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Dufour, M.; Cielo, P.; Nadeau, F.

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A REAL TIME VISION SYSTEM FOR ROBOTIC ARC WELDING

M.Dufour *, P. Cielo *, F. Nadeau *

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ABSTRACT

Fast real-time vision systems for robotic arc welding have been developed and successfully implemented for seam tracking and adaptive welding functions (mass and heat balance). Typical seam tracking errors of 0.3 mm were achieved for single pass type joints (lap, butt, fillet).

In one system the weld preparation profile is first enhanced by a projected laser target formed by a line and dots. A standard TV camera is used to observe the target image at an angle. The rapid pre-processor developed by NRCC and Leigh Instruments Inc as part of the visual aid system of the space shuttle arm is then used to analyse the video signal in real time.

Another active vision system was developped in order to process more complex types of joints. It is based on laser flying spot scanning with a mechanically synchronized scanning system for projection and range finding.

With a passive system the weld preparation temperature is mapped in front of the arc using a fiber optic bundle. The temperature profile of the joint is then analysed by a micro-computer.

Because no single sensor is universal, the combination of active and passive systems on the same robot arm allows the arc welding robot to perform complex tasks.

Furthermore, the use of an off-line programming system greatly simplifies the programming task of an arc welding robotic workcell equipped with vision sensors.

1- An integrated robotic arc welding work cell

The arc welding automation problem for small to medium batch applications could only be solved by the development of adequate real time adaptive welding techniques and of adequate off-line task planning techniques to form an integrated arc welding system.

Adaptive welding is a combination of two interrelated functions. The first one is seam tracking. Without it, automation could not go further than the blind repetition of preprogrammed actions . The torch-to-joint relative position uncertainties caused by the workpiece manufacturing, the jigging and positioning operations and the robot repeatability are large enough to cause an unacceptably high proportion of bad welds even if the selected welding parameters are appropriate to the type of joint.

The second adaptive welding function concerns the heat and mass balance of the process achieved through the real time control of the welding parameters, mainly arc voltage and current, wire feed speed and the travel speed. Optimal values of those parameters are strongly related to the joint geometry variation and also to the thermal caracteristics of the workpiece along the joint. Additional complications arrise from the close interaction that exists between these parameters. A parameter cannot be adjusted alone. Instead, a reliable and realistic model of the welding process in use is required and all adjustments should conform to this model. The main difficulty is caused by the absence of practical sensors which are able to measure directly and in realtime some critical caracteristics of the weld like the depth of penetration or the weld bead metallurgical characteristics. The parameter control relies instead on indirect measurements like the joint geometry in front of the torch or the joint side temperature. This in fact is an open loop control system as shown in figure 1.

Off-line task planning is a combination of several interrelated functions. The first function usually associated with it is trajectory planning. In general this means finding an acceptable path to welds while avoiding collision and respecting the robot and positioner work envelope. For arc welding applications, an acceptable path is also one that will keep a given weld surface-gravity relative orientation. The weld sequence should also be organized to minimize the workpiece thermal distortion and residual stress. The cycle time should be kept as short as possible to improve productivity.

The second function to be executed off-line is the gathering of the information required by the robot to perform the adaptive welding. The torch-to-joint relative position and the target welding parameters need to be defined.

It is then essential that a counter-reaction strategy be defined. At this stage of development of the technology it is utopic to think that the robot could incorporate an adequate counter-reaction strategy for every type of joints and situations and also be able to decide by itself wich one is to be applied. Instead, we need to execute that function off-line.

What we propose is a combination of those important functions. With our approach the robot is specialized for welding, not for learning. This is advantageous in cases of diversified production in small-batch production, where learn runs on a robotic station may occupy a significant portion of the working hours. For this purpose, an off-line task planning system integrating state-of-the-art CAD/CAM technology is well adapted for such task optimization. A block diagram of such a system is given in figure 2.

2. Vision applied to welding

2.1 Generalities

In order to incorporate real time modifications to the program fed into an automated welding station (trajectory and process parameters), real time sensing of the relevant weld area characteristics has to be achieved. In simplified terms, these characteristics are joint axis coordinates, joint profile characteristics (Ex: gap size for butt welds), pool geometry, and pool location with respect to the joint axis. Since these characteristics are rather simple geometrical features whose space coordinates become of relevant significance to improve the welding operation, artificial vision appears to be an essential tool for adaptive welding.

In addition, the effects of the accumulation of heat in the workpiece during the process, as well as those of heat sinks or any sources that may change the heat dissipation regimes are not always properly taken care of in the program. Small adjustments in the setting of the welding parameters are thus required to assure a sound weld.

These caracteristics of the welding process naturally direct us to the development of two main kinds of vision systems that complement each other.

2.2 Active vision

2.2.1 NRCC Camera using a projected light stripe

The analysis of the image made by the intersection of a laminar light beam with the workpiece surface as shown in figure 3 has been the basic approach for seam location and recognition. Adaptive functions such as seam tracking have been achieved through this scheme [1-2].

In order to cope with the processing time requirements imposed by the welding technology the first approach used at NRCC (IMRI) [4] has been to reduce the number of relevant features in the image from which significant and sufficient information can be obtained and used to perform the welding adaptive functions. A modular pre-processor whereby each module is dedicated to a given feature has thus been used to incorporate vision to welding systems.

