APPLICABILITY OF A TRACK-BASED MULTIPROCESS PORTABLE ROBOT TO SOME MAINTENANCE TASKS IN CANDU NUCLEAR PLANTS

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ABSTRACT. Hydro-Québec has developed a six-axis, track-based, multiprocess robot. This lightweight (30 kg) compact robot travels on a bent track with a radius of curvature ranging from 1 m to infinity (straight track). Standard and tandem wires GMAW, FCAW and Narrow gap TIG welding as well as plasma gouging and cutting, electrical and pneumatic rough and precision grinding, and profile measurement functionalities have been incorporated. A description of this technology an its newly developed functionalities is given in this paper. Since 1995, a number of industrial and R&D projects have been performed using this technology now called the Scompi technology. The main field of application is the in situ repair of hydraulic turbine runners. However some applications have been developed in the nuclear field. One particular development was funded by the International Thermonuclear Experimental Reactor (ITER) project. Scompi was selected by the ITER US Home Team* for a demonstration of remote techniques for welding, cutting and re-welding the 30 m diameter, 17 m high, vacuum vessel. The demonstration involved all position robotic plasma cutting and NG-TIG welding of a 316L, 40 mm thick, double wall. In 1998, two Scompi robots working in tandem performed in York, Pa, the joint welding and cutting of a full scale portion of the vacuum vessel. In 1995, the applicability of the Scompi technology to the repair of the divider plates in the four steam generators at Gentilly-2 was evaluated based on a joint proposal by Ontario Hydro Technologies (now Ontario Power Technologies-OPT) and Hydro-Québec. A MIG welding procedure was proposed for the horizontal and vertical divider plates welds. A complete simulation of the robot and primary head demonstrated the feasibility of the concept. However, based on cost and scheduling, it was decided to proceed with a manual repair. Nevertheless it is anticipated that this technology will find its niche in the maintenance of Candu reactors.

* John Maslakowsky from Boeing North American, Rocketdyne Division was the project engineer in charge of this feasibility study

1.0 THE SCOMPI TECHNOLOGY

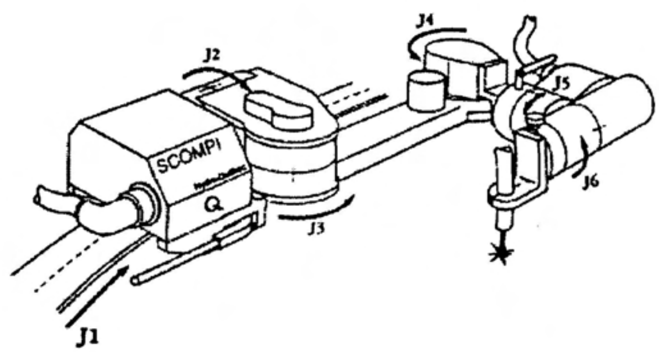


Figure 1 : The six-axis SCOMPI manipulator

This technology comprises :

- A lightweight (33 kg) six –axis track based robot manipulator. The track can be pre-bent to some required radius of curvature (1m minimum value). The robot can be air cooled internally for applications at up to 100°C room temperature. The payload of the manipulator is 15 kg. The manipulator is very compact the total height including the track is 18 cm. Figure 2 shows the very large work envelope of the robot. Note that the track can be bent to adapt the work envelope to the workpiece dimension

- A PC-based master controller with a multitasking, real-time operating system. A dsitributed control mode of operation has been selected, it is based on the BITBUS interconnect standard from INTEL. The main computer is used only to start the system and load the program corresponding to the application, then the robot is operated via a user friendly pendant.
- The menu-based pendant incorporates a 40 x 4 character LCD display and a 3 degrees of freedom joystick. The joystick has two main uses : enabling operator controlled robot movement and selecting an item in the menu.
- Multiprocess capability : welding, grinding, cutting. Each process incorporates an hybrid control where the position of the tool in the tangential plane is pre-programmed while the position along the normal to the surface is adjusted on line based on a signal provided by a sensor (the arc length for the welding and cutting processes, the normal force for the grinding process).
- Fast programming capability. Most of the application performed with the Scompi robot are one of a kind or small series. Thus a very fast on line programming capability has been developed. One-, two- and three-dimensional work areas may be programmed (figure 3).

