2007

Feasibility of robotic weld repair of live pipelines

Alexander D. Nicholson
University of Wollongong, alexn@uow.edu.au

John Norrish
University of Wollongong, johnn@uow.edu.au

Rian Holdstock
University of Wollongong, rh083@uow.edu.au

http://ro.uow.edu.au/engpapers/3082

Publication Details

Nicholson, A. D., Norrish, J. Holdstock, R. (2007). Feasibility of robotic weld repair of live pipelines. 5th Asian Pacific International Institute of Welding (IIW) International Congress 55th Welding Technology Institute of Australia (WTIA) Annual Conference Proceedings (pp. 1-7). Australia: IIW.

FEASIBILITY OF ROBOTIC WELD REPAIR OF LIVE PIPELINES

Nicholson A, Norrish J and Holdstock R

ABSTRACT

Repair of corrosion damage on pipelines is often achieved by depositing weld metal on the external surface of the pipe in the affected area. A study [1] of welding techniques involving GMAW and FCAW has shown that this approach is acceptable on thick-wall high-strength pipes. On thinner-wall pipe the operating parameter range is more restricted by the mutually exclusive risks of blow-out and cold-cracking. Robotic or automated welding offers the possibility of improved heat input control and reduced risk to the operator. Unfortunately, robotic welding usually requires prolonged programming which normally makes such techniques uneconomic. This paper describes an advanced method of robot programming which reduces programming time and simplifies the application of automated welding, and illustrates how such techniques may be applied to weld repair of pipelines.

KEYWORDS

Weld Repair, Pipe Welding, Robot Programming, Vision System

AUTHORS DETAILS

A Nicholson is a Research Fellow for the Faculty of Engineering, University of Wollongong, NSW, Australia.

John Norrish is the Professor of Materials Welding & Joining for the University of Wollongong, NSW, Australia.

R Holdstock is a PhD student in the School of Mechanical, Materials & Mechatronic Engineering at the University of Wollongong, NSW, Australia.

✓

This paper has been refereed by at least two appropriate reviewers selected from the following Technical Committee members or the wider welding research community.

1. INTRODUCTION

Weld deposition repair of corrosion damage is routinely carried out on live transmission pipelines since it offers an attractive alternative to the use of full encirclement sleeves. It is a cost effective and rapid technique but when manual welding is used, it has been shown that very large fluctuations in heat input may occur. Whilst such variations may be tolerable on thicker-wall pipe, the narrow 'safe' band of operating parameters may restrict its application on thinner-wall high-strength pipe where the competing effects of blow-out and cold-cracking must be addressed. The limitations of manual welding are encouraging the use of automated weld repair of pipelines [2].

When welding on critical areas such as pipe walls, welder-induced discontinuities produced using manual processes must be minimised. Automated systems can provide improved quality, efficiency, and repeatability, and can potentially solve or reduce many of the issues relating to the manual methods. Robotic welding systems are particularly appealing due to their intrinsic flexibility; although, this technology brings with it other inherent problems. The ability to quickly program a robot to follow a path (sometimes quite complex) and to control its process is the major impediment to general acceptance of the technology. When robots are used, they often require the workpiece to be moved to a robotic cell in a workshop – which implies that the workpiece is transportable; which is obviously impractical for live pipeline repair. Hence, to realise the benefits of robot technology for this application, two obstacles must be overcome. Firstly, the robot must be portable so it can operate in-situ; and secondly, a means of rapid programming is required. The first issue is relatively easily solved – mini-robots are commercially available and feasible for this kind of work [3]. The second issue of rapid robot programming has been addressed for in-situ weld repair of hydro electric turbines for the power generation industry [4], and will be shown here to be a feasible technique for the application of live pipeline repair.