The pre-processor is based on a joint development made by the National Aeronautical Establishment of the NRCC and Leigh Instruments Corporation. It works with a standard NTSC camera and was first aimed at being a visual aid to the Canadarm manipulation from the NASA Space Shuttle [5]. Each pre-processor module functions are as follows: a) the obtention of a binary image, using a preselected threshold contained within a dynamically programmable rectangular window covering a small portion of the field of view, and b) the determination of the area and of the first moment of the white level feature within the window. Image coordinates, and through simple triangulation, space coordinates of a selected feature within the field of view, are thus obtained at a rate of 30 Hz. By cleverly selecting a number of relevant features in the image, and by properly treating the expected relationships between these features, adaptive functions such as seam tracking of a variety of weld geometries including butt, lap and fillet joints can be performed. It is in this modular approach that lies the interest of the vision system for welding developed at NRCC (IMRI). It can cope with welding travelling speed requirement trends by using rather simple and proven technology.

Figure 4 shows the block diagram of the vision system developed at IMRI. As most systems, the projection unit uses a laser source and the receiver unit uses an adapted narrow band filter to eliminate the intense light noise created by the arc. The optical axes of both units are at an angle so that triangulation can be performed.

At IMRI, we have chosen to put the projection unit near the torch where it is much less affected by heat and spatters. The camera is directly subjected to the hard welding environment. However, the optical components which are directly exposed to the hostile welding environment are particularly rugged. As it is shown in figure 5, only the small aperture of the iris is exposed. An internal gaseous pressure or a small exchangeable window prevents surface contamination by fumes and spatters. This configuration is appropriate to maximize the projected light intensity from the laser source while a lot of attenuation of the image is required for the camera.

The laboratory prototype of the vision head is shown in figure 6. It could be much further reduced in size by repackaging the camera unit.

The camera image is fed into the pre-processor modules that provide area and first moments of individually selected features of the image. The microprocessor carries out logical and mathematical operations to drive the torch coordinates, change the welding parameters, and window locations in the field of view. The window locks on the selected feature, with an imposed relationship between its center and the centroid of the feature.

As an example, figure 7 shows the image sensed by the camera for a fillet joint. The windows from the four modules are superposed. The cross-hair is a representation of the computer solution. Each module gives the precise coordinates in the image plane of the surface center of a short section from one of the two lines representing the joint profile. The line equations are computed from the result of two modules. The joint position and its orientation are computed from the intersection of the two lines.

Figure 8 shows a 6 axis robot welding a fillet joint (GMAW) whose trajectory (height and lateral position) is corrected by the vision system. Typical accuracy of 0.3 mm was acheived for the lateral position of the joint.

2.2.2 NRCC - SRI Camera using a flying spot scanner with synchronized detection.

The first moment method described in the last section is not adequate to deal with the rather complex joint profile geometry that caracterizes multipass types of joints. It would certainly give part of the answer but the detailed measurement of the joint profile is still required for further analysis. The extraction of the joint profile from the camera image is a possible solution [1]. However, the use of a moving projected dot with synchronized detection [2 6 7] instead of a projected light stripe is more promising for the time being because it needs less processing power and because a much better image contrast can be obtained with the same laser light power.

Figure 9 shows the typical configuration of a geometrically synchronized scanner. It is a prototype developped by Servo-Robot Inc. (SRI)[7] in collaboration with NRCC. This principle is different from other moving dot sensors [8] in that the linear detector output is almost constant for a flat surface for a very wide field of view. It simplifies greatly the sensor output processing because the distance information is available directly. Once calibrated, the camera gives very precise results. Appendix 1 gives the specifications of the SATURN camera manufactured by SRI.

The first design step is to define a reference plane for which the detector output will be "zero". As it is shown in figure 10, any object surface not aligned with the reference plane will produce a linear detector output with the following relation if θ is small:

$$p = K \Delta y_0 = Z\theta$$

where
- p detector output
- K constant
- Z position of the object surface from the reference plane
- θ angle of the intersection of the source and detector axis at the reference plane. It is desirable to keep it small for a compact camera.

Figure 11 shows the SATURN camera mounted on a six axis robot and using a seventh axis to align the camera-torch relative position along the seam.

2.2.3 Discussion

To select a seam tracker from a moving dot or a laminar light beam type of active vision systems one has to make several considerations.

The most obvious advantage of moving dot systems is that the laser light power is more concentrated (20mw over $1mm^2$ instead of 1mm x 30mm). Thus, for the same laser source power they provide a much better image contrast of the structured light pattern over the low frequency component of the light noise generated by the arc. For arc welding processes involving high arc power and for processes such as pulsed or spray GMAW for which splatters are inexistant, the light noise low frequency component is the main source of perturbation experienced. For laminar light beam systems, this problem could be overcome by using a much higher total laser source power or by using a better image analysis algorithm. The cost of such high power laser sourse is actually prohibitive. However the semiconductor laser technology is evolving very fast and low cost lasers should be available within a few years. On the other hand, the image from a laminar light beam system is integrated for a much longer time (33 msec at 30Hz instead of tipically 130 msec for the same scanning rate) thus reducing high frequency light noise as the one created by particle-projection, fine surface irregularities (ex. grinded surfaces) or speckle.

The second main advantage associated with moving dot with synchronised scanning systems is that the detector signal requires much less processing power. This is highly desirable even if the technology trends are for a tremendous and accelerated increase in computing power at a low cost and for the development of highly sophisticated and powerful algorithms usefull for laminar light beam systems.

A laminar light beam system requires no moving parts and allows more rugged optical configuration to be used in the hostile welding environnement. Using a telecentric configuration with a small aperture iris the light beam crossing the interference filter will be parallel for both types of system. However, because of the much longer exposure time of each detecting element of the camera compared with the focused-spot detector, the aperture of the diaphragm is much smaller in the laminar-beam approach than in the moving-dot approach. This results in a larger depth of field and increased particle-projection protection (see figure 5) for the laminar-beam techniques. Viewing distances used in welding are short so a laminar light beam system requires less space. Synchronized scanning moving dot systems lose their advantage over short distance because of the mechanical size of components.

