# WIRE ARC ADDITIVE MANUFACTURING IN STEEL FOUNDRIES

E. D. Weflen, M. C. Frank, F. E. Peters

Industrial and Manufacturing Systems Engineering, Iowa State University, Ames, IA 50011

## Abstract

This work presents the system design of a robotic hybrid additive and subtractive manufacturing system for steel foundries to reduce supply chain disruptions caused by a skilled labor shortage and harsh working conditions. Automation promises to ease the labor shortage but falls short in environments with high variation and ambiguous decision-making. These challenges were overcome by leveraging human adaptability and uncertainty in decision-making, paired with automation conducting repetitive tasks in harsh environments. Documenting the existing process revealed the current welding approach for removing and refilling metalcasting production anomalies. Tasks were divided into those suited for automation and those best suited for a human operator. The operator continues to identify and remove anomalies while sensing and robotics automate weld preparation by machining, refilling using Wire Arc Additive Manufacturing (WAAM), and surface blending by grinding. This research serves as a case study for integrating hybrid manufacturing into production environments.

**Keywords:** Metalcasting, WAAM, Wire Arc DED, Human Factors

## Introduction

Harsh working conditions in the production welding process (Figure 1) at job shop steel foundries, paired with a tight labor market, have caused this process to become a bottleneck in metalcasting production. While robotic welding has existed for decades, traditional rigid automation has struggled in this environment due to the low production volumes and high product mixes in these operations. Furthermore, each production (repair) weld possesses a unique location and geometry driven by the geometry of the production anomaly (e.g., porosity, inclusion, crack, etc.) that must be resolved. This work presents an approach for developing job shop automation processes that address human factors needs and challenges. By leveraging a robot's ability to execute repeatable actions in harsh working conditions, the human operator can work in an improved environment and focus on making ambiguous decisions while handling tasks that require adaptability. Expanding the applications where robotic automation can improve productivity can help manufacturers maintain the supply of critical components in the face of skilled labor shortages.

Figure 1. Production welding of a casting in a steel foundry.

Welding is a normal process step in the production of metal castings [1], [2]. Non-destructive evaluation (NDE) techniques are used to inspect castings and identify regions that may contain anomalies that would not meet the customer's requirements (Figure 2a). These regions are removed from the casting by excavating the site using carbon-arc gouging or grinding (Figure 2b). During excavation, the operator will investigate the area to determine the extent of the anomaly and make decisions around the value proposition of welding compared to scrapping the part. Welding is carried out by a qualified welder using a qualified procedure (Figure 2c), typically developed following Section IX of the ASME Boiler and Pressure Vessel Code [3]. The excavation site is overfilled and then blended with the surrounding surface in a grinding process. This process requires artisan skilled labor and has multiple sources of uncertainty and variation, making it challenging to automate. There is an opportunity to improve this process by reducing the repetitive work carried out in harsh working conditions using an assistive automation system that takes advantage of the operators' adaptability while automating repetitive work.

