage and travel speed on the pool geometry.

With increasing voltage, all dimensions of the pool increase. We evaluate three formal features for this enlargement of the pool, see figure 4.21:
Figure 4.19
The average weld pool shape of workpieces without gap presented in the same arrangement as in figure 4.16.
Figure 4.20
The differences of the average pool shape of workpieces without gap from the nominal weld pool shape (arrangement of figure 4.16).
MaxWidth = The maximal width of the pool i.e. the horizontal distance between A and B.
WE-Width = The width of the pool at the end of the extending wire i.e. the distance JK.
Fl-Dist = The sum of the two distances from the wire end to the pool boundary measured along lines that make an angle of 60° with the vertical axis of the image. Of the distances the horizontal exponent is taken i.e. the horizontal distance FG. (By dividing with \( \sin 60° \) one gets the distance FW + WG.)

The three features thus defined appeared to vary roughly to the same extent as a function of the voltage. The most pronounced differences appear in the WE-Width. All three features are influenced by the travel speed. At a high travel speed (welds 15-22 and 23-25) a particular width is reached at a higher value of the voltage.

The repeatability is also important in the evaluation of the features. An estimation of this is obtained by comparing the values determined from the different image series of each weld. The values thus obtained are nearly equal:

\[ \sigma = 4.45 \text{ pixels for the MaxWidth,} \]
\[ \sigma = 4.30 \text{ pixels for the WE-Width,} \]
\[ \sigma = 4.42 \text{ pixels for the Fl-Dist.} \]

Of the three features evaluated, the WE-Width produces the best results. We refer to this feature as the 'width' in the rest of this chapter. Figure 4.22 gives the width as a function of the voltage with lines of constant travel speed. Figure 4.23 gives the width as a function of the travel speed. The travel speed is the other input parameter whose influence on the pool geometry is to be determined.

It was predicted by a welder that a dent in the pool front line would appear when welding with a high travel speed. This was not found in the actual images, probably because we increased the wire feed rate in proportion with the travel speed. We found that the dent sometimes appeared at a low travel speed. The dent gives the impression the pool has two leading extensions, one on each workpiece part. The 4th-degree polynomial is not suited as an accurate approximation of the pool front with a dent, because the dent is relatively narrow and deep whereas the polynomial can have a smooth dent only. The approximation of the front becomes rather wide and flat and sometimes shows a negative curvature with the occurrence of a dent.
Figure 4.22
The measured width as a function of the voltage for the workpieces without gap. The results obtained with the same travel speed are connected with lines.

At increasing travel speed the pool develops a more pointed front shape and the pool front to wire end distance increases. To find a feature that is independent of the size of the pool, we search for a curvature or ratio of dimensions.

From Figure 4.20 it can be derived that the front to wire end distance $WH$ is significant in comparison with the Fl-Dist. We therefore define the slenderness as the ratio $WH / \text{Fl-Dist}$. The distance $WH$ is derived from the front polynomial and the Fl-Dist is derived from the side polynomials. This feature can also be interpreted as indicating a curvature.

In Figure 4.24 the average slenderness for each weld is plotted against the travel speed. An estimate of the repeatability of the slenderness is: $\sigma = 0.024$.

We also derived a feature expressing the front curvature from the front polynomial. It is defined as the average curvature in a small region (20 pixels wide) around H. In Figure 4.25 the average curvature is plotted against the travel speed. This feature appeared to be more sensitive to unknown
disturbances than the slenderness. The average curvature has not been further investigated.

Figure 4.26 gives the slenderness as a function of the voltage. Lines of constant travel speed are given in that figure. Ultimately, we are interested in the relation between the quality of the weld and the value of the image features. In figure 4.27 the results obtained with the workpieces without gap are plotted in the space of image features width and slenderness. The welds with an acceptable quality cluster in a distinct area, which we call the feasible domain. A more or less smooth contour can be constructed around the feasible domain. The welds with undercut are in the upper part of the image, whereas those with a convex surface are found in the lower part.
Figure 4.24
The slenderness as a function of the travel speed. Lines of constant voltage are not constructed because these are crossing which indicates that the relation between slenderness and travel speed is no function of the voltage.

Figure 4.25
The curvature of the front as a function of the travel speed.
Figure 4.26
The measured slenderness as a function of the voltage for the workpieces without gap. The results obtained with the same travel speed are connected with lines. The arrow indicates the direction of increasing travel speed.
The quality of the weld as a function of the image features width and slenderness.

- o acceptable quality,
- - questionable quality,
- u undercut (above the upper line),
- x convexness (below the lower line).

Workpieces with a gap
Most workpieces with a gap have been welded with a higher ratio of wire feed rate to travel speed than those without gap, because some metal enters the gap and because those workpieces require a larger weld to get the desired strength. Some workpieces with a 2 mm gap are welded with the same ratio of wire feed rate to travel speed as the workpieces without gap. These workpieces (105, 131, 132 and 133) are used to study the effect of the gap. Figure 4.28 is a pool image from workpiece 131. Figure 4.29 shows the location of the pool in a workpiece with a gap. The presence of a gap makes the pool narrow and slender compared with pool shapes of workpieces without gap welded with about the same voltage and travel speed. In addition to this the pool has a more or less protruding extension with a vertical edge,
Figure 4.28
Pool image of workpiece 131 (gap = 2 mm). The indentation is characteristic for the presence of a gap.

