Direct-Delivery of Pose (Position and Orientation)

Human-Robot Workflows in the Shop and Field

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ABSTRACT

This paper investigates the ecology of *human-robot workflows* in manufacturing to bring computation to otherwise labor, material, and logistic-intensive operations. Utilizing *Robot-Assisted Workflows*, the research explores direct position and orientation delivery using robots like the *Kuka KR 270 R2700* and the *Leica MS60* Robotic Total Station, alongside custom jigs and software to streamline layout processes. These hybrid workflows support in-shop activities with *Robot-Assisted Welding (RAW)* and on-site tasks through *SurveyLink (SL)*, empowering workers to execute computationally sophisticated buildings with precision and efficiency. By extending computational intelligence to fabrication and installation, the research pioneers automation strategies that create feedback loops between dynamic field conditions and design models. Leveraging robotics for positional data and assembly sequences enables large-scale digital fabrication, blending the precision of machines with the expertise of skilled tradespeople. The integration of robot-assisted workflows and custom jigs revolutionizes construction practices, significantly improving accuracy and efficiency, particularly in low-volume, high-variation production environments. These flexible frameworks elevate craftsmanship by adapting traditional methodologies to modern building demands, linking design models with real-time field conditions to promote a more responsive manufacturing process. This integration represents a major step forward in digital fabrication, enhancing hybrid communication workflows and transforming construction practices.

1   Left image: SurveyLink (SL) used to position layout jig template to mark purlin-anchor attachment locations on pipe. Stud and partial anchors installed on pipe following layout. Installing these anchors using SL enabled Zahner to account for differences in the pipe's 3D design and its actual construction, ensuring we could use already-fabricated panels without the need for remakes or traditional field-measurement. Right image: Weld foreman tack welding the part in place while the robot ensures correct position and orientation.

INTRODUCTION

The architecture, engineering, and construction (AEC) industry has long faced challenges with the layout and assembly of complex prefabricated components, especially when using static 2D documentation and labor-intensive layout methods. These traditional approaches often lead to misinterpretations, particularly with 3D positioning and part-to-part relationships, both in the shop and field. As the industry evolves, integrating computational design and digital fabrication tools has become a key solution for improving precision and efficiency.

Traditional methods involve extensive instructions to locate the *pose* (position and orientation) of parts, including tabular data of 3D position, 2D drawings and part-specific jigs for staging. However, these methods can become confusing when plans change, leading to resource-heavy processes and errors. This problem is magnified with hundreds of unique parts and assemblies that require precise jigs and directives. Additionally, discrepancies between project execution and data from different teams can cause clashes and coordination issues, putting pressure on field crews to resolve problems quickly and avoid cost and schedule impacts.

On the other hand, robots operate directly with 3D positional data. This means they can translate a 3D position from a digital model to the assembly space without the use of part-specific jigs and supplemental instructions. However, robots are known to be used for task-specific roles in the fully automated mode, considering the long history of the mass-production of the automobile. Tasks like welding can be automated when there is a need for a large volume of the same weld, on the same materials, and under the same conditions. However, task-specific robots fall short when considered for flexible production floors. For example, the welds needed across materials, assemblies, and projects are non-repetitive and require a complex balance of heat, speed and tacit material knowledge that come from decades of experience and a trained eye. As such, this paper demonstrates an alternative to the current trend of entirely automated manufacturing methods by hybridizing tasks between craft and the digital and producing a seamless interoperability between the two.

Under the umbrella of Robot-Assisted Workflows, this paper presents Direct-Delivery of Pose as a project delivery method that assists skilled tradespeople in 3D positioning to make complex assemblies into iconic buildings. By directing the positional data and assembly sequence using the robot, we automate the high-risk layout process with embedded instructions in robot programs and remove the need for part-specific jig and directive making. These efforts capitalize on both robots and workforce, combining precision and speed with expertise and knowledge.

In the shop with Robotic-Assisted Welding (RAW) and the field with Surveylink (SL), these methods have yielded high precision assemblies and layout with no remakes (Figure 2). Additionally, embedding instructions into the robot programs for RAW and custom-built interfaces for SL have enabled communicating current state information and reduce paper directives for each unique assembly. With these processes we extend the strengths of computational design tools into the fabrication space and assist skilled tradespeople in the making of complex assemblies into iconic buildings through automation.

STATE OF THE ART

This research builds upon developments within the shop and in the field seeking to mollify the association between construction and high labor, material waste, and logistic intensive operations. The literature frequently highlights the necessity for increased geometric and informational control of prefabricated parts to enhance efficiency, safety, and adherence to the design model (Wang et al. 2023). Additionally, as design possibilities continue to expand, adoption of tools such as robotic arms can help keep pace, as well as offer exciting potentials to integrate with computational design and/or BIM styles of project delivery (Anane et al. 2023). On site, high-fidelity scanning, monitoring, and surveying equipment helps calculate how the construction plan needs to change because of dynamic jobsite conditions causing discrepancies between the design documentation and as-built conditions (Marchetti et al. 2004). Here, where project and safety risks escalate, fabricators and installers are traditionally reliant on the designed adjustability within and between parts, and the tradespeople's abilities to perform the mentally and physically taxing work required to complete these ambitious building projects (Umer et al. 2022).