It is thought that active and passive vision systems should be combined on the same automatic welding system. The same processor used in laminar light beam active vision systems could then be used in a visible band passive vision system to measure weld puddle characteristics.

Some more advanced projected light pattern such as the projection of isolated dots obtained by a fiber-optic array [9] could also easily be added to a laminar light beam system.

2.3 Passive vision

2.3.1 Generalities

Passive systems can be divided into reflective or emissive systems, depending on wheter the observed visual pattern is produced by reflection of the ambient light from the inspected object, or wheter it is produced by direct thermal emission from the hot surface. Passive optical sensors have been used to view directly the thermal emission from the surface being welded [10-11]. The possibility to inspect in real-time the temperature of the welded materials is very attractive, because the temperature distribution around the welding pool provides an important information on the welding status. Measurable variables such as the pool shape, absolute temperature and symmetry of the temperature distribution are directly related to several welding process parameters such as joint mismatch, gap and plate thickness fluctuations, arc blow or the visco-dynamic and thermal conductivity properties of the plates. However, optical inspection by a video camera or a photodiode array operating in the 0.4 to 1.0 µm spectral range is limited to the welding pool and the surface immediately adjacent, because thermal emission in this spectral range falls abruptly at temperatures lower than 1000K. Moreover, arc-shielding is a problem in this spectral range. Operation in the longer wavelength spectral region is thus preferable in order to increase the signal-over-arc-background ratio [3]. Long-wavelength thermographic inspection during welding has recently been proposed for the thermal characterisation of the welding process [12-15].

At IMRI* a specially designed vision system has been designed from that principle [16]. Figure 12 gives a shematic view of the system.

2.3.2 Passive I.R. vision applied to GMAW.

By mapping the surface temperature of a butt joint in front of the welding torch and by adequate signal analysis, precise seam tracking was performed. As it was plotted from a computer simulation (finite element modelling), the diagram at figure 14a shows that highly visible temperature discontinuities caracterise the position of the joint. Figure 14b is the typical output from the I.R. line sensors focused along the line AA of figure 14a. The distance between the two peaks is related to the gap size. The minimum corresponds to the center of the joint. By moving the lateral torch position slightly in order to keep the two peaks at the same level, the system could equilibrate the heat input to the two plates. Using this sensor, joints as the one shown in figure 15 are easily welded.

2.3.3 Passive I.R. vision applied to PAW.

Plasma arc welding is more and more in use by the industry. It produces a very controllable arc and is particularly useful for very thin sheet welding (1mm) and for thick sheet welding (10mm) using the keyhole method. However, the parameter adjustement required to keep the process in the "keyhole" state is very difficult to perform and prevents the use of that process in fully automatic welding systems.

* with the collaboration of the Welding Institute of Canada (WIC).

I.R. vision constitutes an elegant solution to that problem. By focussing the I.R. line sensor on the joint surface from the center of the arc to the outside of the weld puddle it is possible to detect the keyhole condition as the speed changes. Figure 16 shows typical measurements made from an aluminium surface which is particularly difficult to be seen by a welder.

There is a clear signal shape difference between a melt-in condition and a "keyhole" condition. This phenomenon is explained by the fact that the gap column inside the keyhole is more emissive than the solid or liquid metal surface. The reverse situation appears for steel.

The control strategy in this case could be to use the fastest speed possible in order to keep the "keyhole" condition.

2.4 Discussion

The main interest of the passive IR approach as compared to active light-projection systems lies in the capability of the former to directly sense the temperature distribution around the welding pool. Parameters such as the pool width and cooling rate, or the overheating of one side of the workpiece produced by heat-sink or arc-blowing effects could not be monitored by active sensors which supply only morphological information.

Seam-tracking capabilities of passive thermal-imaging systems appear however to be limited to butt-welding at low speeds because of the reduced thermal-propagation rate in front of the welding pool. The integration of the thermal-monitoring capabilities of such sensors with the morphological information from an incorporated light-projection or reflective sensor would thus appear to be most convenient at the present state of the technology.

The use of the information provided by the vision systems is not a trivial problem. As it was stated earlier, there is no direct information available about the caracteristics that need to be controlled like the depth of penetration or the metallurgical properties. Instead, an open loop control strategy has to be defined. Since no working theorical model exists for most welding processes, real-time control strategies have to rely on empirical ones. Because of the large number of variables to deal with, a systematic test procedure to be executed off-line needs to be designed.

3. Off-line welding parameter planning

3.1 Generalities

Welding parameter planning is as important for the weld quality as could be trajectory planning for the robot productivity. It should then be considered as such while developing an off-line task planning system for robotic arc welding applications.

Current practice in the industry doesn't include any structured method to define welding parameters. Most of the time, parameter selection is based on the welder experience or on some documentation available within the company or from standard tables. Successive trials may be performed in some cases to adjust the parameter values. Usually one parameter is varied alone for a given test sequence.

Several drawbacks caracterize this approach. First it is human competance dependent. Second, it gives very little information about the process compared to the work it requires. For example it doesn't provide information about parameter tolerances or about quality variation related to parameter variations. Thirdly, the resulting solution may be acceptable but probably not optimised. Finally, it certainly gives no information about what kind of welding parameter variations should be performed for some concievable joint caracteristics variations.

The method proposed by Galopin and Boridy under a joint IMRI-ETS program looks promising [17]. It is a computer assisted experimentation approach based on statistical analysis of the experimental results with appropriate selection of experiment characteristics. It is a systematic approach in that all aspects of the experiments are considered: geometry variation of the joint, welding parameter variations, material property variations and also all the quality criteria.