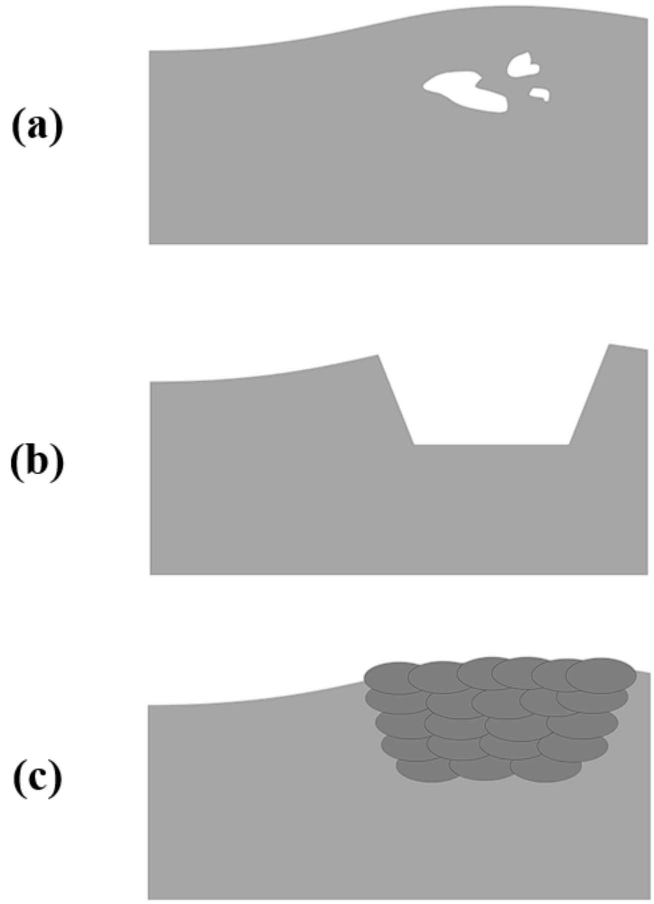


Figure 2. Production welding of a steel casting consists of a) identifying an anomaly using NDE, b) excavating the anomaly using Arc-Air, and c) filling the excavation through welding.

Flexible automation research aims to bring automation to processes with more variability than rigid approaches can typically handle [4]. It is essential to acknowledge that automated systems do not replace humans in the process. Instead, they transform the work the operator does and how they interact with the parts in the process [5]. Automation can be classified based on the level of autonomy and authority held by the system (agent) or by the human operator (Table 1) [6]. Tasks in a process can be categorized into the following types: a) information acquisition, b) information analysis, c) decision and action selection, and d) action implementation [6]. The level of automation in each category of work content can be measured to divide the labor between the human operator and the automated system. By conducting a cognitive task analysis (CTA) to understand and document the process, a sequential process flow chart and hierarchical task analysis (HTA) can be performed [7], [8]. This process can help system designers assign tasks to the automated system or the human operator based on their suitability for automation or the worker's skills. By allowing the human operators to team with the robotic automation in a way where they handle process ambiguity, the automation can succeed in job-shop environments.

Table 1. Levels of automation [6].

| Level | Description |
|---|---|
| 10 | The computer decides everything, acts autonomously, ignoring the human |
| 9 | Informs the human only if it, the computer, decides to |
| 8 | Informs the human only if asked |
| 7 | Executes automatically, then necessarily informs the human |
| 6 | Allows the human a restricted time to veto before automatic execution |
| 5 | Executes the suggestion if the human approves |
| 4 | Suggests one alternative |
| 3 | Narrows the selection down to a few alternatives |
| 2 | Computer offers a complete set of decision/action alternatives |
| 1 | Computer offers no assistance: human makes all decisions and actions |

It is essential to automate the action of welding to meet the goal of improving working conditions in the production welding process. However, the artisan welding motions of a skilled welder filling unique geometries can be challenging to replicate. Therefore, process simplifications are needed to automate the process planning of the welding operation for each casting. Wire Arc Additive Manufacturing (WAAM) has been adopted by several industries, including aerospace and architecture, for the production of near-net shape geometry from metals that may be challenging to process using other techniques [9]. While creating geometry using arc welding has existed for decades [10], this additive manufacturing process, commonly referred to as Wire Arc Directed Energy Deposition (WA-DED or DED-ARC), pairs arc welding equipment with modern multi-axis motion control and automated path planning algorithms to produce the desired geometry (Figure 3). WAAM is often paired with subtractive manufacturing processes (machining) to create a hybrid manufacturing process (HM) [11]. The 2.5D, layer-based process simplification used in additive manufacturing (AM) and employed in WAAM processes has the potential to handle unique geometries resulting from manual excavations in a casting.