Some have looked to completely offload challenging problems to automated systems, looking toward a future that is both exciting and controversial (Brosque and Fischer 2022; Keane 2018). However, not every problem can be automated: often a human hand and an informed eye are desirable where computational systems begin to struggle at specific bottlenecks, even when the automated system can perform what feels like 80 or 90% of the work on its own (Bartoš et al. 2021; Hanna et al. 2022). This type of human-robot collaboration may belong to the category of "Stop-Gap", which provides an exciting degree of creativity
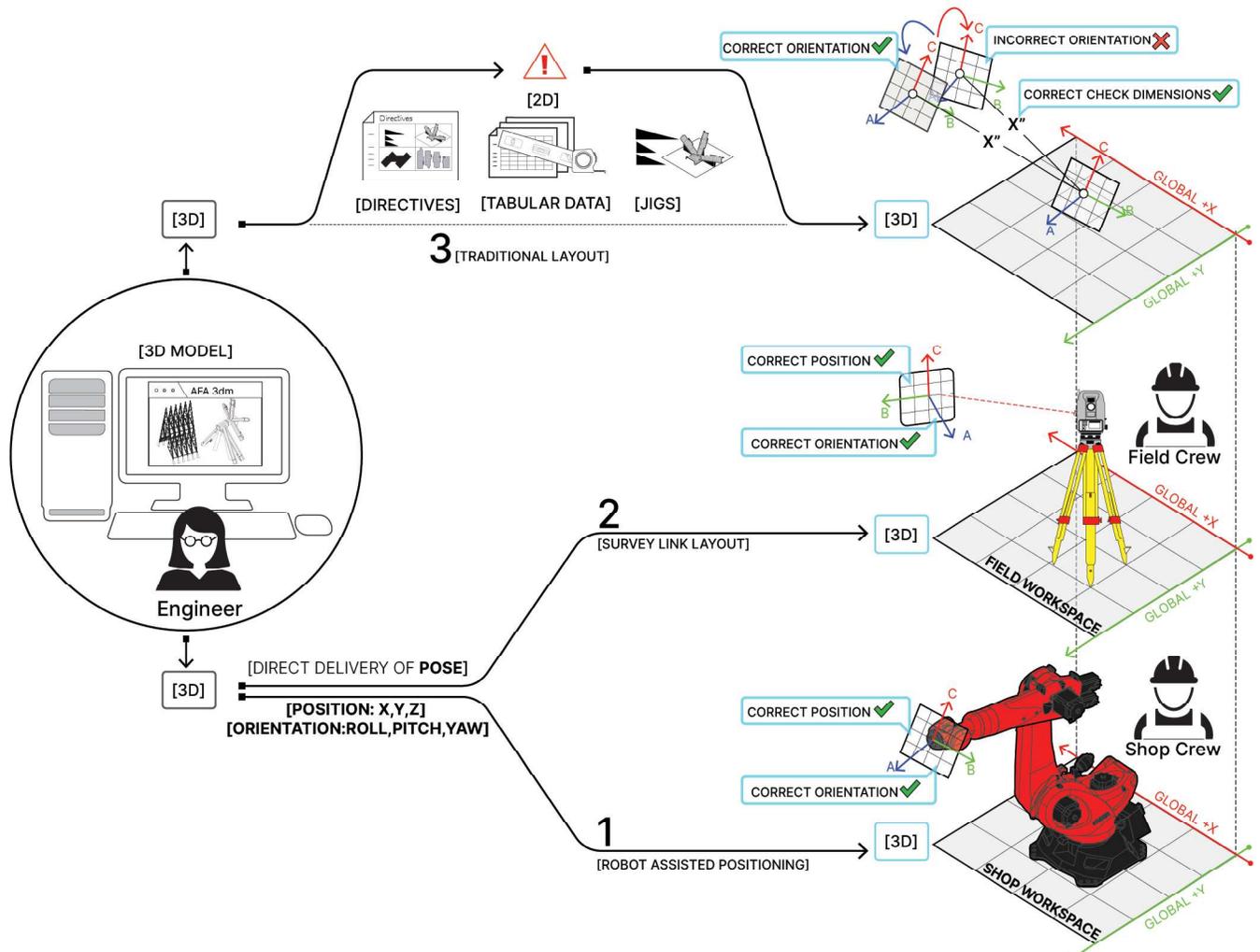
and clarity of need for application (Johns et al. 2020). This investigation thus targets specific problems with computational tools for the tradespeople in the shop and field, aligning with those of task-specific robots with the goal of better and more accurate project delivery (Dusty Robotics 2020; Yablonina and Coleman 2021). Through interviews with shop and field tradespeople it is found that such tools are welcome if they meet criteria such as easy adoption, high predictability, improved quality of work, and accurate, repeatable results and in some of the literature (Coleman et al. 2022; Sam et al. 2022).These tools return agency to the tradesperson to execute their craft by offloading problems better suited to computation.
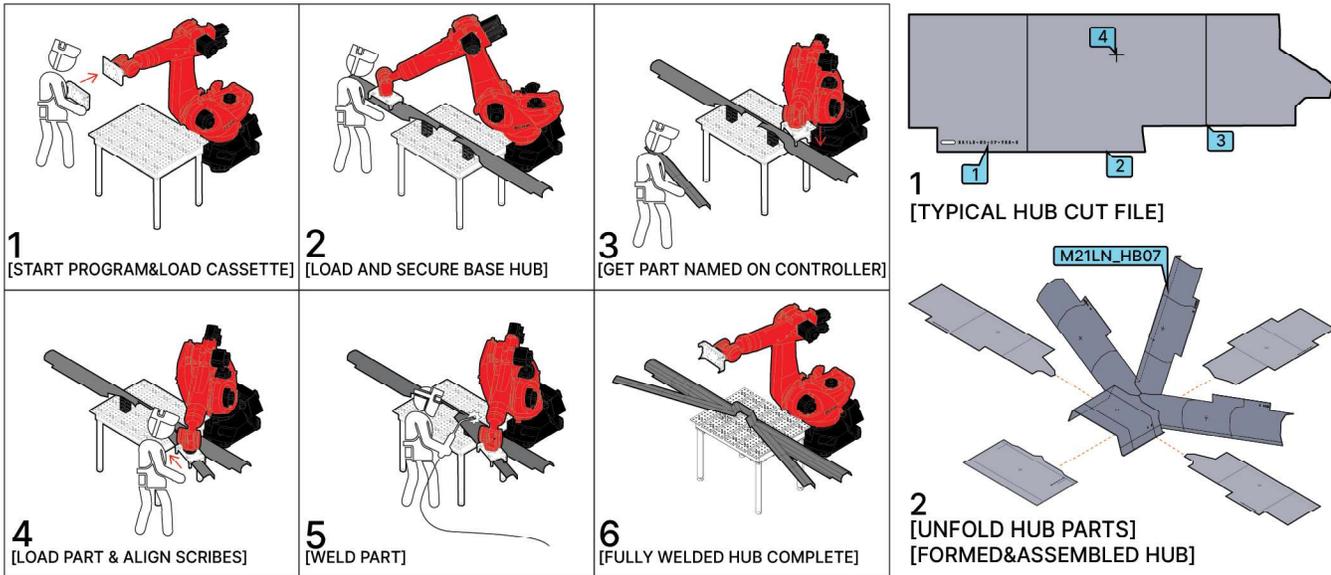
METHODS