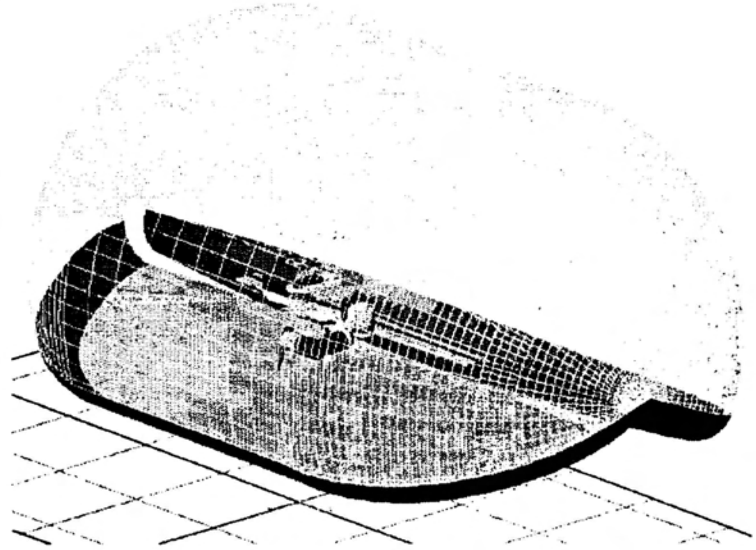


Figure 2: Work envelope of a Scompi robot moving on a 2.5 m straight track.

Each point programmed in the work area is called an hyperpoint. It keeps the tool end point position and tool orientation in memory. All intermediate positions and orientations are interpolated between the hyperpoints. Once a work area has been taught to the system, the manipulator is restrained to displacements within the boundaries of this work area, thus avoiding collisions with the work-piece.

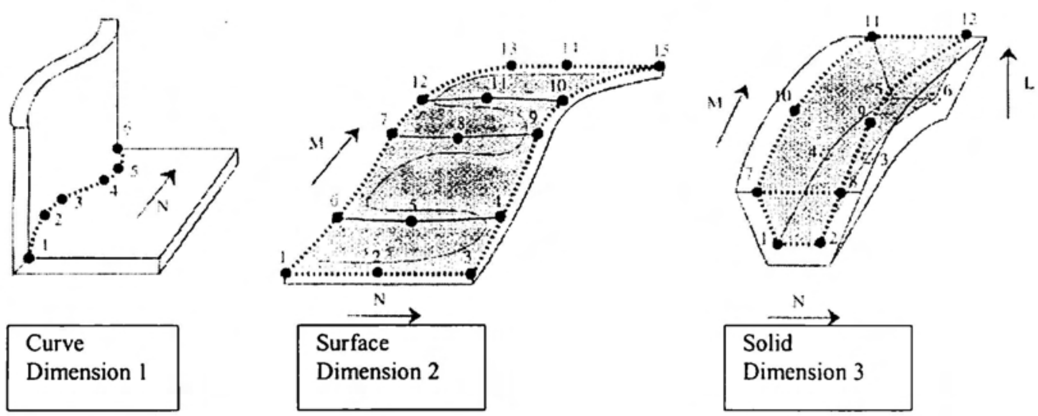


Figure 3: The three types of programmable work areas

2.0 MIG WELDING

2.1 Standard one wire process

The Scompi robot has been initially developed to perform MIG overlay welding on hydraulic runner blades. Typically, a cavity must be filled with weld metal in one or several layers (figure 4). A two-dimensional work area is first taught by the operator. Then he must teach a set of points inside the work area by moving the tool end point of the robot successively to each of these positions using the pendant joystick. The contour thus taught defines the boundary of the layer of weld metal to be deposited. The contour's advantage is that it is easier to teach than the work area since the system already knows the shape of the part. The operator needs only to teach the inter-pass distance and the robot will generate automatically all the trajectories. It must be noted that the direction of each trajectory remains parallel or perpendicular to one of the directions of the work area. Usually welding is done in the horizontal position. All the welding parameters (welding speed, wirefeed speed, voltage etc..) have been pre-programmed in a configuration file. They may be changed by the operator and even overridden during welding.

When welding on a complex shape such as an hydraulic turbine blade, the horizontal trajectories are not parallels. Thus the inter-pass distance may change along the trajectories. In order to keep a constant thickness of the deposit, the deposition rate is adjusted automatically to compensate for this slight variation. The distance between the contact tube and the weld pool is kept constant in real time. This distance is computed as a function of wire feed rate, voltage and current. Figures 5 and 6 show some examples of overlays welded by the Scompi robots.