Figure 4.29
The appearance of the weld pool in a workpiece with a gap.

which might also be described as an indentation with a vertical edge. The indentation with a vertical edge is a local feature of the pool contour typical of the presence of the gap and is independent of the width and slenderness which have a more global nature. The adopted method of polynomial approximation is not suitable for describing and recognizing this feature, because it smoothens the indentation.

In figure 4.30 the measured width and slenderness are compared with those of workpieces without gap welded with about the same values of voltage and travel speed (and wire feed rate). In that figure the arrow represents the shift of the features due to more gap width.

The figure shows the effect of the gap width on the pool width. The effect on the slenderness is not found in the figure. This is caused by the fact that the front approximation of the pool contour deviates systematically from the real pool border because:

- the approximating function cannot have a stepwise transient, therefore the indentation is smoothed by the approximation and the determined wire end to pool front distance is too small,
- the extending pool front end is often relatively dark which makes that little edge points are detected there.

Hence, the defined feature slenderness does not correctly express the pool slenderness of workpieces with a gap.

Workpieces with a 1 mm gap
The workpieces with a 1 mm gap require more weld metal in order to make a correct weld, because some material is necessary to fill the gap and because
The image features width and slenderness of workpieces without gap and of workpieces with a gap of 2 mm welded with the same ratio of wire feed rate to travel speed. The arrow indicates the shift of image feature values caused by more gap width. The shift has been determined by comparing the workpieces with a gap with those without gap welded with the same values of voltage, travel speed and wire feed rate.

- Welds with acceptable quality.
- Welds with questionable quality.
- Welds with a defect.

A wider weld must give the joint the required strength. These welds are produced with the ratio of wire feed rate to travel speed of 9.34 : 1. Without loss of material and a flat weld surface, the throat thickness would be 2.71 mm.

This series of experiments yielded a similar relation between the weld quality and the controlled parameters as the series of experiments without gap: the same defects, undercut, lack of fusion and too large contacting angle, occurred.

For this series of experiments the width and slenderness vary with the voltage.
and travel speed in a similar way as the series with 0 mm gap. Defects occur at a larger width.

In addition to a larger width, the images of welds in workpieces with a gap differ from those without a gap by the occurrence of a more or less protruding extension, often having a relatively low brightness. In some workpieces where the extension is large, the right edge of the extension appears as a vertical line. The vertical contour part ends abruptly where the arc burns a crater in the edge of the workpiece part. The vertical line and crater appear as an indentation in the right pool boundary. The indentation is more pronounced when the travel speed and the voltage are high.

**Workpieces with a 2 mm gap**

Most workpieces of the series with a 2 mm gap are welded with the ratio of wire feed rate to travel speed of 11.67 : 1. Without loss of material and a flat weld surface, the throat thickness would be 3.02 mm.

The quality of most welds in the series having a gap of 2 mm is rather bad. It was difficult to produce a weld of acceptable quality without weaving motion when the gap is 2 mm. This series of experiments was therefore abolished except for the study of the effect of the gap.

The resulting images confirm what we already found in the series with a 1 mm gap, i.e. that the gap comes with a characteristic indentation with a vertical edge at one side (see figure 4.31). This feature is more pronounced in the workpieces with the larger gap.

![Figure 4.31](image)

*Figure 4.31*

Pool image of workpiece 127 (gap = 2 mm).

### 4.3.3 Evaluation of the feasible domain

This section discusses the location of the boundaries of the feasible domain in the space of image features. Different boundaries can be distinguished, each characterized by the type of weld defect it delineates.

A study of the occurrence of weld defects will also show the reference value of the pool geometry, i.e. what geometry is to be attained to obtain a weld with an acceptable quality.

In the experiments with fillet welds the defects encountered are: undercut, lack of fusion and a too large contact angle. The last two defects have a
convex weld surface in common. Because this gives the weld the same appearance, welds with a convex surface are classified in one category of defective welds.

**Undercut**

Undercut is one major defect occurring in our experiments. An indentation of the side contour just above the torch centre is not recognized in the images. This may be caused by the disadvantageous position of the camera for recognizing a width reduction. The projection of the unfilled part of the crater in the image is very narrow, see figure 4.32. No other local features typical of the workpieces with undercut have been identified in the grey-level images or the averaged pool shapes.

The averaged shapes of the pool of the workpieces in which undercut occurs all have in common that the width of the pool is very large. We have seen that the amount of filler metal is sufficient for a weld with a flat surface and a throat thickness of 2.345 mm. This theoretical weld has a width of 4.69 mm $\approx 103$ pixels (corrected for thermal shrink of the weld). When we assume the weld surface to be flat or convex, undercut will appear because of insufficient filler metal when the width of the crater in the workpiece (which is the width of the area that has been liquid) exceeds 103 pixels.