RAW and SL both use robots to extend part-specific position and orientation data to assist in assembly and layout of digitally fabricated parts.

Robot-Assisted Welding (RAW)

RAW brings direct-delivery of pose to the shop floor using a Kuka KR 270 R2700 robotic arm, custom-built end-effectors, and *Kuka PRC* plug-in. Specifically, this method is currently deployed to assist the workforce on a renovation project, in the making of 300 unique "hub covers" that protect existing structural steel and ensure water shedding. Hub parts are designed to tailor-fit the scan of the existing structural steel, embedded with transformation matrices (part-to-part relationships), fabricated using CNC equipment, and formed using trade methods (Figure 3).

Embedded transformations in Grasshopper generate custom toolpaths into two robot programs per hub assembly. Programs are named to match part names and include instructions for the tradesperson on the controller, detailing part sequence, cassette names, and positional info (weld vs. Q.C. positions). The first program sequentially prompts and assists the worker through loading,

1	2	3
[START PROGRAM&LOAD CASSETTE]	[LOAD AND SECURE BASE HUB]	[GET PART NAMED ON CONTROLLER]
4	5	6
[LOAD PART & ALIGN SCRIBES]	[WELD PART]	[FULLY WELDED HUB COMPLETE]

1
[TYPICAL HUB CUT FILE]

M21LN_HB07

2
[UNFOLD HUB PARTS]
[FORMED&ASSEMBLED HUB]

3

2   Comparison of direct-delivery of pose (position and orientation) for layout and traditional methods. Workflows of (1) and (2) show as digital information directly translated into physical actualization, bypassing the potential error by misinterpretation of 2D documentation (directives), measuring tools, and jig making processes. Workflow of (3) shows the traditional method where 3D information translated into 2D instructions, with a set of jigs, directives, and tabular data to be interpreted into assembly in 3D.

3   Left image: Robot-Assisted Positioning for hub assembly and welding. Right image: Hub parts modeled in 3DX, post-processed in Rhino and Grasshopper with embedded identifiers, positioning, and Q.C. planes. These files are used to generate unfolded parts for fabrication (CNC cut and brake formed). Embedded identifiers help automate robot-assisted assembly, streamlining workflows for unique and compound angles and handling all unique parts.

positioning, and welding hub parts until assembly is complete. (Figure 3).

Specifically, part-to-part relationships are extended into the physical assembly space by loading parts to the robot by aligning scribe-lines on part to the HDPE cassette (end effector), which correspond to the positional information in the 3D model (Figure 4). In order to extend each unique transformation into assembly information, six different cassettes (end effectors) are used to register ~1,780 hub parts to the robot in the making of 300 unique hub assemblies. Combining two profiles per cassette effectively cycles through the positioning process with the least number of tool changes needed. Once a hub assembly is welded together, the worker is prompted to start the second program, which robotically assists with the Quality Control (Q.C.) process, using an index tool to assist the measurement and verification of compound angles, ensuring the parts are within tolerance and parallel to their respective steel members on the site (Figure 4).

SurveyLink (SL)
SurveyLink is the field direct-delivery approach that assists with pose for installation using a robotic total-station (Leica MS60), jigs and prisms to register physical parts to the 3D model, local server, and a web-app interface

for visualization and control between the installer and the station, providing real-time feedback on part position (Figure 6).

In the browser, the 3D model coordinates are registered to field/site coordinates. This allows surveyed points to be streamed into a local context where they can be compared against the 3D model, calculate deviation from target plane and send instructions that guide parts into place. This method builds on the precision and embedded intelligence from CNC for parts and assemblies that enables the index of physical and digital spaces and activity (Figure 8). This library and much of the web application was developed by *Zea inc* company (version 1.5, Zea Inc.).