2. APPLICATION BACKGROUND

During in-service welding, there are two primary concerns resulting from the energy transferred to the pipe wall. These concerns are: burning through the pipe wall, and the increased susceptibility to hydrogen cracking through the formation of 'hard zones' in the welded area. When in-service welding repairs or modifications are carried out, it is sometimes necessary to reduce the operating pressure of the pipeline, remove the system completely from service, or use diversions to facilitate removal or repair of the damaged section. The costs associated with these factors and the possibility of environmental contamination during pipeline venting necessitates the development of processes which offer increased safety and economic incentives. Performing in-service weld repairs and attaching hot tapping tees on pressurised pipelines can reduce service downtime and associated costs.

Automated welding systems can provide greater heat input control and produce superior quality welds than manual methods, particularly if GMAW or FCAW processes are used. This is simply a result of more accurate positioning and travel speed control than achievable by human operators. The control of the welding process is particularly crucial when welding thin plate. Earlier investigations [5] have shown that for GMAW conventional Constant Voltage (CV) power supplies are incapable of providing the level of control required when welding thin-walled objects. Excessive heat input increases the base metal liquidity/mobility and can cause blow-through or weld sag. In addition, inconsistencies in the power supply output can also cause blow-through which can destroy the object or surface. This situation is particularly hazardous to operators when welding pressurised pipelines.

Burning through the pipe wall could have disastrous consequences which may lead to human fatalities or venting of the pipeline – which in itself may create an environmental hazard. A blow-out during welding may occur if the reduced yield strength of the un-melted area beneath the weld pool is insufficient to contain the pressure within the pipe. The risk of blow-out is a function of arc energy, weld penetration, remaining wall thickness, and pipe internal pressure. The risk obviously increases as the pipe wall thickness decreases or the weld penetration increases. Penetration increases with higher heat input, and as such, it is paramount to adhere to the specified heat inputs in the welding procedure when working on live pipelines to avoid excessive heating. On the other hand, too little heat input introduces other metallurgical problems.

Welds made in-service have accelerated cooling rates due to heat being dissipated into the carrier pipe. The carrier pipe is effectively a large heat sink that causes the weld to cool at an accelerated rate. This rapid cooling of welds is likely to produce hard microstructures in the Heat Affected Zone (HAZ) which is then susceptible to hydrogen cracking [6]. HAZ hardness is known to be one of the most important factors affecting cold-cracking [7]. The weld cooling rate needs to be controlled as it may have detrimental affects on the metallurgical structure of the welded area. Apart from heat input, preheat temperature and combined plate thickness also affect weld cooling rates, and ultimately the final microstructure. These factors together control the susceptibility of the HAZ to hydrogen cracking [8].

3. PREVIOUS WORK

A study at Cranfield University in the UK [1] using an automated system and flux-cored wire electrodes has shown precise, reproducible, controllable welding conditions can be obtained on large diameter X80 pipe. It was found that both fillet welding of sleeves and weld deposition repair could be successfully applied. It was shown that close control of heat input could be maintained by precise control of bead placement, current, and travel speed, and the importance of maintaining a constant contact tip to workpiece distance (CTWD) was also demonstrated.