The feature MaxWidth (defined in section 4.3.2) can be compared with the measured width of the crater or weld. This is done in figure 4.33. The dashed line in this figure indicates the projection of the camera (1 mm $\approx 21.5$ pixel). From this figure we conclude that we may assume the feature MaxWidth to be the width of the crater in the workpiece.

So, with the assumptions made above we expect undercut to be present when the measured MaxWidth exceeds 103 pixels.

All workpieces without gap in which undercut is present, have a MaxWidth above this value, see figure 4.34. At intermediate travel speed, undercut appears above a higher value of the width. There, a concave weld surface is found, which is not found at very low or high travel speed.

**Convexity of the weld surface**

The convexity in our experiments is not caused by the shape of the seam profile, but appears when the voltage is relatively low. It is therefore not surprising that no typical feature is recognized for convexity.

Two defects can be distinguished in the workpieces with a convex weld surface: at lower values of the travel speed lack of fusion occurs and at
The feature MaxWidth compared with the width of the weld (in mm). The dashed line represents the projection of the camera.

higher values of the travel speed a too large contact angle occurs. The results confirm that convexity of the weld is present when the pool width is relatively low. In addition to this, it appeared that the images of the pool were relatively dark.

Weld convexity can be recognized by evaluating the width of the pool. All welds with a convex surface have a value of MaxWidth below 103 pixels, see figure 4.34. The reduction of the pool width with respect to the nominal shape is not substantial. It looks as if there is a lower limit for the width of the pool. At that limit, lowering the voltage will worsen the weld quality, but will not reduce the pool width. On the other hand, increasing the voltage will improve the weld quality and increase the width.

The darkness of the pool can be used for detecting weld convexity by evaluating the number of edge points detected. The number will be rather low because of the supercooling caused by the low value of the voltage (see section 4.3.2).

At all travel speeds a good quality can be obtained with a MaxWidth of about
Figure 4.34
The feature MaxWidth as a function of the travel speed.

- o  welds with acceptable quality,
- - questionable quality,
- u  undercut,
- x  convexity.

103 pixels. However, both at a travel speed above 150 cm/min and below 40 cm/min the boundary delineating undercut is very close to the line MaxWidth = 103 pixels. It seems better to produce welds with MaxWidth ≈ 100 pixels. The small difference between this practical value and the theoretical value of 103 pixels can be explained by the loss of material through spatter and evaporation, or through the hypothesis that a fillet weld of acceptable quality and with the dimensions used in the experiments is always slightly convex.

Other features that can be used for recognizing undercut and convexity are WE-Width and Fl-Dist defined in section 4.3.2. Observing the differences with the nominal pool shape (figure 4.19) yielded that the largest deviations from the nominal pool shape occur at the wire end (WE-Width). A weld with a good quality can be obtained when WE-Width ≈ 90 pixels. A disadvantage of using the feature WE-Width is that this value of 90 pixels has not a direct
relation with the design throat thickness as is the case when using the feature MaxWidth.

4.3.4 Discussion

This section goes further into the assumptions made in the beginning of this chapter.

Figures 4.22 - 4.27 all show that there is a systematic relation between the controlled process parameters and the pool geometry. The width of the pool increases with the voltage at constant travel speed and the slenderness increases with the travel speed at constant voltage. However, it must be mentioned that there seems to be an unknown disturbance that affects the pool geometry. This is probably due to unintended variations of one or more parameters that are supposed to be constant in the experiments. One of these unintended variations may be found in the surface condition of the workpieces. The relation between the pool geometry and the operating parameters is such that the geometry can be modified by adjusting the operating parameters. A wider pool will be achieved by increasing the voltage, and a more slender pool shape will be achieved by increasing the travel speed. These relations will be explained as follows.

A large voltage will cause the arc to be wide, which causes a large crater in the workpiece and thus a wide pool. At a large travel speed one can expect the arc to be at the front of the pool, which gives the pool a low slenderness. However, the wire feed rate is increased in proportion with the travel speed in our experiments. Hence, the current is high at a high travel speed, and the heat penetrates deep into the seam. As a result the pool is pushed forward at the root, which makes the pool slender. At low values of the travel speed and wire feed rate a dent is found in the pool front boundary. This is because the root is hardly penetrated. The dent appears when the wetting by the pool at the root is running behind the wetting of the workpiece a little higher up in the seam, see figure 4.35. It seems as if two areas of penetration exist, one on each workpiece face. A similar effect is found in the end crater of the weld, see figure 4.36. More experimental work has to be done to determine the influence on the pool geometry of other input parameters like other ratios of travel speed to wire feed rate and the relations for other seam types.

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1 The end crater of a weld is the pool that solidified after the moment of switching off the power source at the end of a weld.
The assumption formulated in section 4.1 is that it is possible to identify some disturbances from the deviation of the pool geometry, given the settings of the controlled parameters.

In our experiment, the gap width can be considered a disturbance of the process.

The presence of a gap introduces a specific local feature of the pool contour: an indentation of the pool contour with a vertical demarkation line. This can be identified without knowing the settings of the controlled parameters. Recognition of the presence of a gap is important because this requires a different setting of the process to produce a larger weld.