The 3D model used to drive the CNC fabrication is developed using computational software (Dassault Catia 3DX and Rhino/Grasshopper) is the same one deployed in the web app. The model is post processed with metadata for defining local planes that correspond to index jigs, then is converted to a proprietary format that compresses it and formats for loading into a lightweight geometry engine in the web.

Utilizing the fabrication model, index locations are coordinated via 3D printed or milled jigs that hold *MPR122* survey
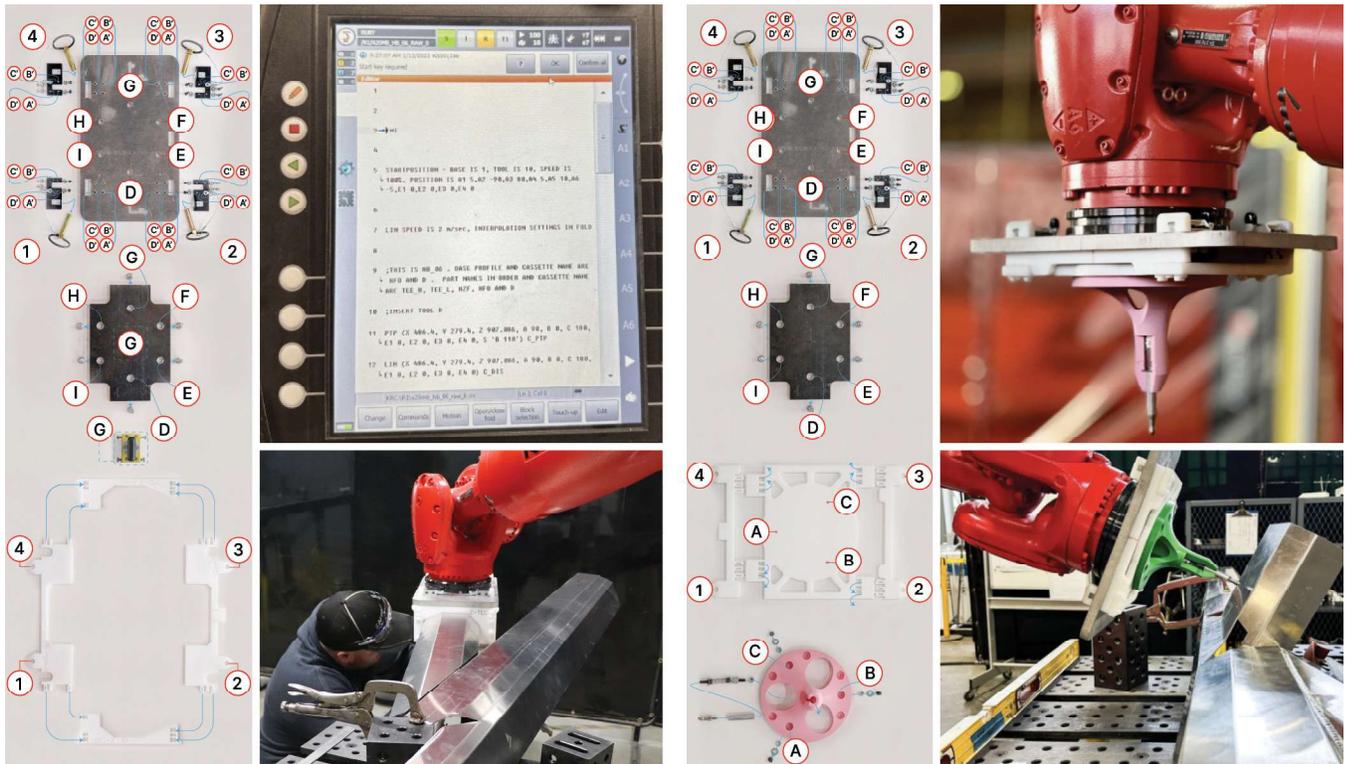
prisms and provide the registration between the high tolerance part/assembly and their digital model locations (Figure 8). Both the fabricated part, the jig and the prism exist in the model, their relationship is explicitly mapped. Once in the model, calculations can be performed based on predefined function that can provide accuracy to that of the station and the prism of 1-2mm (Lackner and Lienhart 2016).
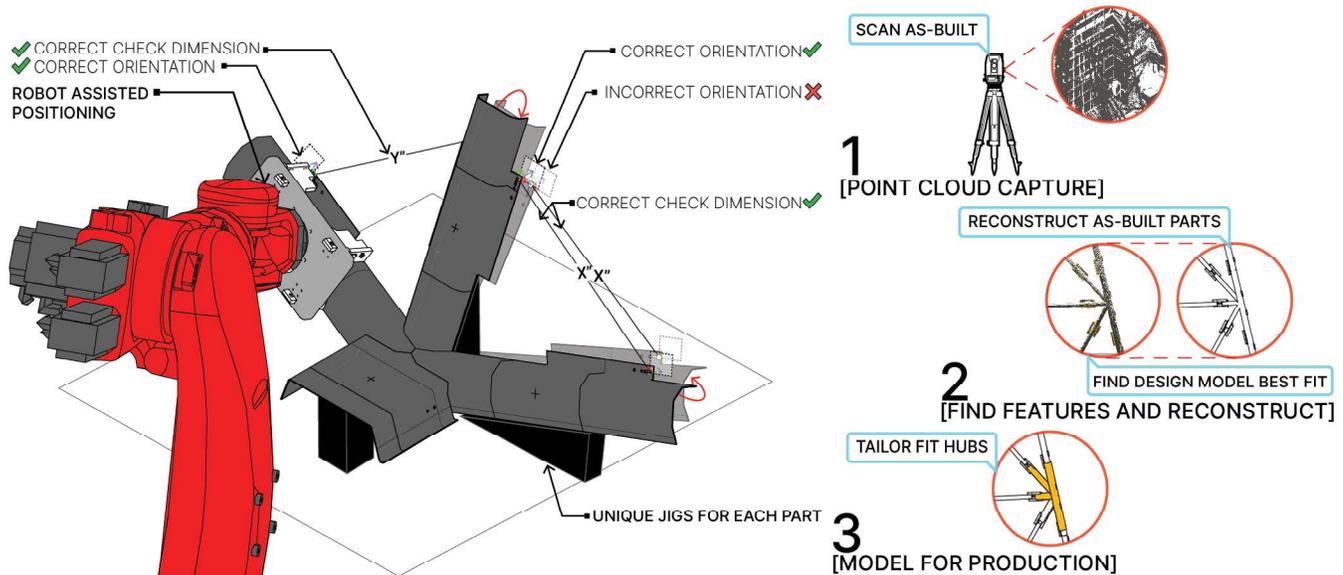
RESULTS AND DISCUSSION