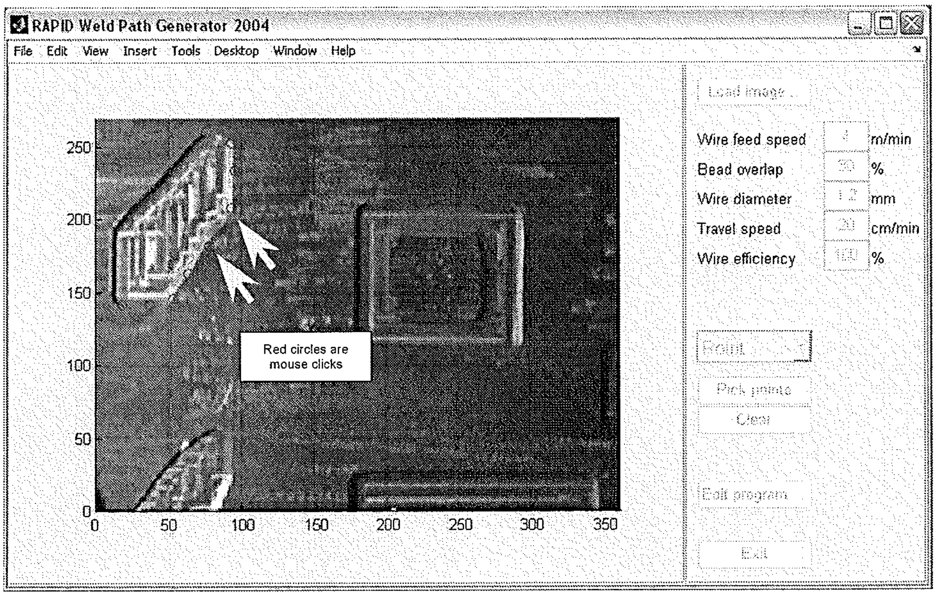
Using a rutile flux-cored wire (70T-12H4) and a 75% Ar / 25% CO_2 shielding gas there was no evidence of blow-out at reduced wall thickness and it was possible to reinstate a 7mm wall loss with a heat input ranging from 0.5 to 0.8 kJ/mm. Tempering the weld beads and closely controlling the CTWD resulted in low hardness values ranging from approximately 240 HV_{10} in the base metal and 280 HV_{10} in the HAZ.

This work was undertaken using a 6-axis robot and conventional robot programming techniques. Whilst the work illustrated the viability of the process; in practice, wear and damage are often unpredictable in both location and extent; and in these circumstances conventional programming would not be feasible due to repeated reprogramming of the robot.

In separate work at the University of Wollongong (UoW), a rapid offline programming technique has been developed and tested for hydro turbine repair using image data from a standard digital camera. Once the damaged area has been identified, (in conjunction with the software interface discussed further in [9]), welding can usually begin in less than one minute. This gives the system a substantial advantage over conventional methods and offers the possibility of 'one off' repair application.

4. AUTOMATIC ROBOT PROGRAMMING

For pipeline repair, a robot would need to consider the curvature of the pipe. Additionally, a fast method of acquiring repair area data and reprogramming the robot is required. Solutions to these issues have been provided by Nicholson [9]. Various touch-sensing algorithms were developed for inclined and curved surfaces, including pipes. For flat surfaces, a simple 1-point touch-sensing technique can be used. For inclined or curved surfaces, a 3-point plane touch-sensing routine followed by one or more 3-point line touch-sensing routines is recommended. To rapidly obtain repair area information, Nicholson [10] used a torch-mounted CCD camera to acquire and transmit 2D image data to a remote PC (see Figure 1). The position of the camera could be determined at any time relative to the TCP (Tool Centre Point) coordinates. This, in conjunction with touch-sensing, allows calibration of the captured image data.



Wire feed speed 4 m/min
Bead overlap 30 %
Wire diameter 1.2 mm
Travel speed 20 cm/min
Wire efficiency 100 %

Figure 1. RAPID Weld Path Generator GUI

Flat surfaces are generally the easiest to deal with (see Figure2). A 1-point touch-sensing routine can be used to determine the workpiece distance from the camera. The field of view of the camera can then be calculated and the photograph axes calibrated. A 2D photograph is captured by the camera and the weld paths are generated in relation to the calibrated image axes (1st and 2nd dimension), and the touch-sensed profile (3rd dimension). This method is most suitable when the camera is positioned relatively square (perpendicular) with the workpiece; otherwise, the 3-point touch-sensing routines (explained below) are more suitable.

For curved surfaces (Figure 3), a 3-point line touch-sensing routine could be used to determine the workpiece profile for the 3rd dimension and represents a more complex scenario. A spline or curve may be fitted to this data and the weld paths made to follow the workpiece curvature.