3.2 A systematic method for welding parameter selection.

3.2.1 Experiments characteristics definition

Even with simple types of joints many variables have to be considered if usable results are to be obtained. One may have to make a selection in order to keep the complexity of the analysis within some reasonable figures. For example, a butt joint from thin metal sheets with shear cutted sides experiment should consider the following variables:

1- gap size
2- alignement errors
3- voltage variation (GMAW)
4- wire feed speed
5- advance speed

It is then desirable to restrict possible variations of these parameters to some probable values. Variation margins should however be wide enough to include even some unacceptable quality results in order to give an operational knowledge of the process dynamics. For example, the gap size variation limits for a butt joint may be computed from the workpiece tolerances and other associated dimensional uncertainties and the voltage variation limits may be based on standard tables.

Using the computer, it will then be possible to define the caracteristics of the experiments by randomly combining the selected welding parameters. This is the only way to produce workable results from a limited number of tests when there are many variables. Obviously, the greater the number of experiments the better will be the reliability and the better will be the resolution of the empirical model that will be obtained from the analysis.

3.2.2 Experiment results analysis

Some quantifiable quality criterias first need to be defined. For the first welding pass for example, the depth of penetration should certainly be considered. One may also be interested by the size or the number of inclusions.

A statistical analysis of the results may then be performed. Polymonial regression curves are computed to relate the quality with the welding parameters. Depending on the number of experiments and on the number of variables, regression factors of the first, second or third degree will be available.

Using these multidimensional curves, it will then be possible to determine if some variables are uncorrelated to the weld quality. It will be possible to find maxima from the multidimensional field or to determine what new experiments to perform in order to find a "quality" maximum.

The results from the analysis are of great value for a real time adaptive welding system. From the statistical analysis, a multidimensional volume in which the weld quality is found acceptable can be selected thus providing the welding system with a reliable counter-reaction model instead of only some target welding parameter values.

CONCLUSION

There is no single sensor that could provide all the information required for adaptive welding. A possible solution is to combine active and passive sensors within the same vision system.

It has been demonstrated that the vision head of an active vision system based on the projection of a laminar light beam can be packed in a small volume while being particularly well adapted to the welding environment. For simple types of joints (laps, butt and fillets), image analysis using a simple and fast algorithm is possible.

For the time being, moving-dot active systems are more advantageous because they need less processing power and a smaller laser source. This contributes to produce a lower cost system. A state-of-the-art commercial product has been built using such a method.

With the recent introduction on the market of long wavelength (5 μm) optic fibers it is now possible to monitor the temperature down to about 200°C inside and surrounding the welding pool. A rugged industrial prototype has been built at IMRI and successfully used for seam-tracking butt joints and to measure weld puddle size and position for GMAW and GTAW, and to detect "keyhole" state for PAW.

We have proposed a practical solution for the selection of welding parameters. The method gives high level information which would enable efficient real time adaptive arc welding.

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APPENDIX 1 - CHARACTERISTICS OF SRI SATURN CAMERA

Operating wavelength	830 nm
Field of view	10 mm x 10 mm
Depth of field	100 mm
Magnification	1,5
Scanning frequency range	10 to 100 Hz
Laser power	20 mW
Maximum welding current tolerance	500 A
X and Y precision (at a range of 150 mm)	± 0,2 mm
Overall dimensions	100 x 60 x 60 mm
Overall weight	800 Gr