Both methods discussed in this paper have been deployed on the *Air Force Academy Cadet Chapel* renovation in Colorado Springs, where all exterior elements have been removed down to the structural steel to rebuild using SL and RAW. Here, the unique conditions of the steel itself result from construction tolerances of the 1960's, and necessitate frequent survey for accurate as-built information driving the fabrication of tailored parts (each unique to its local condition). However, traditional uses of survey in a typical construction workflow are a siloed process. Often, surveyors are assigned by a single party to sample partial locations and results can come in varying forms, ranging from point clouds to PDFs, giving selective information. There is little feedback between the surveyor and the fabricators or installers, until out-of-tolerance installation and/or collision is identified at a point which often leads to remake of parts from scratch that impact project timeline, budget, and redo of a labor-intensive process.

In contrast, the implementation of survey equipment at multiple points throughout the lifecycle of a project can provide feedback far upstream to stakeholder teams: project management, structural engineering, design, and fabrication teams for the renovation project have strategized well ahead of production to develop the project delivery method highlighted in this paper (Figure 6). In order to set the SL process for success with high-precision assemblies, RAW initiative was deployed to streamline the assembly of tailored parts for the multitude of unique existing conditions directly. Both direct-delivery methods were concurrently developed with computational tools into workflows that address the challenges faced by tradespeople on large scale architectural projects.

RAW and Direct-Delivery

The initial investigation for assembling hub parts in the renovation project evaluated traditional layout methods, which rely on jigs, measuring tools, and tabular data from drawings. These methods can be time-consuming, costly, and prone to errors, especially with complex assemblies. Misinterpretations often occur when parts align with the tabular dimensions but are oriented incorrectly. To address the project's high-precision requirements, RAW was deployed, providing a more accurate and efficient solution (Figure 5).

The RAW workflow for the renovation project begins by modeling existing conditions and using a best-fit process

SCAN AS-BUILT

1 [POINT CLOUD CAPTURE]

RECONSTRUCT AS-BUILT PARTS

2 [FIND FEATURES AND RECONSTRUCT]

FIND DESIGN MODEL BEST FIT

TAILOR FIT HUBS

3 [MODEL FOR PRODUCTION]

5

4   Left image: Robot-Assisted Positioning tools and process. Right image: Robot-Assisted Q.C. tools and process. Both end-of-arm tools consist of (1) 5/8"
    aluminum base base plate and (1) 5/8" steel plate secured with (6) M10 screws, along with any one of the HDPE welding cassettes or the Q.C. tool, and precision
    parts with custom 3D-printed brackets. The cassettes are milled to match specific brake shapes and feature snap-fit connections with tabs that mount or
    demount using a linchpin and braided wire, held by (4) 8-32 machine screws in 3D-printed brackets. An asymmetrical tab design ensures correct orienta-
    tion during rapid tool changes. Instructions like 'INSERT TOOL D', on the left image top right, guide tradespeople during tool changes, while on the left image
    bottom right, union members secure the aluminum profile into the welding cassette for precise robot positioning based on the 3D scan and reconstructed
    digital model of the unique site condition. Once welding process is complete union member moves to Q.C. process using the Q.C. tool, right image top right,
    that has a spring-loaded depth gauge right image bottom right.

5   Left image: Overlay of Direct vs. Translated Delivery of Positional Information: Traditional methods for unique and compound angles require fabricating
    and laying out custom jigs for each assembly, large drawing sets and long tables. These are often difficult to interpret, and tape measurements might show
    correct values even if the part is positioned incorrectly. In contrast, direct-delivery of pose leverages 3D file information to handle unique factors, posi-
    tioning parts faster and with higher accuracy directly from the digital 3D model. Right image: Point cloud to Anchor to Hubs relations diagram.