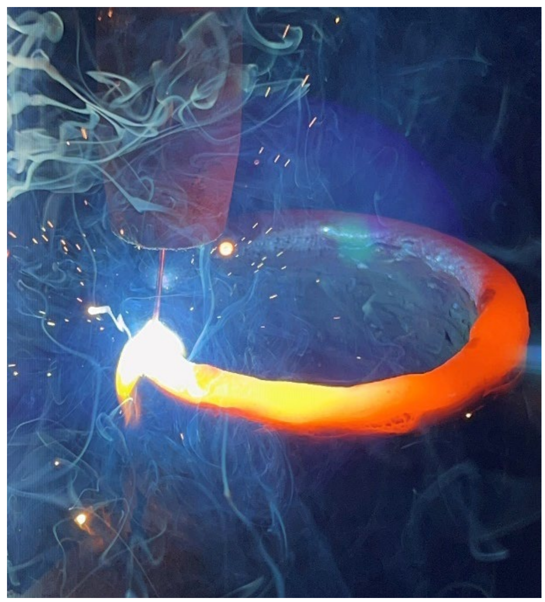

Figure 3. WAAM process executed on a Fanuc six-axis robot.

This work presents an approach to automation system design that overcomes the limitations of rigid automation by bringing together human factors considerations and the process simplifications used in hybrid WAAM processes. This approach is applied to the production welding process used in steel foundries as a case study. A high-level system architecture is presented along with the level and type of automation in the system. A proof-of-concept implementation is presented that evaluates the novel aspects of the system design. The method shown can improve working conditions in steel foundries, enabling them to attract a new generation of workers. This approach can be applied to other applications with ambiguity and variability, broadening the scope of work that can be automated.

## System Design Overview

The existing production welding process was documented in a sequential flow chart containing the tasks, which is not shown here. Tasks possessing a high degree of ambiguity or requiring complex decision-making were labeled. These tasks were determined to be better suited for humans, while the other functions had potential for automation. Tasks were clustered through a hierarchical task analysis (HTA) to identify groups of tasks that are suited for automation. Minimizing the work transition between the operator and automation can reduce the need and complexity for user interface elements. The top level of the HTA is presented (Figure 4), with tasks suited for automation labeled and colored red. Two process steps were included to act as a user interface. The first interface step has the operator mark the location and size of the indication directly on the casting. The second interface consists of a computer vision system in which the robotic automation will employ a 3D scanner to register and interpret the user input.

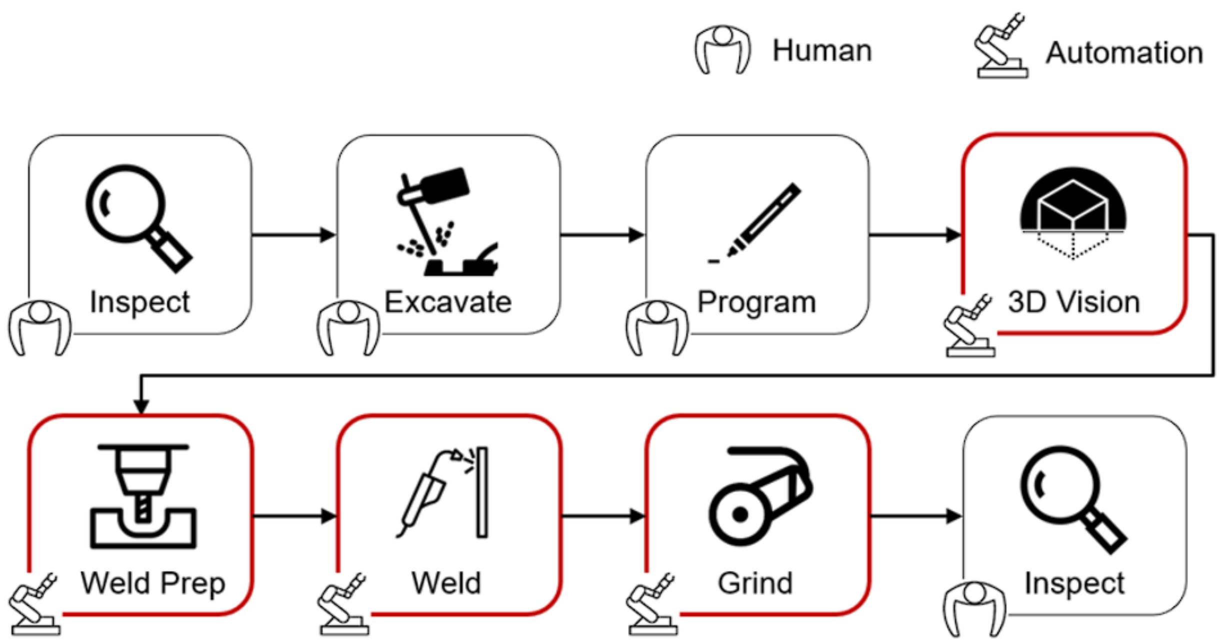


Figure 4. High-level process steps in the proposed casting production welding automated system.