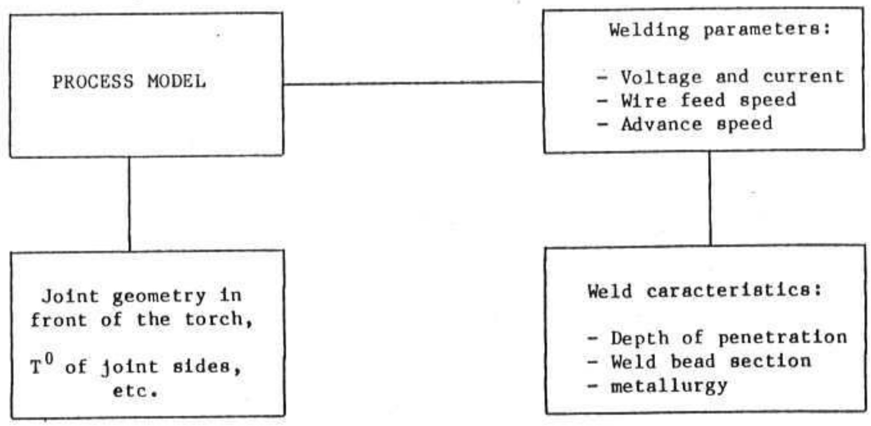


FIGURE 1 - Adaptive welding using an open loop strategy

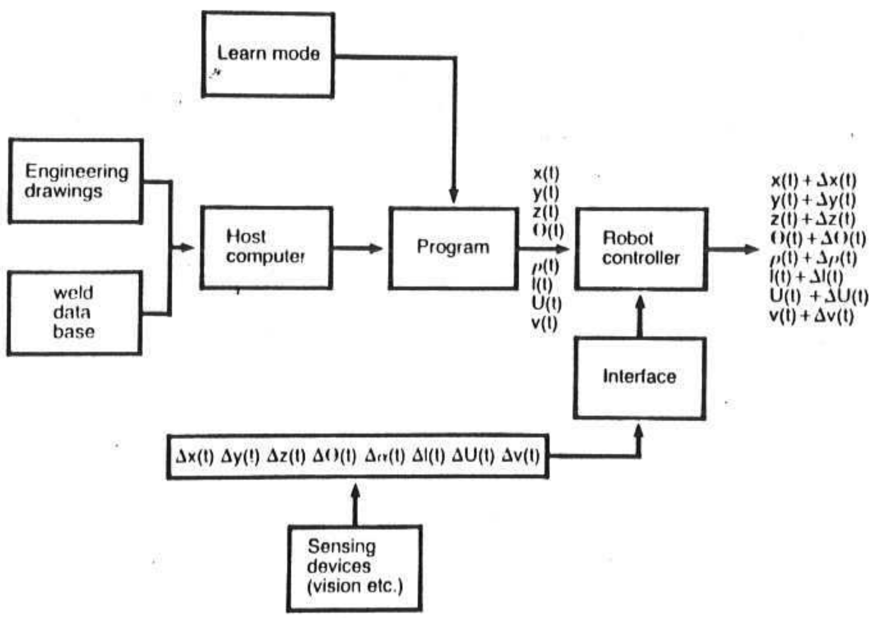


FIGURE 2 - Block diagram showing an ideal integrated automatic welding system.

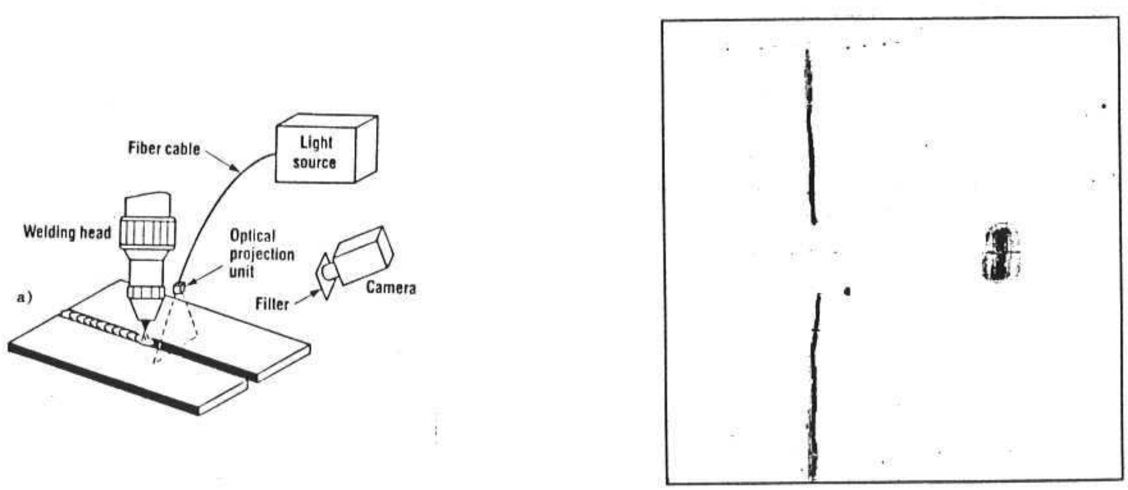


FIGURE 3 - Intersection of a laminar light beam with the spaced plates to be welded (a) and its image viewed from the camera displayed on a monitor (b)

COMPUTER AND PRE-PROCESSOR COMMUNICATION

BLOCK DIAGRAM

MICRO COMPUTER

PRE-PROCESSOR

a

WINDOW SIZES AND POSITIONS

analyse the next image from the camera

AREA AND FIRST MOMENTS OF THE WHITE LEVEL FEATURE INSIDE EACH WINDOW

compute the next window sizes
and positions in order to place
the selected singularities in
the desired region of the windows

check for any malfunction

compute welding parameters and
send it to the welding equipment
controller

GO TO a

HARDWARE BLOCK DIAGRAM

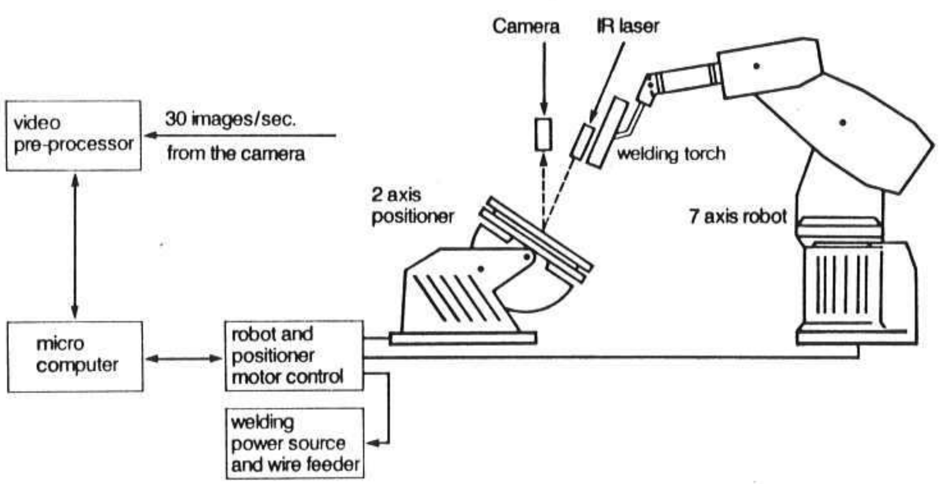


FIGURE 4 - Vision system based on the first moment technique.