to match the point cloud's resolution, accounting for pipe profiles and deviations. Custom scripting in 3DX automates part design, embedding useful data for tradespeople and downstream algorithmic workflows.
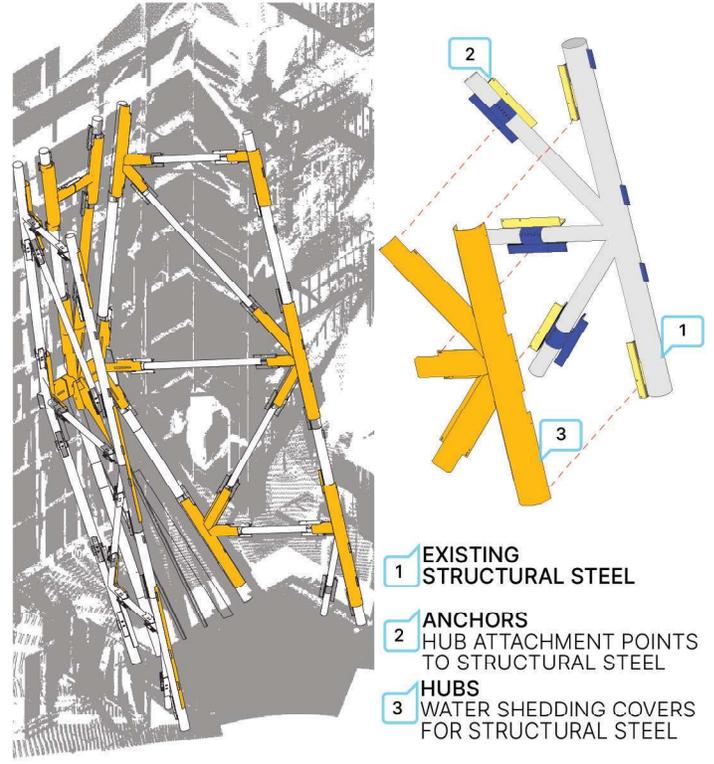
To ensure quality, metadata is automatically transferred between platforms, controlling and circulating information throughout the workflow. Parts with embedded descriptors in 3DX are used in Grasshopper to generate fabrication files and robot programs. In the shop, tradespeople use scribe geometry to align parts accurately with the robot's coordinate space. The robot then places each part in sequence for welding, leveraging workforce expertise. Fully welded assemblies are checked for quality with a robot-assisted procedure, allowing easy switching of quality control programs and providing more reliable measurements than manual checks. Instructions on the teach pendant effectively update the shop floor compared to outdated paper directives. The case study showed success with no remakes and demonstrated that RAW reduces risks, eliminates the need for jigs and paper directives, and speeds up welding for complex parts (Table 1).

Robots, as versatile "generalist" machines, support a

variety of tasks and flexible manufacturing plans essential for complex projects. However, there is a need to further develop these methods to lower costs and enable quick turnaround automation. This would facilitate the broader deployment of Robot-Assisted workflows across projects. The collaborative human-robot approach is a valuable alternative to traditional manufacturing methods, combining the strengths of both to achieve tasks more efficiently and effectively, making complex projects more feasible.

SurveyLink and Direct-delivery

In the Chapel renovation, traditional methods for positioning over 6,000 anchors on the 180' faceted exterior façade were unfeasible due to accuracy and setup time. The SurveyLink method addresses these issues by integrating real-time model feedback with survey accuracy. It uses a 3D printed jig to attach to each anchor type and holds a survey prism at key points for measurements by a robotic total station. This setup allows for computing the anchor's 3D plane as an offset from the prism coordinates. The process simplifies complex positioning tasks for tradespeople by providing clear instructions, such as in-out adjustments based on anchor serrations, thus enhancing

Direct Delivery of Pose   Nalinci, Barnes, Rothbart, Koliyaee

EXISTING
1 STRUCTURAL STEEL

ANCHORS
2 HUB ATTACHMENT POINTS
TO STRUCTURAL STEEL

HUBS
3 WATER SHEDDING COVERS
FOR STRUCTURAL STEEL

6

6   Left image: Kit of parts for index jigs allow for the index of the digital and physical space. (1) Leica MS60 Robotic Total Station, (2) Device for viewing and interacting with webapp (3) Server running Node JS application for TCP communication with station, (4) example of one of the anchors to be located along a steel pipe. (5) 3D printed indexing jigs which locks into the anchor and opens and closes in order to establish a plane and describe the anchor's position and orientation. (6) Leica MPR122 reflector prism. Right image: (1) Scanned with the survey equipment. (2) Anchors positioned on structrual steel using Survey Link. (3) Hubs laser cut, brake formed, welded with RAW.

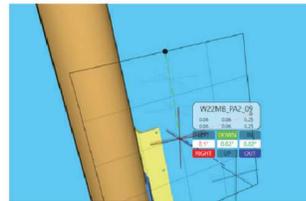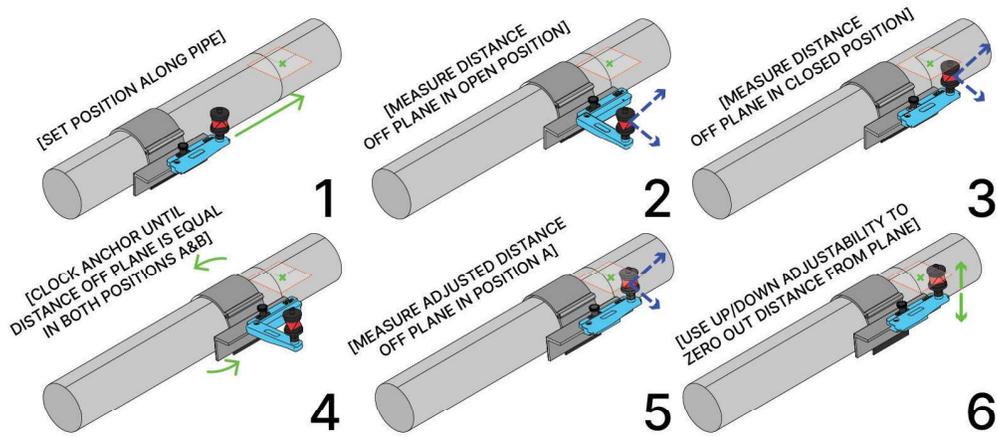precision and efficiency in the installation (Figure 7).