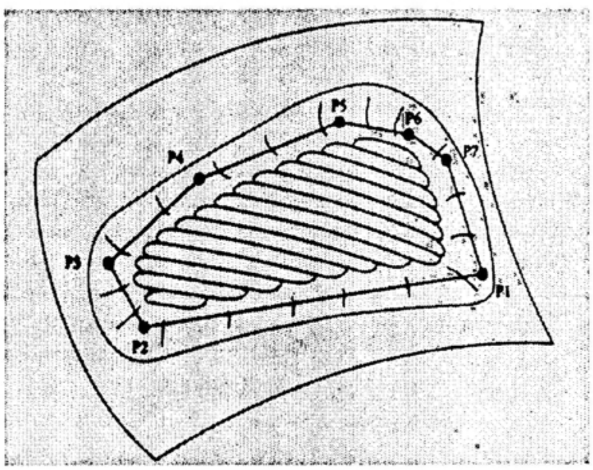


Figure 4 : Teaching a contour inside a work area

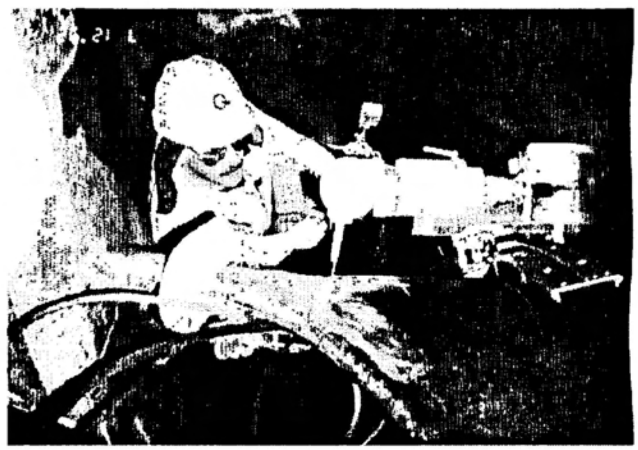
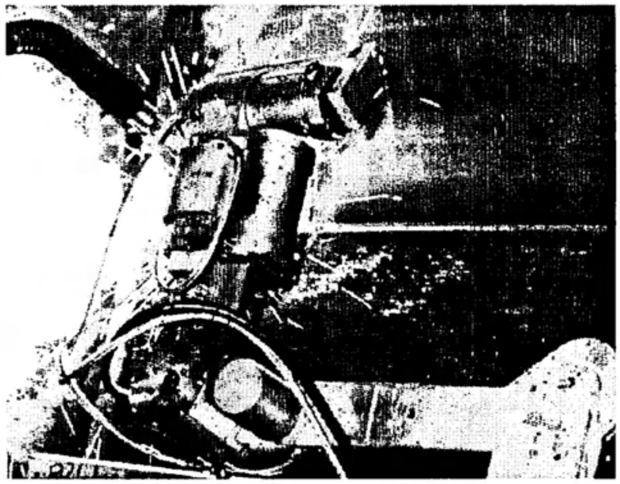


Figure 5 : Example of a weld overlay deposited on a Francis runner blade :

- Horizontal robotic MIG welding in an overhead position;
- 309L underlayer, final layer made out of high cavitation resistant alloy (Cavitec);
- Inter-pass distance : 4,5 mm;
- Welding speed : 7,5 mm/s;
- Stickout : 18 mm;
- Mean current : 200 A;
- Mean voltage : 25 volts;
- Arc deposition rate : 4-5 kg/h
- Duty cycle : 30%

Figure 6 : Welding at the Alstom Canada manufacturing plant (Tracy) a cavitation resistant overlay on a propeller turbine blade for the LG1 power house :

- 3 m2 of high cavitation resistant alloy on each carbon steel blades (5 blades per runner);
- Thickness of overlay : 6 mm after welding, 3 mm after machining;
- A total of 20 blades have been welded;
- Blade distortion can be predicted from one blade to another;
- 4 times more productive than manual welding;
- Arc deposition rate : 6-7 kg/h;
- Duty cycle : 30 %.



2.2 The tandem wires MIG process

Recently a new process has been developed in Europe and North America : the tandem wire process. In this process two wires are fed simultaneously in one weld pool. Several variations of the process exist : two wires in the same torch or two torches aiming towards the same weld pool, asynchronous pulsing of each wire to reduce magnetic interference etc...

The main objective is to increase by almost a factor of two the productivity while keeping the same quality. This process is now being implemented on the welding robots and it can be seen as a breakthrough in robotic welding productivity.

With the Scompi robot we have developed a two wires/two pools process where the robot holds two torches simultaneously, but the torches are depositing two distinct beads. We had two objectives in mind :

- Increase the productivity
- Provide a better control of the thermal cycle of the weld pool

One application of the process is the on site overlay of the internal wall of large horizontal vessels. Two torches are welding simultaneously in the flat position while the vessel rotates at a constant speed. Figure 7 illustrates this application.