Tasks were analyzed to determine the level of automation appropriate for this system design (Figure 5). The human operator is responsible for information acquisition, information analysis, and much of the decision-making needed to determine the right course of action to fill the excavation. Many action tasks are automated to remove the operator from harsh working conditions. While the actions are automated, the operator will review and approve them before letting the system execute them. This results in what appears to be a relatively low level of automation across the four areas, with much of the automation focused on the action type. While keeping the operator in the loop and giving them the responsibility and authority to review and reject keeps the level low, it can keep the operator engaged and aware of what the system is doing. Keeping the operator actively engaged can be essential for building an appropriate level of trust between the operator and robot in a situation where unique process plans are executed for each welding operation.

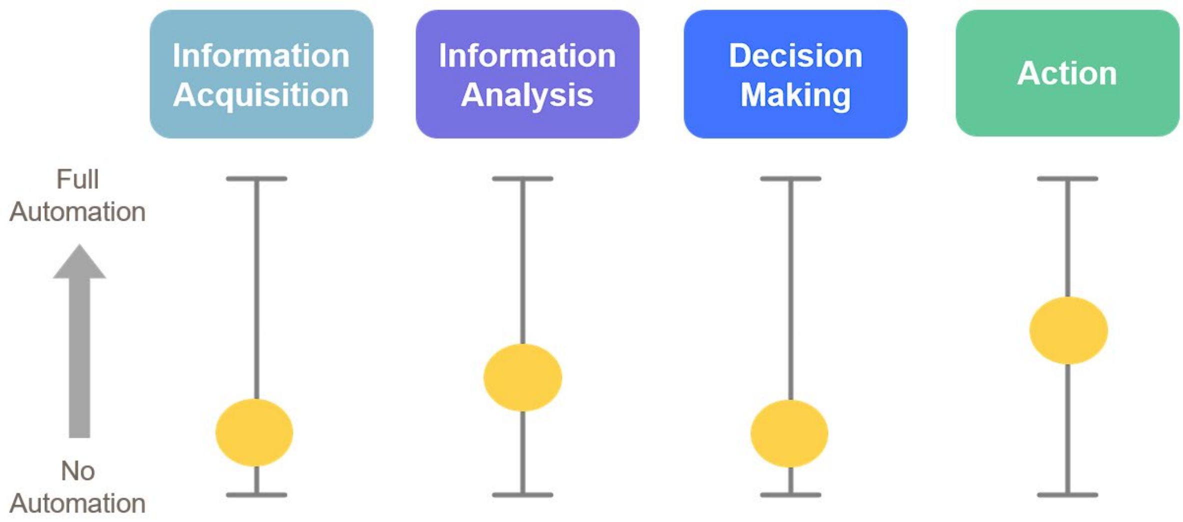


Figure 5. Approximate level of automation in each of the task categories.

**User Interface Design**

A more detailed user interface description is provided (Figure 6). This system borrows the fundamental elements of a user interface design used for the automated blending of risers and gating on castings; this interface relies on the user making physical markings on the casting surface [12]. These markings identify the excavation and a surrounding surface that can be extrapolated over the excavation to recreate the desired surface. Castings consist of complex geometry, which can make the automated detection of geometry that may be undesirable a challenge. However, the skilled workers in a foundry have gained experience that supports the quick identification of the excavation geometry. Relying on the operator to make this determination can simplify the complexity of the 3D vision system.