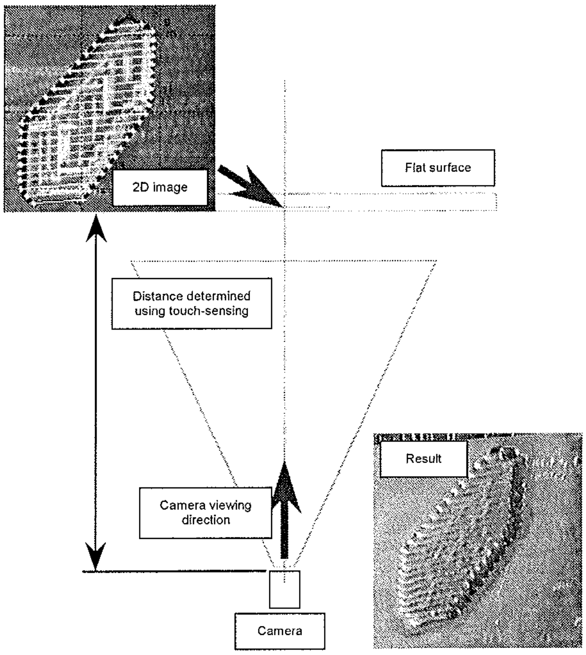


Figure 2. Flat Workpiece Positioning Algorithm

For inclined surfaces (Figure 4), a 3-point plane touch-sensing routine can be used to determine an effective plane in which the workpiece lies. The camera is positioned perpendicular to this plane at some pre-defined offset distance. As in the flat or curved surface approaches, this distance is used to determine what size the camera's field of view is. With fixed-focal length camera lenses it is most practical to set the camera offset distance to be one where the object in the field of view is in focus.

Once the camera has been positioned with the 3-point plane routine, the flat or curved surface approach can then be applied. In most cases the curvature routine should start with the inclined surface algorithm as it can handle all 3 cases with minimal extra cost in terms of time and/or programming effort.

The 3-point plane touch-sensing routines automatically calculate the normal to the surface and provide the preferred robot position for taking a photo of the surface. Position suitability is intuitively determined by the operator such that the damage is in good view of the camera and that the robot pose is acceptable. The robot position is used to calibrate the image and the weld paths are constructed relative to the calibrated image dimensions and the touch-sensing information. Weld locations are automatically determined based on a few 'damage identifying' mouse clicks in the Graphical User Interface (GUI) by an operator on a remote PC.