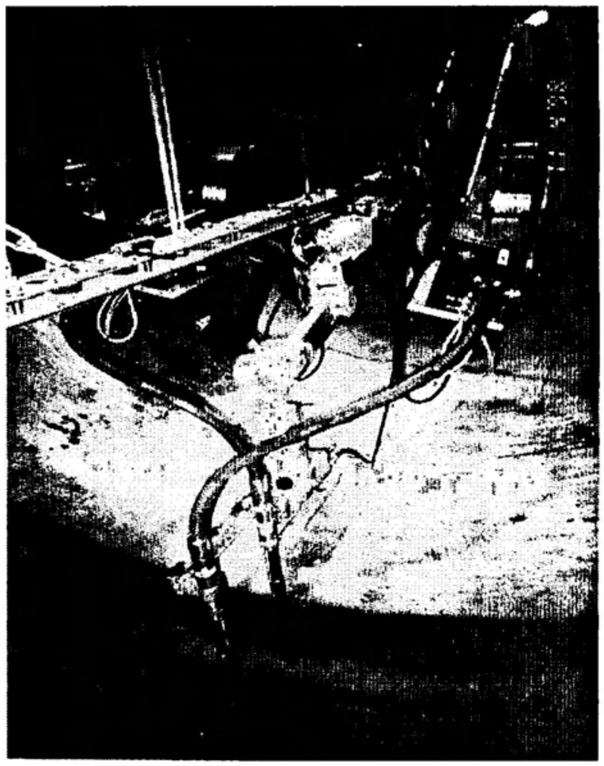


Figure 7 : Tandem MIG overlay welding of the internal wall of an eroded carbon steel vessel :

- Distance between torches : 30 cm
- Arc deposition rate (two torches) : 17 kg/h
- Duty cycle : 80%

Another application of the tandem MIG process is to allow control of the thermal cycle of the heat affected zone (HAZ) in order to avoid a costly and sometimes impractical preheat treatment.

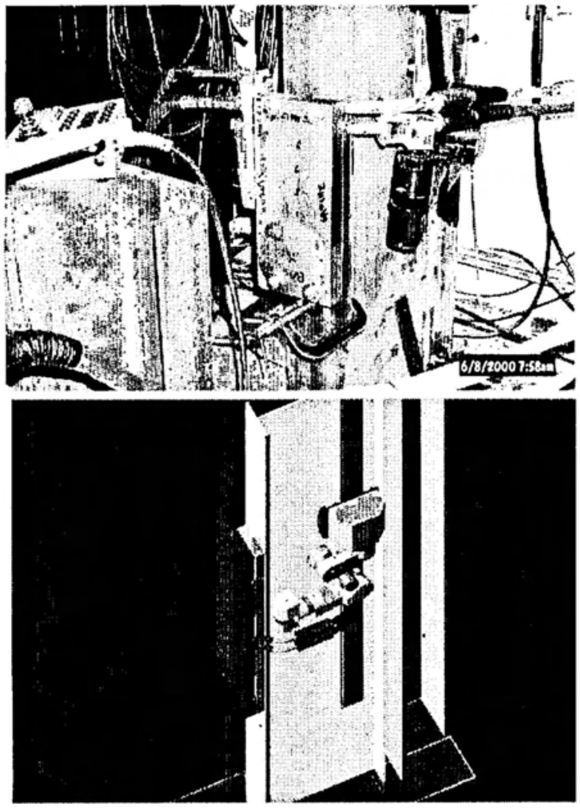


Figure 8 : Vertical up tandem MIG welding of a 25 mm thick 17-4PH plate to a 50 mm thick 1045 carbon steel plate. (top : laboratory set-up, bottom : simulation)

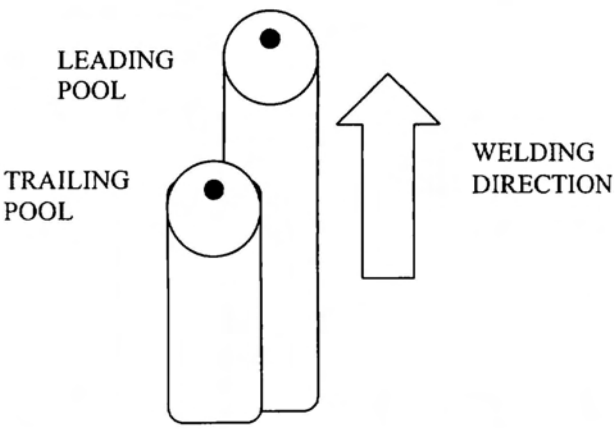


Figure 9 : Schematic view of the two weld pools in the SCOMPI tandem MIG process.

Figure 8 shows the SCOMPI tandem MIG welding of a 17-4 PH stainless steel plate over a 1045 carbon steel plate.

Two robots can weld simultaneously the two welds using two torches each. In this application the two torches are welding two beads simultaneously, the second torch following the first one at a distance of 50 mm (left) or 70 mm (right) and with a lateral offset of 5 mm.

It must be pointed out that in this process there are two distinct weld pools (figure 9). A number of tandem MIG application have been developed recently were the two wires are feeding the same pool, thus increasing the deposition rate by a factor of two. This is considered as a breakthrough for the productivity of the robotic applications. With the Scompi robot we have developed two pools tandem MIG which, to the increase in productivity, adds the possibility to modify substantially the thermal cycle of the HAZ.

The thermal cycle can be computed using an equation derived by Kenneth Easterling from the Rosenthal model[1]. The thermal cycle is computed for a point located just below the fusion line of the first bead. The heat input of 10 000 J/cm. The distance between the two torches is 50 mm (figure 10).