After marking the casting, the operator triggers the robot to search for excavation locations using a stereo vision 3D camera providing depth and color information (RGBD). The system can then reconstruct the desired surface, defining the void that needs to be filled. An algorithm will fit a standardized and tested welding operation to fill the void, including the associated weld preparation, welding, and grinding toolpaths. Standardizing the welding geometry and paths allows for testing of the welding operations before implementing them in the foundry and reduces the artisanship in this task that made it challenging to automate. This approach also mimics the existing process used in foundries to communicate between operators in the production welding process, reducing the need for additional training.

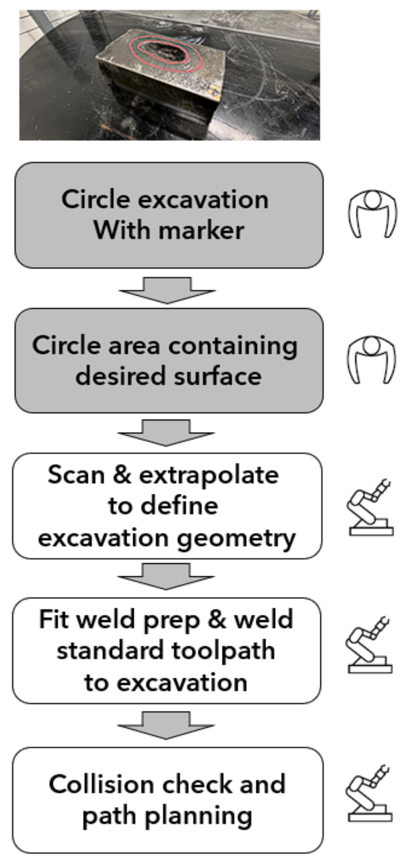


Figure 6. User interface steps.

## Results

The novel elements of the system design were tested using a proof-of-concept prototype system. This low-fidelity prototype implemented the system as a series of process steps to evaluate the process before implementing it as an integrated system. A section approximately 100 x 200 x 75 mm was extracted from a casting. Phased array ultrasonic testing (PAUT) was used to identify the location and depth of an indicated anomaly. Manual carbon arc gouging was used to excavate the anomaly. The surface was scanned with a laser scanner, and a weld preparation geometry was fit using computer-aided design (CAD) software. Machining of the excavation was carried out in a HAAS UMC750 5-axis machining center, but it is anticipated that robotic machining will be used in future implementations. A welding toolpath was generated based on the size of the excavation. Grinding was used to blend the weld with the surrounding geometry to prepare the part for reinspection. Implementation of the proof-of-concept prototype evaluated the technical capability of implementing the system, but further evaluation of the user interface design is needed to measure system design performance.