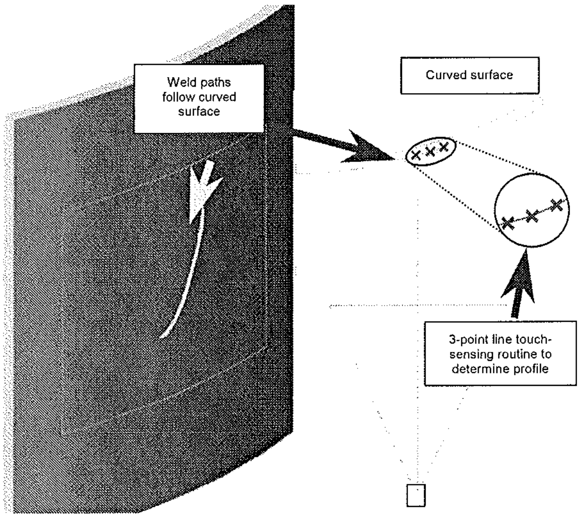


Figure 3. Curved Surface Profiling

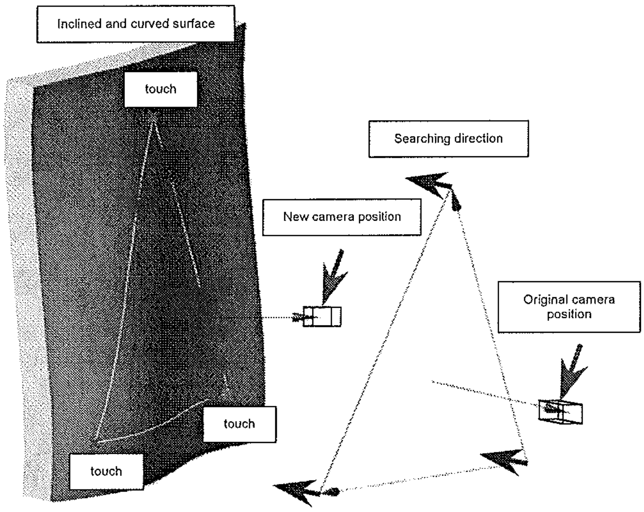


Figure 4. Curved-Inclined Surface Positioning Algorithm

The result is that the weld paths are mathematically transformed from image coordinates to real world coordinates on the workpiece surface. The adaptively coded program is automatically generated, downloaded, and executed on the robotic system to complete the weld repair. The sequence is illustrated in Figure 5. The whole process from image acquisition to weld-start is typically less than one minute, depending on how much time the operator takes to define the repair area.

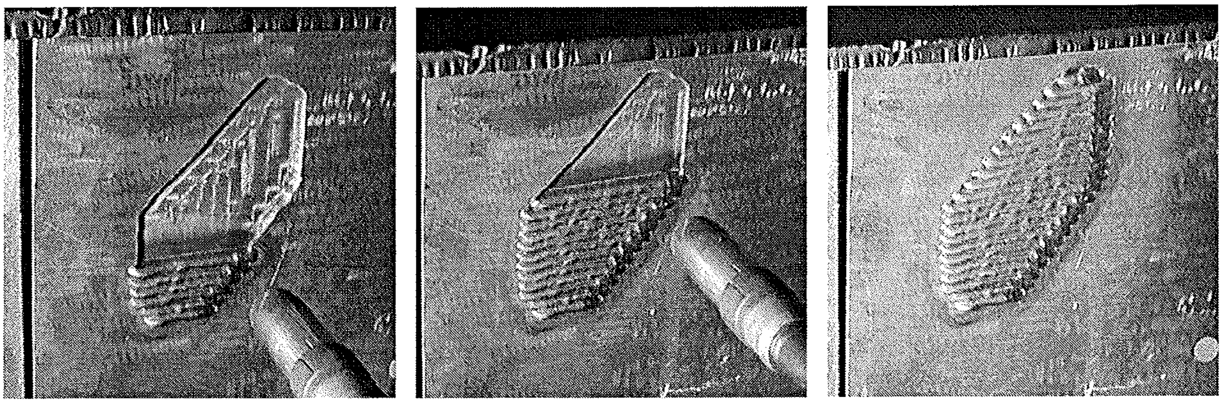

1. 2. 3.

Figure 5. Build-Up Sequence

In the case of non-uniform damage (where the depth of the worn area varies), there are several options; the simplest approach is to manually assess the wear depth during initial damage assessment using a simple depth gauge. The wear area may then be built up by defining several layers on the image corresponding to the average weld layer thickness. Alternatively, more extensive touch-sensing can be performed or more advanced laser structured light or range finders may be used.

5. DISCUSSION

Dip transfer was used in the hydro repair situation due to its low heat input characteristics and excellent stability. Low heat-input welding processes reduce the possibility of distortion, especially when welding thin-walled objects. Positional welding is difficult with conventional GMAW, and pulsed-arc or controlled-dip transfer operating modes may be more appropriate. When welding pipes it is common to encounter a variety of welding positions (locations and postures) and therefore the chosen process must be able to compensate accordingly. The FCAW process described previously would be compatible with the proposed programming approach.

For repair on small diameter pipes (high curvature), the curved-inclined surface profiling approach is more appropriate. When the pipe is positioned horizontally, a camera and welding torch repositioning routine can be performed, followed by a vertical line touch-sensing algorithm to provide the curvature information. For larger diameter pipes (with lower curvature) or for small repair areas, the curved surface line touch-sensing algorithm (without weld torch repositioning) may be used. If the curvature is low and the weld torch orientation is already relatively square to the pipe then a basic single point touch-sensing algorithm is sufficient.