The need for manual conversion is removed, enabling tradespeople to focus on zeroing out values from computational directives and assessing whether the total station's position and orientation make intuitive sense for accurate anchor installation (Figure 8). Integrating as-built models with design models of prefabricated parts enhances analysis beyond traditional survey methods, allowing precise updates of assembly positions in the digital model to match as-built scan data.

SurveyLink (SL) enables installers to request and receive precise positional information digitally, greatly improving coordination and reducing their mental workload. It eliminates the need for numerous custom jigs and extensive manual labor by relying on the precision of robotic stations and indexing jigs to seamlessly connect digital and physical elements.Digital fabrication tools like CNC and 3D printing are crucial for designing, prototyping, and rapidly deploying jigs. These tools effectively manage complex part relationships with compound angles and three-dimensional structures, where traditional measurement methods fall short.

DISCUSSION

While robots have been extensively utilized in fully automated tasks in industries such as automotive manufacturing, their application in the custom-oriented workflows of architectural projects presents challenges. The complex balance of heat, speed, and material knowledge required for non-repetitive welding processes makes complete automation infeasible. Additionally, due to the variation of architectural projects at Zahner, the fabrication spaces and workflows require a high degree of flexibility.

Introducing new technologies like RAW and SL always takes time for tradespeople to adopt, but strong communication between engineers and tradespeople eases the process. This connectivity not only smooths implementation but also helps identify critical tools needed to enhance their workflows. As the primary users, tradespeople provide vital feedback on these methods, with their willingness to embrace new workflows being crucial. Shop personnel have reported increased confidence in part accuracy and efficiency, attributing this to reduced mental and physical stress due to fewer multivariant factors. Granted the stress of the adaptation period, there is longer-term satisfaction and excitement for these new tools. The results of

[SET POSITION ALONG PIPE] **1**

[MEASURE DISTANCE OFF PLANE IN OPEN POSITION] **2**

[MEASURE DISTANCE OFF PLANE IN CLOSED POSITION] **3**

[CLOCK ANCHOR UNTIL DISTANCE OFF PLANE IS EQUAL IN BOTH POSITIONS A&B] **4**

[MEASURE ADJUSTED DISTANCE OFF PLANE IN POSITION A] **5**

[USE UP/DOWN ADJUSTABILITY TO ZERO OUT DISTANCE FROM PLANE] **6**

7 Composite diagram and imagery of prism jig for the Chapel renovation project, which registers to a pipe anchor designed specifically for the project. Above: the measurements built into the design of the 3D printed jig: (1) sliding the pipe anchor along the structure and measuring the prism location verifies that the anchor is in the right location along the pipe. (2, 3, and 4) can encompass two axes of rotation until the 3-dimensional plane of the anchor is parallel with the target plane, and (6) can simply be described by shifting the anchor up or down several serrations until the prism is in the correct location in position A and B.

7

adoption of these tools can be seen below (Table 1).

In a renovation project with around 1,600 hub assemblies, only 300 were fit for the RAW process, while the remaining ~1,300 used traditional layout methods. This project set criteria for future RAW use, considering unique angles and part quantities. On the other hand, SurveyLink has been deployed on 3 projects and assisted with the install of 90% of the anchors on the Chapel renovation (~5400) with each deployment further refining the application to leverage computation in the field. Scalability in computational methods is key, and performance mock-ups have validated the approach for analysis, design, fabrication, and installation, emphasizing the importance of allowing tradespeople to focus on their craft.

CONCLUSION

This paper underscores the significance of computational tools in addressing position and orientation challenges faced by tradespeople in fabrication and construction. It highlights how traditional methods can overwhelm tradespeople, especially as project complexity increases. By incorporating computational tools, such as direct delivery systems, we effectively shift the burden of complex 3D problems away from the workforce, enabling better communication, assembly, and installation.

Through collaborative testing with both shop and field personnel, the goal is to strike a balance between automation and craft through human-robot collaboration. This approach has led to increased part accuracy and reduced tack time, empowering tradespeople to work more

confidently with complex parts. The SurveyLink workflow further reduces reliance on 2D printed instructions by leveraging robotic total stations and digital tools for accurate positional information.

Future work will focus on integrating robot-assisted workflows with complex-geometry building surfaces, balancing digital and craft tools. Enhancing access to end effectors and automation, such as sensors and auto tool changers, will improve precision in delivering positional information. RAW will be scaled up to include multiple robots and personnel as needed. In the field, we will expand sensor inputs and model connections to reduce manual calculations in real time. We will also design physical interfaces with greater flexibility to facilitate direct delivery. Both RAW and SurveyLink will continue to refine these tools to improve adoption and collaboration, ensuring that automation supports tradespeople and enhances project delivery while prioritizing their well-being.

ACKNOWLEDGMENTS

Table 1 Efficiency gain of human machine digital craft for direct delivery using RAW and SL on the Air Force Academy Cadet Chapel. Alternative ways of looking at this is the waste usage saved.