a Detector

b Interference filter

c Spherical lens

d Small aperture in the plastic covered aluminum shield

e Gaz flow direction

f Aligned optic fibers

g Cylindrical lens

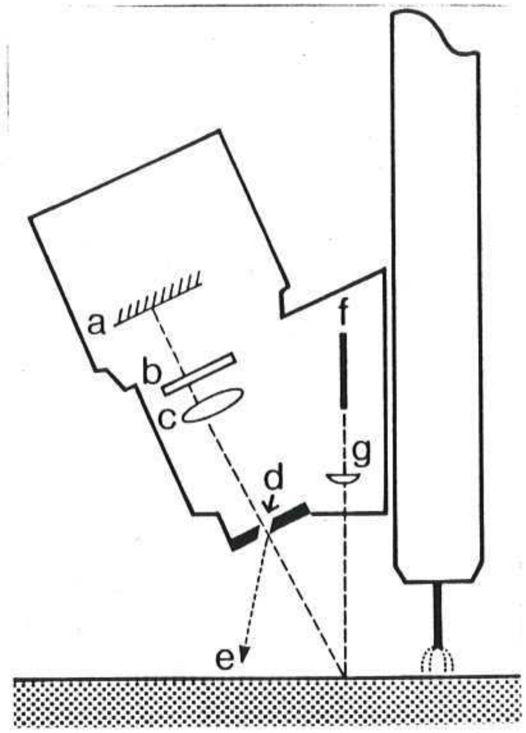


FIGURE 5 - Optic configuration of the vision system based on the first moment technique

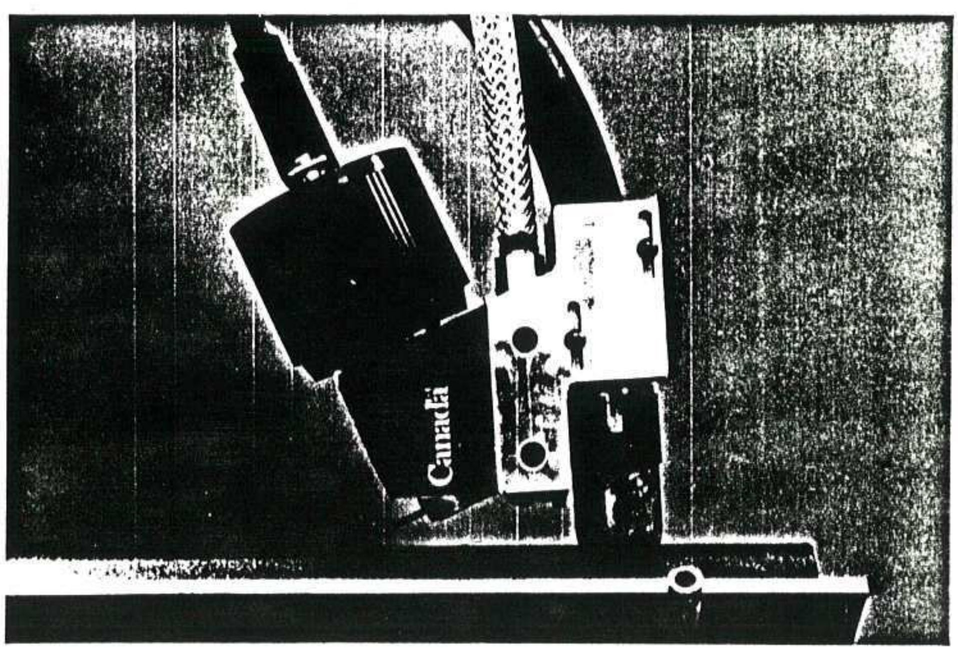


FIGURE 6 - Vision Head prototype of the system based on the first moment technique.

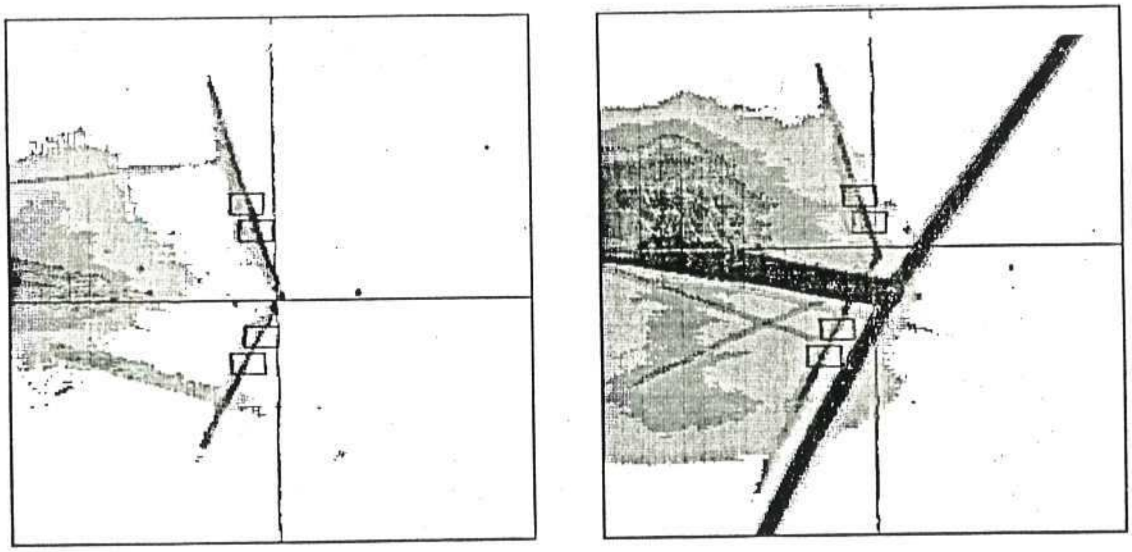
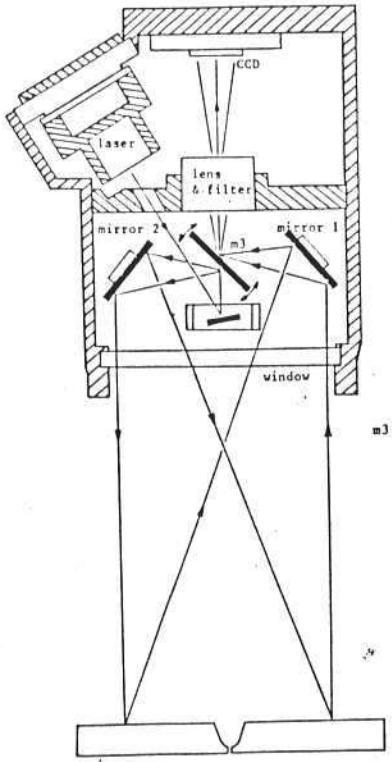


FIGURE 7 - Camera image of the intersection of the laminar light beam with the fillet joint. The rectangular window and the crossed hairs are supperposed by the computer.