The controlled variations of the input parameters voltage and travel speed may also be considered as disturbances of the welding process. The deviations of these parameters from their nominal value can be recognized by evaluating the width and slenderness derived from the images.

We also made the assumption that much of the relevant information is contained in the shape of the pool as represented by the set of edge points detected. In the experiments we have seen that additional information is found in the brightness of the pool near the border. At low values of the voltage, the pool is relatively dark and this obstructs the edge detection. This means that when the pool is relatively dark, the number of edge points detected is low. Hence, the information that the pool is dark still is in the set of edge points. However, the information on the slenderness and width is lost when too few edge points are detected.

Another assumption was that the approximation with polynomials is information preserving.

The results showed that the approximation is sufficient for recognizing the influence of the voltage and travel speed.

The appearance of a 'dent' in the pool front line is not described by the polynomials. However, the presence of the dent influences the approximation, by making it wide and flat. So, some information is
The appearance of an indentation with a vertical edge at the presence of a gap cannot be recognized with the polynomials. For the recognition of the presence of a gap, another type of approximation is desired. A suggestion for this is found in the polynomial approximation with the Hough transformation described in section 3.2.2.3. The presence of a gap will lead to two local maxima in the parameters space of the right side boundary, one caused by the vertical edge of the indentation and the other by the (curved) crater in the workpiece.

### 4.4 Other experiments

In addition to the experiments described in section 4.3 using fillet welds, experiments were also conducted exploring the usefulness of weld pool measurements in welding V-grooves. These experiments aim particularly at:
- the penetration at the root,
- the formation of undercut.

In these experiments the parameters were not varied in a systematic way like in the experiments with fillet welds, but were set to obtain welds with and without specific defects.

The experiments were conducted using the same facility as the experiments with fillet welds. The facility comprises a horizontal table and a carriage with horizontal axis of motion. On the carriage a support is mounted holding the GMA torch and the camera. The support allows manual adjustment of the torch and camera position. The carriage is moved over a workpiece with a constant speed, without superimposed weaving motion.

A conventional GMA welding power supply unit was used (Philips type 
PZ 2325/31). We used a solid copper clad welding wire: \(0,9\) mm quality SG2.

The shielding gas used is a mixture of 80 % Ar and 20% \(CO_2\), and is supplied during welding with a rate of 12 l/min.

A workpiece fixture for butt-joints which can hold workpieces of up to 10 mm thick sheet metal was used. It is mounted on the table and aligned so the axis of the seam and of the carriage are parallel.

The torch and camera are mounted with their axes in the vertical plane through the seam axis in the horizontal workpiece. The torch points forward, making an angle of 80° with the seam axis. The camera points backward, viewing the pool from the front. Its orientation is such that the torch axis is projected on the vertical axis of the camera. The camera and torch axes form an angle of 60°.

The welding input parameters (including the travel speed) were kept constant during each welding run.
Pool measurements were performed on-line using the auxiliary digital hardware described in section 3.3.2. In addition, the images were evaluated visually and registered with a video recorder.

In the vision system analyzing the images automatically, instead of detecting the position of the wire end in the image as in the experiments with fillet welds, the centre of gravity of the arc region is determined. We defined the arc region as the region that exceeds a certain intensity. This takes less computation time on our system than detection of the wire end.

Two feature measurements were implemented:

- the width of the pool and
- the (centre of the) arc to pool front distance.

These measurements were performed with time intervals of about 1.4 s.

A butt-joint was produced in strips with a thickness of 6 mm and a V-groove preparation, see figure 4.37. This is obtained by placing strips of 400x50x6 mm in the fixture. The strips are made of commonly used mild steel (Fe360). Prior to welding dust and oil are removed from the strips as this might become visible in the image at the border of the pool hindering recognition of the pool contour.

Under the conditions described in the foregoing the critical root run of the workpiece was studied.

The penetration at the root must be strong enough to avoid lack of fusion at the root, but on the other hand the heat input may not be too much, as this will cause a bulging back face of the weld.

At excessive values of the heat input, the process will be burning through the workpiece.

The root pass is welded with a relatively low wire feed rate, which causes the material transfer to be in dip transfer mode. In this mode the surface tension is the main force acting on the weld pool. This surface tension must avoid a bulging weld back face.

When a good weld was produced, there was a typical so called key-hole present at the front of the pool. Seen from above this is an evenly curved concavity at the front of the pool. A concave contour part is pulled into the pool front surface spanned between the workpiece parts, because this has a sharp convex curvature in the plane of the seam and torch axes. The convexity is sharp because the workpiece is completely penetrated, while the pool back side is not bulging below the workpiece. The concave contour part
can be slightly wider than the gap because the workpiece has been penetrated completely. In this case the concave contour part and the gap form the key-hole shape.

The presence of the key-hole appearance leads to a characteristic shape of the pool in the images captured, see figure 4.38. The pool front has two leading extensions with distinct corners. Between the corners, the pool front line has a concave curvature. Recognition of the corners is interesting for the distance between them might be an indication of the gap width between the workpiece-parts. The gap width is an important parameter influencing the root weld. Attempts to automatically recognize the corners and concave curvature were not successful. The irregular movement of the pool over the workpiece and spatters disturb the recognition. Further development is necessary to obtain a successful and reliable recognition.