SCOPE	TIME STUDIES PER ASSEMBLY UNIT		TOTAL HOURS SAVED	TOTAL UNITS	JIG WASTE ELIMINATED
	WITHOUT PROCESS	WITH PROCESS			
3D HUBS (RAW)	4hours	1hour	1,200hours	300hours	2,200sf
ANCHOR LAYOUT(SL)	2hours	0.5hours	13,200hours	6250hours	1,350sf
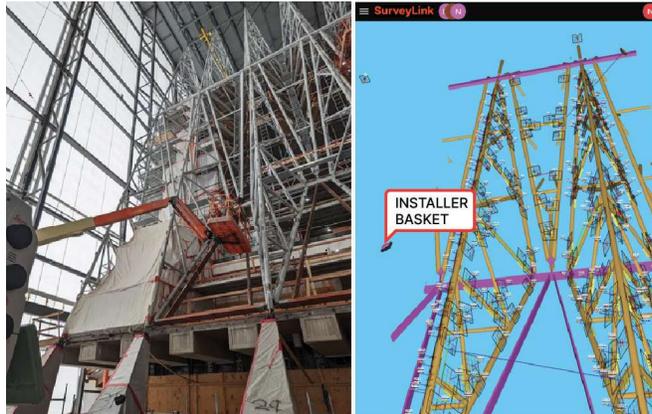
8 Deployment of SL onsite at the Chapel renovation, on left; survey station sampling prisms that are indexed to the anchors in open and closed positions to make a plane calculation. installers controlling station from the basket with a tablet running the web app requesting measurements on demand with feedback. The right is a web model view with deviations in local planes on each anchor in a live collaborative session.

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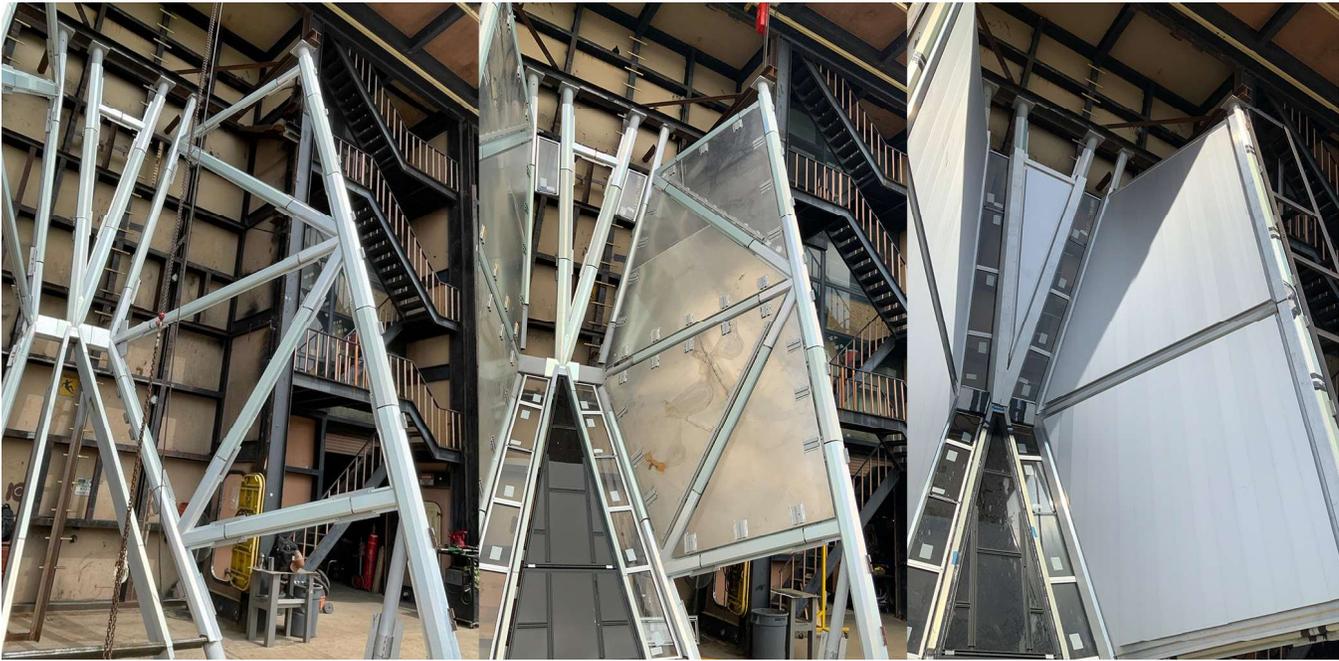
9   Composite of 3 images of one of the performance mock-ups for the Chapel renovation project: from left to right, the primary structure shown with anchors positioned and oriented, in the process of attachment of hubs. Infill panels with attachment hardware for finish panels, and finish panels in process of installation.

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Burcin Nalinci leads robotic frameworks at Zahner R&D, where she focuses on extending computational design tools into the physical space. Her work, centered on human-robot collaboration, leverages both robots and human expertise to handle high-volume and complex projects. Current research includes Robot-Assisted Welding, Assisted Patina, and Assisted Robotic Layout.

Nathan Barnes leads the computational frameworks at Zahner R&D with a focus on seamless interoperability between the digital and physical. His work looks at streamlined delivery methods of fabrication instructions by extending computational tools to shop and field.. He is passionate about encapsulating solutions to problems through technological solutions. His current research is developing software and hardware improvements to nudge forward fabrication capabilities.

Dan Rothbart coordinates the design, engineering, manufacturing, shipping, and install of custom architectural metal systems. Collaborating to balance the needs of the engineer, the architect, the owner, the shop, and, often, the custom manufacturing process. Interfacing with R&D on custom automation for projects, research, and workshops.

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