FIGURE 8 - The trajectory of a six axis robot is corrected (height and lateral position) while welding (GMAW) of fillet joint using the first moment vision system.



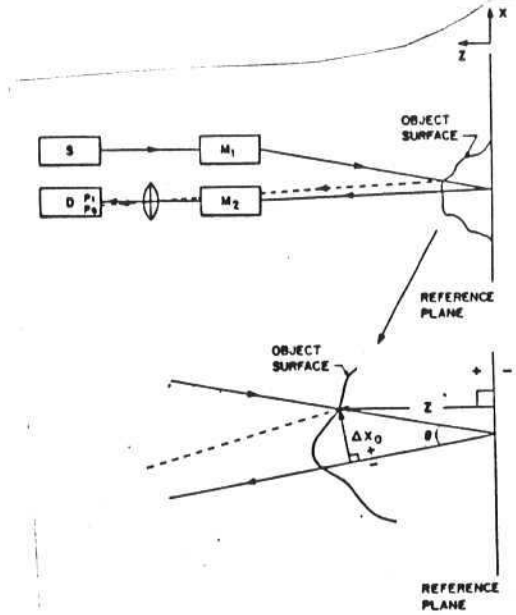


FIGURE 9 - Saturn Vision head from Servo-Robot Inc. is an example of geometrically synchronized scanner.

FIGURE 10 - Synchronized Geometry

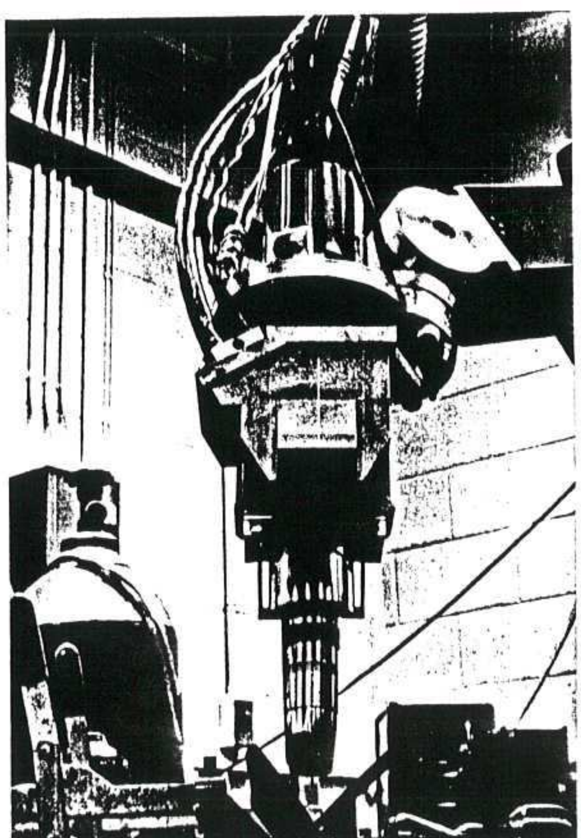


FIGURE 11 - The Saturn camera is mounted on a six axis robot using a seventh axis to enable its rotation around the torch.

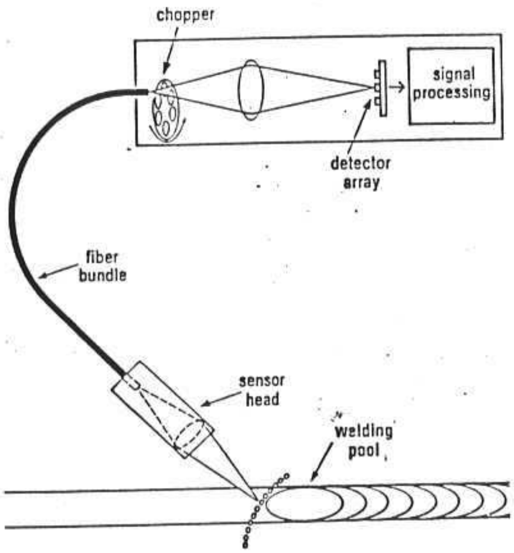


FIGURE 12 - Schematic view of the linear-array fiber-optic thermographic sensor.

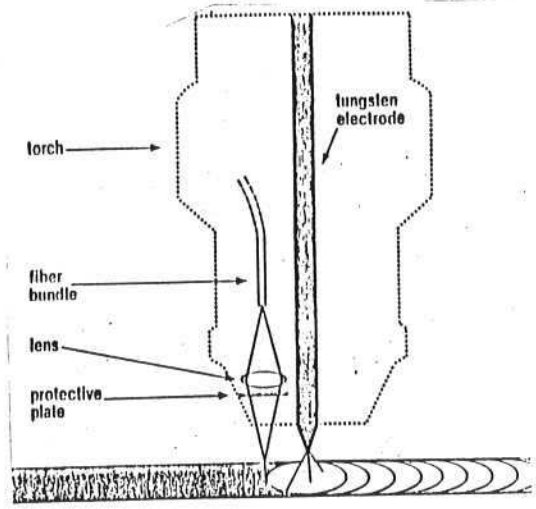


FIGURE 13 - Detail of the sensor head mounted inside the welding torch.