By visual evaluation of the images we found in both the case of lack of fusion and the case of excessive penetration that the pool front has no concave curvature. At excessive penetration, the pool is bulging which reduces the pool surface curvature in the plane of the seam and the torch axes and with that the concave contour part seen from above. At incomplete penetration, the pool front is not pulled to the root and no concave curvature is present either. We found that when the heat input to the workpiece is low (low voltage), the pool develops a round shape. When the heat input is high (high voltage), the pool develops a slender shape; the arc to pool front distance is low. In workpieces where the voltage was too high, burning through occurred (excessive penetration). The weld process was halted manually when this
occurred. The shape of the pool became slender\(^1\) and the arc to front distance reduced significantly just before burning through from about 30 pixels to about 10 pixels. In workpieces with a good penetration and those with lack of fusion the measured arc to front distance was always larger than 30 pixels. It was concluded that the arc to front distance is related with the occurrence of burning through. Unfortunately, burning through takes place within about 1 s, which makes on-line analysis with our system impossible. However, the reduced arc to front distance could be recognized visually and confirmed by measurements in occasionally well-captured images.

In the images of workpieces with undercut no typical local feature was found indicating the presence of this defect. However, the measured width was relatively large for those workpieces. We suppose that the measured width together with the material balance will be of interest. This result does not differ from that of the experiments with fillet welds.

We must note that there is a strong resemblance between the results obtained for the fillet welds and those for the V-groove. In both cases a slender shape of the pool indicates there is a relatively deep penetration at the root and a more round shape of the pool front indicates insufficient penetration.

### 4.5 Suggestions for control

This section presents suggestions for control of the welding process using pool measurements. The principles of operation sketched below are based on the results described above.

**Fillet welds**

In section 4.3.3 we found that a fillet weld with an acceptable quality is obtained when the gap in the workpiece is zero and when the pool has a MaxWidth of about 100 pixels. This value is twice the design throat thickness\(^2\) of the weld, corrected (-3\%) for some loss of material. The correction is supposed to be necessary for loss of material through spatter, evaporation, or a slightly convex weld surface.

The wire feed rate must be set so as to supply just enough material for the weld. The correction for loss of material mentioned above can also be incorporated in the wire feed rate. In that case the reference value for

\(^1\) Here, with a slender shape, the overall appearance of the pool is meant, which not necessarily implicates a high value of the already defined feature slenderness.

\(^2\) The design width of a fillet weld is twice the design throat thickness. In manufacturing a fillet weld is specified by its throat thickness rather than by its width.
MaxWidth is twice the design throat thickness of the weld without correction factor.

Section 4.3.4 showed that the desired width of the pool can be achieved by adjusting the voltage.

This yields a control loop which is supposed to correct for certain disturbances.

In section 4.1 it is pointed out that in general, the presence of a disturbance requires adjustment of the reference values of the pool geometry features, and that the nature of some disturbances might be such that it suffices to restore the pool to its previous shape.

A gap in the workpiece is an example of a disturbance which requires adjustment of the reference value of MaxWidth. In the control scheme the presence of a gap must be watched. Section 4.3.2 reported that the presence of a gap causes a typical feature: an indentation with a vertical edge at one side. When this feature is detected indicating the presence of a gap, the reference values (set points) for the width and the amount of material deposited must be raised.

An example of a disturbance that can be compensated without changing the reference values is the presence of a heat sink in the workpiece (a workpiece with a larger thickness than expected for instance). When a heat sink is present, the desired weld quality is expected to be obtained without altering the reference value of MaxWidth.

So far no technological knowledge is required for choosing settings of the input parameters. Only the design throat thickness is a set point of the control function. However, the travel speed yet is to be set. No solution is found for this yet, because no speed limit was found in the experiments.

In practical applications one wishes to produce a weld as fast as possible. Therefore an upper limit for the travel speed has to be explored. In our experiments we have not encountered such a limit. Further research on this is desirable.

**V-groove root run**

Section 4.4 yielded that the penetration of the root run in a V-groove is acceptable when a characteristic concave contour part with two distinct corners appears at the pool front (figure 4.38). This shape appears neither at excessive nor insufficient penetration. The disappearance of the concave contour part cannot be used to control the penetration because the direction of the correction cannot be determined from that feature.

A shape property that can be used is the overall slenderness. A feature characterizing this property is the arc centre to pool front distance. It is expected that the penetration will be correct when this feature is properly controlled. The feature is very similar to the wire end to pool front distance, which is the feature used by NADEAU et al. (1988) in controlling the quality of a V-butt joint, produced with the GMA process. They claimed that the camera must make an angle of about 15° with the seam axis, which implies
that the measurement tends toward measurement of the depth of the pool extension penetrating the workpiece.

With our camera position, which is higher up, it might be possible to determine the gap width from the distance between the corners. The gap width is a major source for process disturbance of this kind of weld.