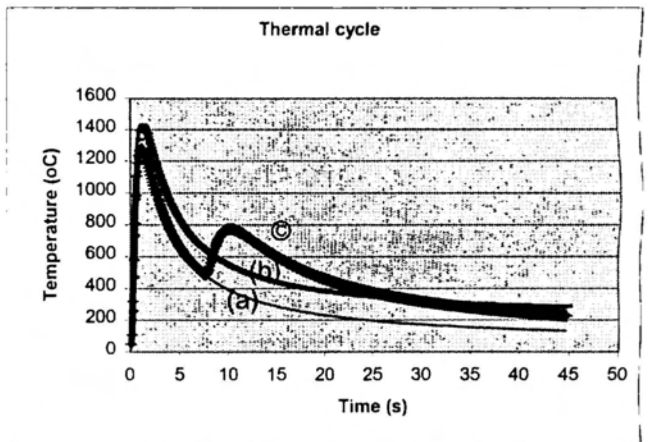


Figure 10 : Computed thermal cycle : (a) one wire 50°C preheat; (b) one wire 200°C preheat; (c) two wires (tandem) 50°C preheat.

Table 1 shows the effect of the preheat temperature compared to the tandem process. The cooling time between 800°C and 500°C is

[1] Easterling, J.F., Introduction to the Physical Metallurgy of Welding, Butterworths & Co Ltd, 1985, p20

14,5 s with the tandem process compared two 3,3 s when welding with only one torch. The tandem wire process is much more effective than preheating in increase the cooling time. The hardness of the HAZ is a strong function of cooling time in a high carbon equivalent steel such as 1045. Figure 11 compares the Vickers hardness profile in the HAZ of the first bead for one wire and two wires for the same preheat temperature of 50°C. The maximum hardness with one wire is very high (700 HV) due to the formation of a martensitic phase in the HAZ. The maximum hardness falls below 400 HV with the tandem process due to the slow cooling rate which promotes a bainitic structure in the HAZ.

Preheat (°C)	Cooling time 800-500 (s)
25	3,3
50	3,6
100	4,2
150	5,2
200	6,6
250	6,6
50 + tandem	14,5

Table 1 : Comparison between preheat and tandem welding

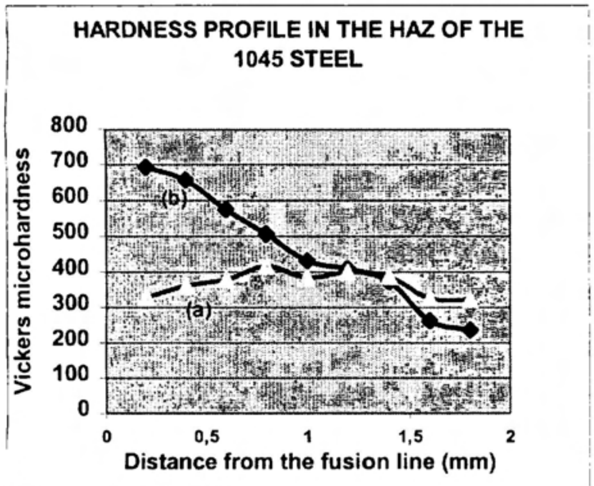


Figure 11: The effect of the tandem process on the maximum hardness in the HAZ of the 1045 steel. (a) One wire; (b) Tandem.

3.0 NARROW GAP TIG WELDING - ITER PROJECT

The International Thermonuclear Experiment Reactor (ITER) is a large-scale fusion energy project. The design of a large torus is a cooperative venture between the main partners of Europe, Japan, the United States, Canada and Russia. The ITER reactor vessel supports the high electromagnetic forces from the plasma-facing components. The double wall (30m diameter, 17m high) vacuum vessel must be designed to accomodate welding and cutting from inside the vacuum vessel. Twenty prefabricated 18° (pie-shaped) sectors will be positioned side-by-side to form the vessel. ITER Task T301 involved the demonstration of remote techniques for welding, cutting and re-welding the vacuum vessel. The ITER US Home Team was responsible for the vacuum vessel field joint welding, cutting and re-welding portion of this task. Boeing North American selected the Scompi robot for this demonstration. The NG-TIG process with a rotating electrode was selected for this application (Figure 12). The robot had to weld two J-shaped narrow gap joints 12 mm wide on each wall. The NG-torch was fabricated by Arc Machine Inc. (AMI). it was attached to the robot arm. The position and orientation of the tungsten electrode was adjusted by the robot arm. In particular, the robot controlled the arc length via an AVC control.