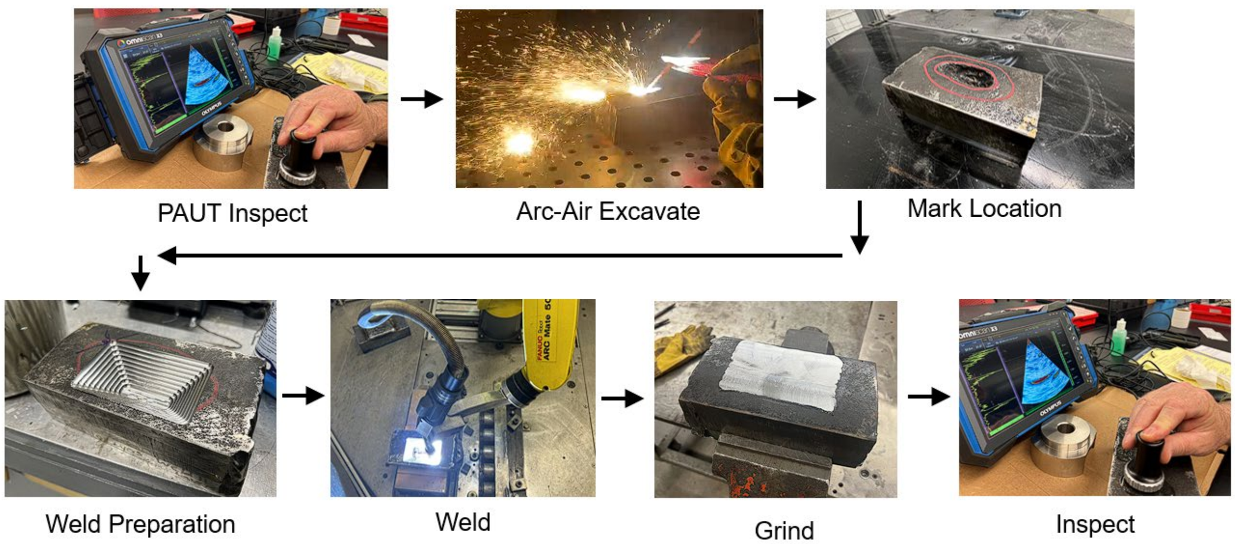


Figure 7. Prototype system proof of concept testing was conducted by executing each process step on a section of a steel casting.

## Conclusions

An approach to automation system development for ambiguous and highly variable applications was presented. This approach attempts to solve the challenges faced by rigid automation in these applications by employing human factors approaches and hybrid WAAM process simplification methods. The existing process was documented into a process flow chart, and an HTA was used to cluster tasks having automation potential while minimizing transitions between the human operator and the automated system. The types of work were evaluated for the appropriate level of automation, and a user interface was designed that relies on physical surface markings and computer vision. Proof-of-concept prototype testing was conducted to evaluate the process. This work demonstrates the potential for automation to be deployed in low-volume, high-mix production environments by integrating the user into the process design.

Further work is needed to evaluate the user interface design and the user experience of the fully integrated system. This evaluation will require a higher fidelity and functional prototype system to be produced. However, individual elements of the system can be evaluated. The research here is focused on the production welding of steel castings. Still, there is potential to apply the approach presented here in other repair and rework applications, such as remanufacturing field deployed components or modifying production tooling. The method used to develop this system that integrates human factors and human-computer interaction methodologies may find applications in other manufacturing system designs when rigid automation approaches fail to handle process variation or uncertainty in the decision-making process.

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## Disclaimer

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## References

[1] "Specification and Qualification of Welding Procedures for Production Welding of Steel Castings." ISO 19970:2016, 2016.

[2] R. Monroe, "Welding Steel Castings," *Steel Founders' Soc. Am.*, 2019.

[3] "BPVC Sectin IX - Welding, Brazing, and Fusing Qualifications," ASME, p. 424.

[4] J. D. Lee and B. D. Seppelt, "Human Factors in Automation Design," *Springer Handb. Autom.*, pp. 417–436, 2009.

[5] D. Romero Díaz *et al.*, "Towards An Operator 4.0 Typology: A Human-Centric Perspective On The Fourth Industrial Revolution Technologies," in *46th International Conference on Computers & Industrial Engineering 2016 (CIE46)*, 2016.

[6] R. Parasuraman, T. B. Sheridan, and C. D. Wickens, "A model for types and levels of human interaction with automation," *IEEE Trans. Syst. Man, Cybern. Part ASystems Humans.*, 2000.

[7] J. Rasmussen, A. M. Pejtersen, and L. P. Goodstein, "Cognitive systems engineering," Wiley, 1994.

[8] K. J. Vicente, *Cognitive work analysis : toward safe, productive, and healthy computer-based work*. Mahwah, N.J: Lawrence Erlbaum Associates, 1999.

[9] S. C. A. Costello, C. R. Cunningham, F. Xu, A. Shokrani, V. Dhokia, and S. T. Newman, "The state-of-the-art of wire arc directed energy deposition (WA-DED) as an additive manufacturing process for large metallic component manufacture," *https://doi.org/10.1080/0951192X.2022.2162597*, vol. 36, no. 3, pp. 469–510, 2023.

[10] R. Baker, "Method of making decorative articles," US1533300A, 12-Nov-1920.

[11] T. Feldhausen *et al.*, "Review of Computer-Aided Manufacturing (CAM) strategies for hybrid directed energy deposition," *Addit. Manuf.*, vol. 56, p. 102900, Aug. 2022.

[12] D. W. Schimpf, "Objective surface inspection and semi-automated material removal for metal castings," Iowa State University, 2021.