**Seam tracking**

Suggestions for seam tracking with weld pool image measurements were already presented in section 4.2. Control functions are the torch height, based on measurement of the wire extension length, as well as the lateral position of the torch over the seam, based on measurement of the asymmetry of the pool.
Appendix 4.A Welding conditions of the experiments with fillet welds

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Chapter 5
Conclusions

A vision based system for measurement of the weld pool geometry in GMA welding has been developed. The system observes the pool by registering the radiation emitted by the pool in the presence of the arc. The excessive intensity of arc radiation relative to the intensity of the radiation from the pool can be reduced effectively using optical filtering within the spectral band determined by the sensitivity of a solid state camera. This type of camera is sufficiently small and light to be mounted on a robot end effector. Images in which the contour of the weld pool can be recognized are captured in welding of low-alloy steel products. Weld pool observation is feasible in the presence of the arc in the dip transfer, globular transfer and spray transfer regimes. Recognition of the pool contour is not possible when the arc is too intense in comparison with the radiation emitted by the pool. This is for instance the case in:

- GTA welding of stainless steel products (high arc temperature and low emission coefficient),
- welding of aluminium products, (low pool temperature)
- pulsed arc welding (GMA) (high arc intensity during pulses).

In pulsed arc welding, the recognition of the pool is supposed to be possible by using a camera with a shutter that closes during the high-current periods.

In the images captured the pool has not a constant brightness. The brightness of the pool diminishes towards the border. This is caused by differences in surface temperature and differences in reflection of arc radiation. The brightness contrast at the border of the pool is not constant either. This is caused by blur due to motion and differences in the temperature gradient. Recognition of the rear boundary of the pool is hardly possible with the system.

When welding with a very low voltage the intensity of the pool at the (front) border is significantly lower than when welding with an intermediate or high voltage. Supercooling seems the most attractive explanation for this.

In the image the shape of the pool as well as the position of the wire end are considered to contain useful information. In welding under different conditions, different shapes of the pool were registered. The pool shape is subject to various temporal fluctuations of a local nature, that are considered to contain no useful information. The features to be derived from the image must therefore be based on an averaged pool description. The averaging process must be performed both in the spatial domain and in the time domain.
A method for analysis of weld pool images has been developed. The nature of the weld pool images is such that thresholding will not uncover the geometry of the pool. The pool contour is detected using image segmentation based on (conventional) edge detection. Edge detection locates not all points on the contour, it leaves breaks, and it locates spurious edge points as well. Edge detection is considered to locate edges with an accuracy of ± 1 pixel. Contrast edge detection has a better selectivity than (conventional) edge detection. Contrast edge detection requires no extra processing time on our hardware. However, it detects the edges 1-3 pixels shifted outside the pool.

The system analyses the global shape of the pool and disregards minor contour irregularities by approximating the pool with 3 polynomials, each valid in a distinct area:

- a 2nd degree polynomial approximating the left side of the pool,
- a 2nd degree polynomial approximating the right side of the pool,
- a 4th degree polynomial approximating the front side of the pool.

The approximation is an intermediate result in the study of relevant features. The polynomials are obtained by least squares approximation. This method is very accurate, but not robust against spurious edge points. Therefore, it must be preceded by a selection of the pool edge points from the set of detected edge points. The selection is performed by recurrent tracing. In this approach, the knowledge is used that the shape of the pool differs not much in successive images of one weld. For generating polynomials in the first image of a series, where no previous shape information is available, the Hough transformation is used.

The Hough transformation is an alternative for recurrent tracing and least squares approximation. An algorithm for recognizing 2nd degree polynomials has been developed and implemented in such a manner that it requires about the same processing time as the recurrent tracing and least squares approximation method. The Hough transformation is more robust against spurious edge points, but it is less accurate. For this reason it is only used for the first image of a series. However, in the experimental exploration one image feature has been encountered that cannot be represented by the polynomial approximation and for which the Hough transformation seems to be more appropriate.

Determination of the side approximations and the wire end position can be established with our system in about 240 ms including the capture of the image. Both conventional and contrast edge detection could be implemented by analogue electronics. This gives true real-time performance (= at the rate of the video signal from the camera). However, a digital system is more flexible as prototype.

The system is intended for control of weld quality. The quality of the weld cannot be determined directly by weld pool measurements. However, pool measurements are valuable when disturbances can be detected and identified that cannot be measured by other means.

A limited number of experiments have been carried out to verify that the
measured pool geometry depends in a systematic way on the process parameters and that process disturbances other than tracking errors can be identified. The case of tracking errors has not been considered because several sensor systems (mostly less complex than sensors used for weld pool measurements) already are commercially available for the seam tracking function.

In experiments with fillet welds three input parameters have been varied: the wire feed rate, the voltage and the gap width. The travel speed is increased in proportion with the wire feed rate. Features of the pool identified as important are:

- the width,
- the slenderness,
- an indentation of the contour, see figures 4.28 and 4.29.