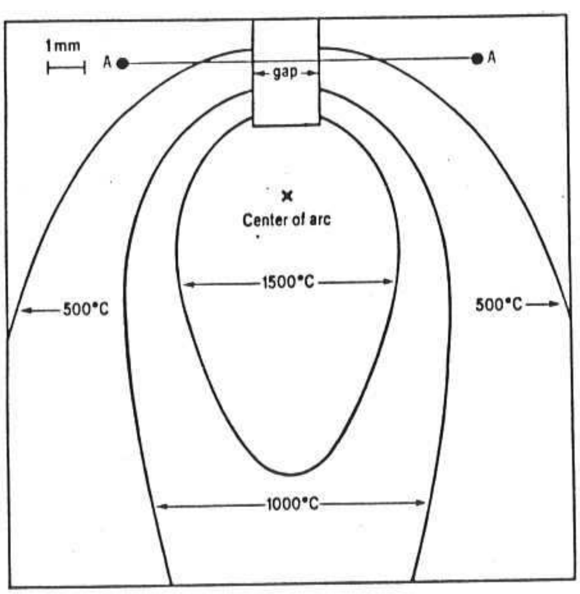


FIGURE 14a - Thermal distribution at the surface of the weld area as obtained from the numerical model (carbon steel, weld speed 2.6 mm/s).

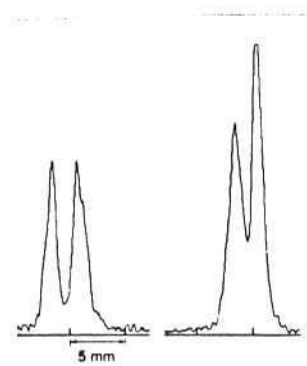


FIGURE 14b - Records of the emission profile during scanning ahead of the pool during a welding operation.

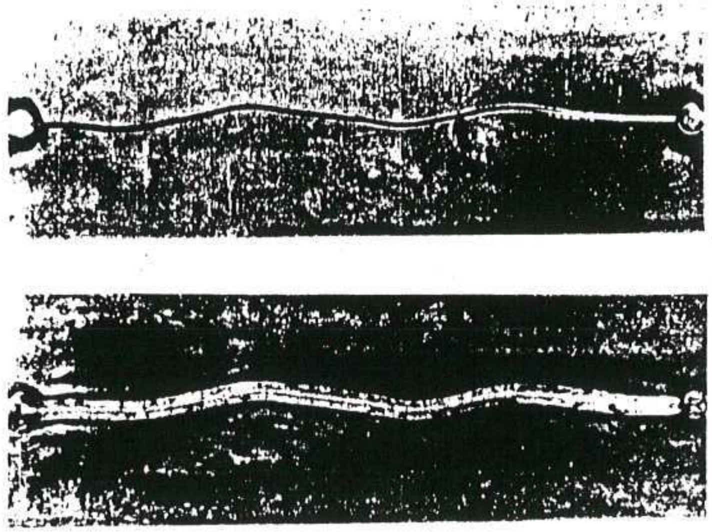


FIGURE 15 - Example of an irrigular welding path followed by a GMAW head guided by a fiber-optic thermographic sensor, before and after welding.

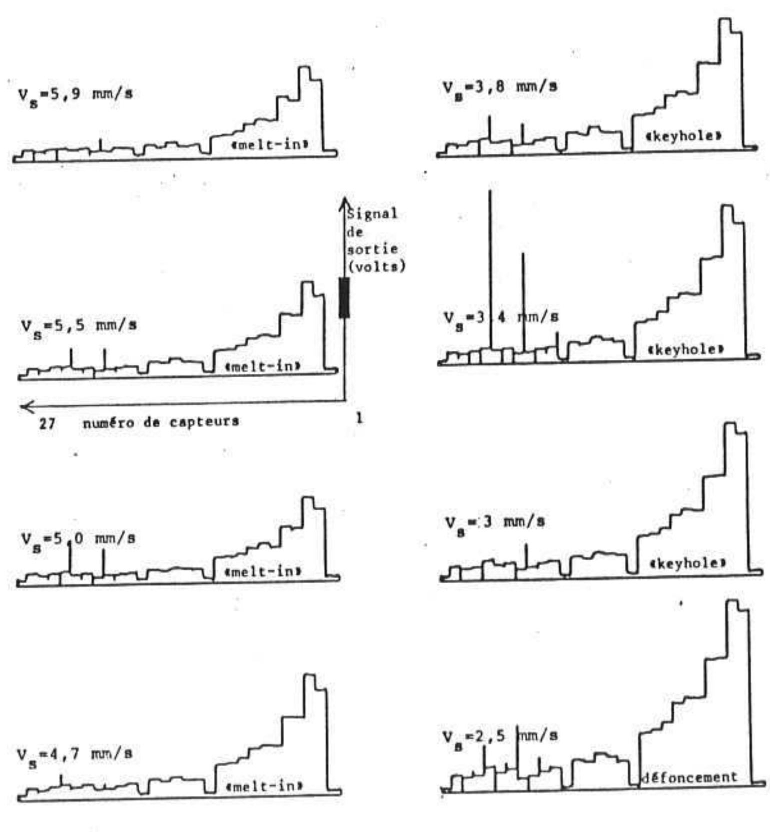


FIGURE 16 - Emission profile taken from far outside the weld pool created by a PAW torch up to the center. Material is Aluminum 6061-T 6.