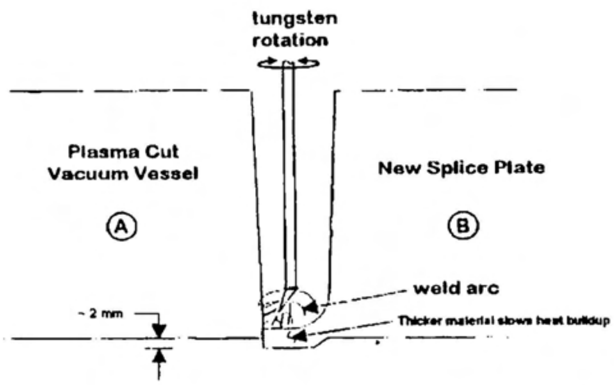


Figure 12 : The rotating tugsten electrode of the NG-TIG process. This features improves sidewalls fusion.

A full scale mock-up of a portion of the vacuum vessel (located between two ports) was built by the US home team and welded with the Scompi robot. Figure 13 shows a simulation of the mock-up and the two robots. Total joint length was 12.5 m. The NG rotating tungsten system fills a groove by putting one weld layer on top of the other. Layer are generally made with one pass. A joint typically requires 22 weld layers. Thus, total travel per robot to fill the 4 joints is 240 m.

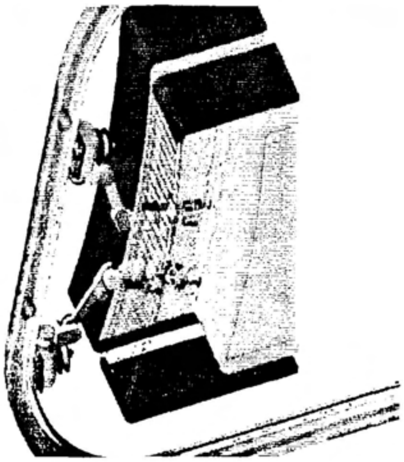


Figure 13: Simulation of the mock-up with the two Scompi robots travelling on a curved track. The robots are pictured welding the outer wall of the double wall vacuum vessel.

In the summer 1998, two robots working in tandem performed in York, Pa, the joint welding and cutting of the mock-up (figures 14 and 15).

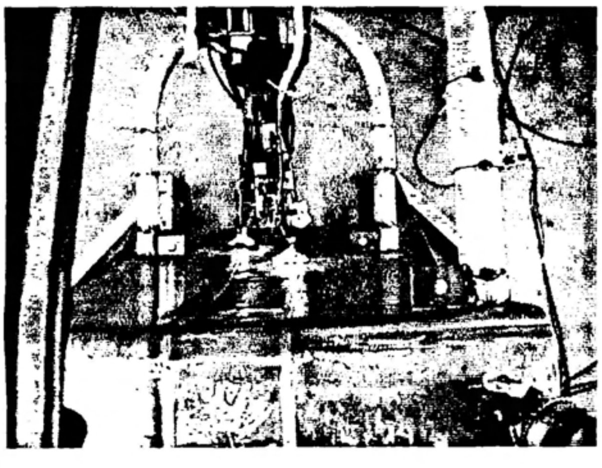


Figure 14 : Welding the final layer on the upper part of the mock-up.

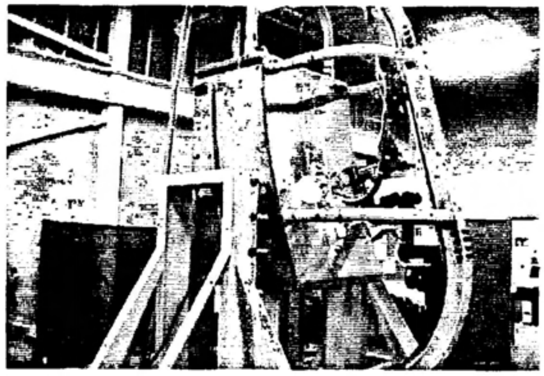


Figure 15 : Welding the final layer in the vertical position. The two robots are welding in tandem.

The key features of the Scompi technology for this application were :

- The fact that the manipulator could travel on a track with variable radius of curvature while keeping a coordinated movement of the six axis.
- The small size of the Scompi robot compared to its work envelope and its ability to work in a confined space.
- The open architecture and distributed control allowing easy interfacing of the NG-TIG process.

For this application the trajectory was programmed using the curve (dimension 1) programming mode. At low TIG welding speed (1 mm/s) the robot could easily maintain 0.2 mm relative accuracy.