Obvious features like wire stick-out length and asymmetry of the pool are not evaluated because these are only of interest for the seam tracking function. The width can be used to identify undercut and weld convexity. The width can be controlled with the voltage. Three slightly different features are evaluated all indicating the width. One of these, the maximum width of the pool equals the width of the weld. For this feature, a set point can be calculated with which undercut and weld convexity can be avoided.

The slenderness responds primarily to the travel speed. In the experiments no defective conditions occurred that could be identified using the slenderness. The indentation is typical for the presence of a gap.

Experiments with the root run of a V-butt joint yielded:

- The width of the pool is of interest in identifying undercut.
- A correct root penetration can be recognized by the presence of a concavity of the pool front.
- The occurrence of burning through in a V-butt joint is preceded by a significant reduction of the wire end to pool front distance. This distance seems appropriate for controlling the root penetration in a V-groove weld.

The results of image analysis are such that it shows potential for application of the system in process control.
Samenvatting


Voor het MIG/MAG lassen (het veel toegepaste booglasproces met een afsmeltende elektrode in de vorm van een draad) is een systeem ontwikkeld dat het lasbad waarneemt met een CCD-camera die de straling uitgezonden door het lasbad opvangt. Tijdens het waarnemen hoeft de boog niet te worden verzwakt of kortstondig te worden onderbroken. De hoge intensiteit van de boogstraling, die lasbadwaarneming bemoeilijkt, wordt voldoende onderdrukt door toepassing van een optisch filter.

Bij het lassen van proefstukken zijn met het systeem beelden verkregen waarin de contour van het lasbad herkenbaar is. Lasbadwaarneming is haalbaar gebleken bij het lassen van laaggelegeerd staal in het kortsluitboog gebied, het globulaire gebied en in het sproeiboog gebied.

Een beeldverwerkings-computer analyseert de opgenomen beelden. Programmatuur is ontwikkeld waarmee de geometrie van het lasbad geanalyseerd wordt. Bestaande systemen voor lasbadmeting zijn alle gebaseerd op drempeling (thresholding) van het beeld. Gebleken is dat drempelen van de verkregen beelden niet een voldoende nauwkeurige benadering van de ware contour van het lasbad oplevert. De beeldverwerking in dit onderzoek is daarom gebaseerd op randherkenning (edge detection).

Het lasbad-meet-systeem is bedoeld voor beheersing van de laskwaliteit door aanpassing van de toortspositie (gewoonlijk met naadvolgen aangeduid) en aanpassing van de lasparameters. Het systeem is getest met een beperkt aantal experimenten. Hierbij is niet gekeken naar positioneerfouten, omdat voor het naadvolgen reeds verschillende sensorsystemen op de markt zijn (veelal minder complex dan het lasbad-meet-systeem). De resultaten van de experimenten bieden uitzicht op toepassing van het systeem bij automatisch lassen.
Nawoord

De ontwikkeling beschreven in dit proefschrift vindt zijn oorsprong in het door de interfacultaire werkgroep 'Industriële Robots' uitgevoerde onderzoekprogramma 'Flexibele Automatisering en Industriële Robots' (FAIR). In deze werkgroep wordt deelgenomen door de vakgroep 'Produktietechnologie en Automatisering' (WPA) van de faculteit Werktuigbouwkunde en de vakgroep 'Meten en Regelen' (ER) van de faculteit Elektrotechniek, beide van de Technische Universiteit Eindhoven (TUE). Het onderzoek van FAIR heeft zich vanaf het begin gericht op flexibele automatisering van het booglassen omdat dit een voor robots jonge en sterk opkomende toepassing was.

Het onderzoek werd gestimuleerd met een subsidie van de door het ministerie van Economische Zaken ingestelde onderzoekstimuleringscommissie 'Flexibele Automatisering en Industriële Robots' (FLAIR). Met deze subsidie werd een verbreding van het onderzoek mogelijk, hetgeen onder andere resulteerde in de onderzoeksoordracht waarop ik in februari 1984 bij de TUE (toen nog Technische Hogeschool Eindhoven genaamd) in dienst trad.

Deze opdracht luidde: "Onderzoek en evaluatie van verschillende sensorprincipes voor het detecteren van vorm en plaats van lasvoegen bij het booglassen met bijzondere aandacht voor optische sensoren werkend op het principe van doorsnijding van de lasnaad door een lichtvlak (z.g. profielsensors)".

Na verkennend werk werd ervoor gekozen het onderwerp lasbadobservatie nader te bestuderen. Een voorstel tot ontwikkeling van een systeem voor lasbadobservatie werd opgenomen in het voorstel tot realisering van een 'Flexibele Assemblage- en LasCel' (FALC) van FAIR.

Met het in dienst treden bij het toenmalige ITP-TUE/TNO, dat nu opgenomen is in het 'Instituut voor Produktie en Logistiek TNO' (IPL), in augustus 1986 werd ook dit instituut bij het onderzoek betrokken.

Medio 1987 ging het onderzoekproject FALC van start dankzij een subsidie van het 'StimuleringsProjectteam Informaticaonderzoek Nederland' (SPIN), waarin FLAIR inmiddels was ondergebracht. Binnen het onderzoekproject FALC vormde lasbadobservatie een op zichzelf staand onderdeel.