There appears to be an inherent problem with image acquisition when structured light is not used. Great care is needed to achieve consistent and uniform illumination and even then, automatic feature recognition is still extremely unreliable with contrast variations likely to be experienced in this application. For these reasons it is suggested that manual selection of the damage area is used. As demonstrated in the hydro-turbine repair situation, manual selection is simple and quick; taking only a few seconds. It also avoids problems in damage characterisation and hence erroneous auto-identification. While this involves an extra step it is far more robust.

An enhancement of the system would involve the use of laser structured light inspection systems for fine positioning and post-weld inspection. For example, the Flexible Laser Gauging System

(Flexcell) manufactured by Servo Robot [11] was designed primarily for weld bead inspection, and includes an image processing control unit with a high speed vision processor to perform real-time image analysis. The system can be used to detect typical weld defects and for seam tracking. Though more costly, this structured light system avoids many of the problems encountered using unstructured light and can provide quantitative measurements for further processing if required.

A further advantage of the proposed approach is the ability to incorporate real-time monitoring of heat input and CTWD and if necessary adaptive control may be used (e.g. to maintain CTWD).

6. CONCLUSION

Automatic in-service weld repair of pipelines has been shown to be both feasible and beneficial. However, every repair situation will be different depending on the location, size, depth, orientation, and extent of the damage. Therefore, in-service robotic repair requires a robotic system capable of fast reprogramming and adaptive control. Field implementation of such a system would involve the use of mobile mini-robots (as successfully applied in the shipbuilding industry [3]) and a calibration or repositioning routine to accommodate final robot-pipe positioning errors.

The literature available and this work indicate the current feasibility and limitations of the technology, and demonstrate the possibility of developing a new, practical, and cost effective approach to in-service weld repair.

7. REFERENCES

[1]. Holdstock, R. 2006. "Automated In-Service Flux Cored Arc Welding of X80 Pipelines". Masters Thesis. Cranfield University. UK.

[2]. Blackman, S. A., *et al.* 2004. "Mechanised Welding on In-Service Pipelines". Proc. 4th Pipeline Technology Conf. May 9-13. Oostende. Belgium. No. 1.

[3]. Skjolstrup, C. E. 1990, "The Introduction of Robots in a Shipyard". Welding Review. Vol. 9. No. 1.

[4]. Nicholson, A., *et al.* 2006. "Novel Offline Robot Programming Software Development". 16th Int. Conf. Computer Technology in Welding and Manufacturing & 3rd Int. Conf. Mathematical Modelling and Information Technologies in Welding and Related Processes. June 6-8. Kiev. Ukraine.

[5]. Dean, G., *et al.* 2005. "Evaluation of Control Techniques for Dip Transfer Gas Metal Arc Welding". Australasian Welding Journal. 3rd Quarter 2005. Vol. 50.

[6]. Bubenik, T. A., *et al.* 1991. "Investigation and Prediction of Cooling Rates During Pipeline Maintenance Welding". American Petroleum Institute.

[7]. Suzuki, H., Yurioka, N. 1986. "Weldability of Linepipe Steels and Prevention of Cracking in Field Welding". 7th Symposium on Pipeline Research. October. Houston.

[8]. Bailey, N., *et al.* 1995. "Welding Steels without Hydrogen Cracking". Abington Publishing. Cambridge. 2nd Ed.

[9]. Nicholson, A. 2005. "Rapid Adaptive Programming using Image Data". PhD Thesis. University of Wollongong. Wollongong. Australia.

[10]. Nicholson, A., *et al.* 2005. "Rapid Adaptive Programming using Image Data (RAPID)". Proc. 53rd WTIA Annual Conf. October 10-13. Darwin. Australia. No. 24. ISBN: 1-92076-117-9.

[11]. The Servo Robot Flexcell System. www.servorobot.com. Accessed: 10/01/2007.