4.0 PNEUMATIC GRINDING

4.1 Rough grinding

Since 1995, the Scompi robots are used by Hydro-Québec for the in situ repair of cavitation damages. This application involves grinding of the excess weld metal to restore the original profile of the blade. Two types of pneumatic grinders may be used with the robot. The cup type grinder operating with 12.5 or 15 cm diameter cup wheels at about 7000 rpm and the plug grinder operating with 7.5 cm diameter plug wheels at about 18000 rpm. The nominal air pressure is 90 psi and for best performances, these grinders are lubricated continuously thanks to a capillary tube inside the air supply hose. The robot is programmed in the same way as welding. The operator teaches a contour, the inter-pass distance and the grinding parameters (grinding speed, wheel rpm). The robot

automatically grinds the surface while keeping a constant grinding force, thanks to an eddy current sensor mounted on each grinder to monitor the rpm of the wheel.
At a constant wheel rpm, the robot removes a layer of metal of constant thickness within the contour. Thus it is the responsibility of the operator to determine the location of each contour and the thickness of metal to be removed in order to reach the final profile. Usually, a trained operator can restore a profile with an accuracy of 2-3 mm.

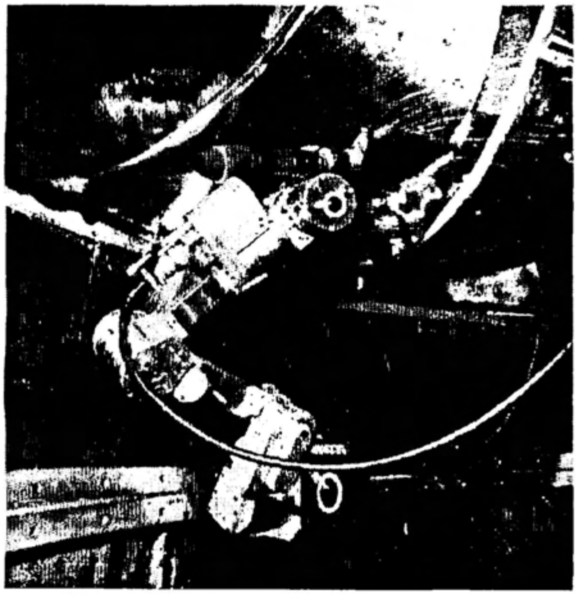


Figure 16 : Robotic grinding of a Francis runner blade at the Hydro-Québec's Manic 5 hydropower plant.

4.2 Precision grinding

- Recently a precision grinding technique has been implemented. The objective is to perform on site machining using a flexible lightweight equipment. The accuracy of the robot manipulator by itself is not sufficient to perform precision grinding based on a pre-programmed trajectory because the grinding forces applied to the manipulator deflect the arm by several centimetres and the wear rate of the grinding wheel is not known accurately enough. However, the depth of cut per pass can be predicted accurately enough. For example, with a 1.4 kW pneumatic cup grinder the depth of cut may be varied between 0,025 mm and 0,25 mm. Thus, provided we can measure the work-piece profile with a precision better than 0.25 mm, it should be possible to grind the profile with this kind of accuracy. A key feature is the measuring technique. This is achieved by comparing the work-piece profile to a reference plate profile as shown in figure 17 for a flat plate. Two proximity transducers (TQ 402 from Vibro-meter) are mounted back to back on a bracket. With this set up, the vibrations of the robot arm are cancelled. The accuracy of the measurement is $\pm$ 20 microns.

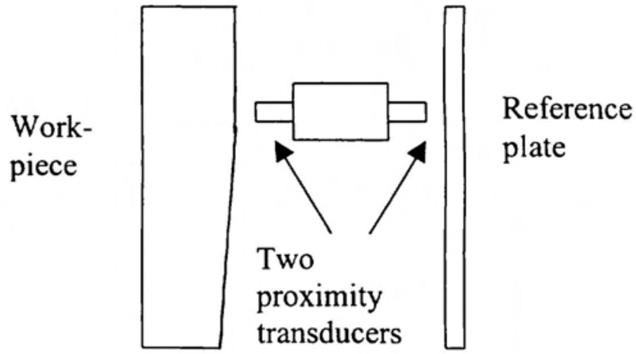


Figure 17 : Schematic of the sensors set-up.

The experimental set-up is shown in figure 18. The reference is a straight steel plate 100 cm x 15 cm x 5 cm. The work-piece is a steel plate of the same dimensions. The distance between the two plates is approximately 15 cm. The work-piece surface was machined to simulate an irregular profile which had to be ground flat.

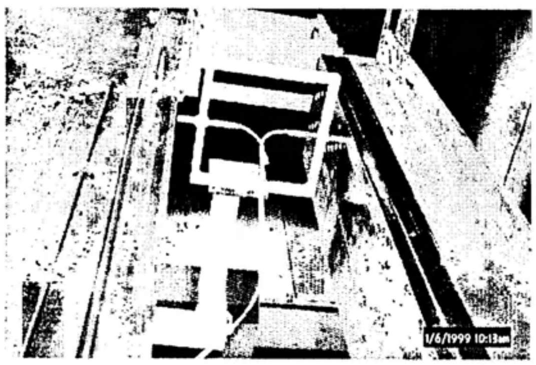


Figure 18 : Photography of the laboratory set-up.
The robot scan the work-piece profile back and forth with an inter-pass distance of 5-10mm. Thus generating thousands of points. Each point is a measurement of the distance between the reference plate and the work-piece along a normal to the reference plate.