De aanschaf van een snelle en kostbare beeldverwerkingscomputer werd mogelijk door combinatie van middelen uit het FALC project en uit het STW-project 'Snel naadvolgsysteem voor de besturing van robots' dat door ER naast het FALC-project werd uitgevoerd.

De ontwikkeling van de software voor verwerking van de beeldinformatie is tot stand gekomen in een samenwerking van IPL en ER, waarbij verschillende afstudeerders een bijdrage leverden.

De experimenten genoemd in hoofdstuk 4 van dit proefschrift zijn uitgevoerd in het toenmalige Metaalinstituut TNO te Apeldoorn, dat nu deel uitmaakt van het IPL, waar ruime lasexpertise en geschikte experimentele faciliteiten aanwezig zijn.

De vele personen bij de genoemde organisaties en daarbuiten, die met grote en kleine bijdragen hebben geholpen aan de totstandkoming van dit proefschrift wil ik daarvoor van harte bedanken.

Eindhoven, februari 1992
Eric Wezenbeek

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Curriculum Vitae

15 november 1956  Geboren te Breda


1975 - 1983  Studie Werktuigbouwkunde aan de Technische Universiteit Eindhoven

1980 - 1981  Student assistent aan de Technische Universiteit Eindhoven


1984 - 1986  Wetenschappelijk Assistent bij de vakgroep Meten en Regelen van de faculteit Elektrotechniek van de Technische Universiteit Eindhoven

vanaf 1986  Project Ingenieur bij het Instituut voor Produktie en Logistiek TNO (IPL) te Eindhoven.
Stellingen behorende bij het proefschrift

A system for measurement and control of weld pool geometry in automatic arc welding

H.C.F.M. Wezenbeek

- 1 -
Sensoren voor booglassen worden slechts op beperkte schaal toegepast omdat sensorgestuurde lassystemen veelal slechts voor één type variaties ontworpen zijn, terwijl er behoefte is aan systemen die in uiteenlopende situaties correct kunnen reageren. Aandacht dient daarom uit te gaan naar een meer intelligente verwerking van door sensoren geleverde informatie.

Hoofdstuk 1 van dit proefschrift

- 2 -
De drijfveer voor ontwikkeling van sensoren voor booglassen is veelal kwaliteitsbeheersing. In de toekomst zal kwaliteitsborging in toenemende mate de drijfveer worden voor gebruik van sensoren bij het automatisch booglassen.

- 3 -
De meeste systemen (hardware en software) voor verwerking van videobeelden in de industrie worden op de markt aangeboden als universeel toepasbaar. Dit is een teken dat beeldverwerking een nog niet uitontwikkeld vakgebied is.

- 4 -
Bij CCD-camera's wordt veelal een spectrale gevoeligheids-karakteristiek gegeven die ontleend is aan eigenschappen van het chip-materiaal silicium. Door dotering van het silicium tijdens de chipfabricage wijkt de werkelijke spectrale gevoeligheid af van de opgegeven karakteristiek.

Hoofdstuk 2 van dit proefschrift

- 5 -
Bij zeer lage waarden van de lasspanning treden bindingsfouten op. Dit ondersteunt de hypothese dat onderkoeling de oorzaak is van de lage beeldintensiteit van de voorzijde van het lasbad.

Hoofdstuk 4 van dit proefschrift
Inoue vermeldt dat men de drempelwaarde toegepast in de beeldverwerking zorgvuldig moet kiezen om de juiste lasbadbreedte te meten. De te kiezen waarde is bovendien afhankelijk van de lasparameters. Dit is een aanwijzing dat boogstraling een grote rol speelt in de beeldvorming.


Hoofdstuk 2 van dit proefschrift

Drempelen is een eenvoudiger beeldverwerkingstechniek dan randpuntdetectie en levert in veel toepassingen sneller meetwaarden op maar kan ook tot foutieve beeldinterpretatie leiden. Randpuntdetectie biedt meer mogelijkheden om bij de beeldherkenning ook de waarschijnlijkheid van het resultaat aan te geven.

Hoofdstuk 3 van dit proefschrift

Ter verhoging van de verkeersveiligheid wordt gepleit voor het voeren van groot licht overdag door automobielen. Deze maatregel maakt impliciet gebruik van het feit dat ook in de menselijke perceptie beeldherkenning gebaseerd op drempelen een snelle respons oplevert. Maar ook hier kan dit gepaard gaan met foutieve beeldinterpretatie, waardoor deze maatregel zal leiden tot een verlaging van de veiligheid van de kwetsbare weggebruikers.

Voor het naadzoeken en naadvolgen met sensoren zijn cartesische robots geschikter dan knikarmrobots.

Uit de matige standaardisatie en documentatie van bij afstudeeronderzoek geschreven software blijkt dat studenten er niet van doordrongen zijn dat creaties van ingenieurs zelden op zichzelf blijven staan.

Het verdient aanbeveling om besluitrobots te ontwikkelen voor politieke processen. Met deze robots zal men niet alleen publieke interesse kunnen terugwinnen, maar ook grote bezuinigingen kunnen realiseren.