Once the profile has been scanned, a special algorithm computes automatically the contours joining points located at the same level. The operator can select one or several contours to be ground by the robot as well as the depth of cut. A 1.4 kW pneumatic cup grinder with a 15 cm diameter wheel was used for this experiment. Two robots work either in tandem or sequentially. The first robot measures the profile and the second performs the grinding step. Once the first contours have been ground, the surface is scanned again and new contours are generated. Layer by layer, an exact replica of the profile of the reference plate is generated on the work-piece. In our experiment, the final straightness of the plate was better than 0,1 mm over a length of 500 mm.

Figure 19 shows the original and final profile of a 2D section of the plate along its length. The initial maximum surface irregularities of 0.8 mm have been erased. To achieve this result 5 scans had to be performed.

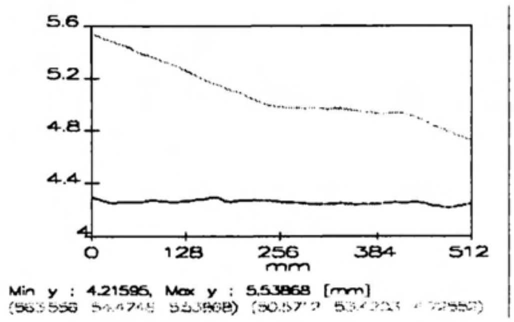


Figure 19 : Comparison between the original (top) and final profile of the work-piece. All units are in mm.

The mean metal removal rate was 1,3 kg/h. At the beginning, relatively thick layers can be removed without scanning the surface and the duty cycle of the process is very high (over 80%), a straightness of 0,25 mm over 500 mm is easily reached. Improving the straightness down to 0.1 mm requires more time and the duty cycle falls down to 30%. However it is remarkable that such an accuracy can be achieved with a flexible robot arm.

5.0 APPLICABILITY TO ROBOTIC WELDING OF DIVIDER PLATES IN CANDU REACTORS

The replacement of leaking dividers plates in primary boilers head has been performed in a few Candu reactors including Gentilly II in 1995. This task has been performed manually. It involved welding and precision grinding operations in a confined environment. In order to reduce the radioactive dose (man rems) of the workers the applicability of the Scompi robot to perform this task has already been evaluated in terms of accessibility (figure 20).

Figure 20 shows a simulation of the Scompi robot working inside the primary head of a Gentilly 2 reactor.

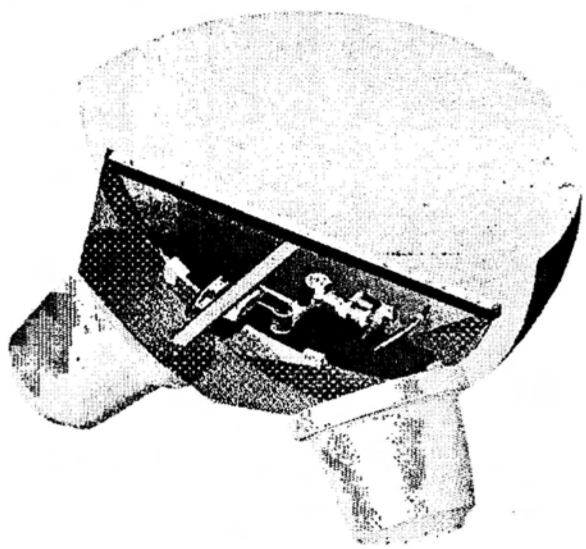


Figure 20 : Simulation of a Gentilly 2 steam generator primary head showing robotic welding of the joints between three sections of the divider plate. The track is mounted onto the tubesheet

The simulation proves that the robot manipulator can reach all the locations required to weld the joints between the three sections of the divider plate.

The dividers plates are inserted in a seat bar welded to the inner wall of the boiler. This seatbar must be ground to a precise profile before installing the plates. Two Scompi robots working in tandem (mesuring and grinding) could perform the precision grinding task provided a reference plate with the same curvature as the primary head is installed temporary in front of the seat bar.

Up to now, the Candu maintenance service providers have not been able to justify he investment in a robotic technology for this type of repair. However, this could change in the future as the level of radiation is increasing with time in some plants.

6.0 CONCLUSION

On site robotic TIG, MIG welding and precision grinding is now feasible with the Scompi technology. Two very important developments are the capability to control the thermal cycle of the welds using tandem MIG welding and the new precision grinding technique allowing machining with an accuracy of 0,25 mm.
The compact portable Scompi robot should be considered for applications with restricted accessibility but requiring multiprocess capability and in particular on site machining.
It is anticipated that besides the divider plates project a number of maintenance tasks in Candu reactors could benefit from this technology.

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