ROBOT ASSISTED ASSEMBLY OF STEEL STRUCTURES

Optimization and Automation of Plasma Cutting and Assembly

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Abstract. The digitization of the construction industry integrates innovations in design and fabrication to achieve increased efficiency and performance. This paper details the development of a process for optimizing and automating the design and production of branching steel structures including the use of robotic construction, evolutionary optimization of path planning and the creation of an automatic height control robotic end effector.

Keywords. Digitalization; optimization; automation; steel structures; plasma cutting.

1. Introduction

This paper covers our research into the robot assisted steel workshop of the future. The research was motivated by our developments regarding the optimization and automation of branching steel structures. Trees naturally optimize structure so that branches bridge large spans with minimal material usage. Many architects have drawn inspiration from tree-like structures, utilizing their high-performance nature to create iconic spaces (Rian and Sassone 2014). Our research is similarly inspired by these natural structures. This paper describes the process for algorithmic design of a file to factory workflow which provides the user with early design decision assist tools to optimize the design with regards to structure, construction and robotic fabrication.

1.1. MANUAL PROCESS

The challenges for manual work in steel fabrication include the complex and time-consuming nature of translating 2D plans to 3D objects. This includes the difficulties of marking the position of the cut lines and connection points on material. Further difficulties are encountered when clamping different parts together in compound angles. These challenges are increased when many parts are required to have diverse combinations of assembly locations and angles. It is commonly said that good metal fabrication is 90% setup and 10% operation of the tool. The resulting limitation of productivity provides an opportunity to develop a new way of working.

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1.2. DIGITAL OPPORTUNITY

Robots offer a unique opportunity for the future of steel construction. They are strong accurate tools capable of being adapted to a wide range of industrial processes . "Robotic steel fabrication is a common technique in many industrial fields such as automobile and manufacturing industry, where the robots have been successfully performing high speed and high precision tasks to improve the quality of product and deal with difficult and dangerous situation" (Chu et al 2013). In a factory setting, the role of the robot is to increase productivity through increased speed and accuracy. This process should add efficiency with minimal user interaction. The manufacturing process is segmented into tasks that the robot accomplishes with handover points in between. The resulting configuration of work-space often uses safety fences to physically section off the robot from the production worker.

The robot is likewise digitally sectioned off in its workflow, with the programming of its movements often done by a robotic integrator who sets up a work process once and leave the robot to run until a change in the production line requires reprogramming. This works well for a manufacturing process where customization is minimal. For architecture to achieve individualized robotic fabrication of steel structures, a new digital process is required.

1.3. CURRENT STATE OF THE ART

New digital tools increase the accessibility for designers to engage in robotic programming. Parametric design leverages the robotic arms potential for complex customization of movement, process and interaction. The use of robots can be found in academic workshops and conferences such as Rob|Arch and CAADRIA. Still, while the robots and programming may be increasing in accessibility, architectural steel is an industrial process that remain challenging to integrate into this new paradigm of digital fabrication. The development of industrial processes for robotic fabrication in steel is an intensive enterprise. Leaders in the architectural steel fabrication industry have developed enclosed systems which consists of a gantry-based system of crane, turnstile, and linear axis hung mounted robots that can produce mass customized steel sections by welding supports and connection plates to create the bespoke steel beams. Companies like Voortman and Zeman offer such systems capable of mass customization of beams.

The large scale of the system requires programming of many individualized parts and is most efficiently utilized on large production runs. The time it takes to program/set up the machine for small runs is prohibitive, limiting the ability of small and medium size contractors to utilize the production capacity of the system. The automation process is constrained to a factory setting with the prefabricated beams assembled using traditional on site methods. This leaves a digital gap where agile, low investment, mobile solutions capable of factory or onsite works could both prepare parts and assemble them in a flexible and individualized process. Technology capable of bridging this gap would extend the role of a robot to engage in collaborations rather than digitally sectioned off workflows. The scope of this research is to develop such a processes for optimization and automation of creating steel structures. By furthering the development of file to factory workflows this research develops processes enabling designers to mass customize digital fabrication processes and receive early stage input on fabrication and assembly considerations.

2. Process

To empower designers with mass customization in industrial levels of steel requires an informed and optimized file to factory robotic process. Parametric designs customize architecture and optimize form through individualization. File to factory workflows allow the robotic tool path to be created/informed/updated by individualized part descriptions/data/plans. The robotic production process has to adapt to changing tool paths or orientation unique to every part throughout the whole fabrication process. Due to the limits of the robot, the material and the work space, not every element is able to be fabricated. By providing early design feedback regarding these issues the design can be rationalized for robotic fabrication.

A pre-rationalized design embeds construction considerations into the underlying design principles so that the project is engineered for efficiency. A pre-rationalized design adopts changes earlier in the design stages where revisions to the projects principles are low in cost and high in impact. This is in contrast to a post rationalized design where the project is adjusted for constructability considerations after the design development is complete. Such changes are high in cost and low in impact. Relevant information can be provided to the designer regarding constructability, size, stability structure, safety, reachability and assembly sequencing allowing for easier pre-rationalization, validation and optimization. This process simultaneously generates the robot control code thereby creating data ready for production.

The process is illustrated in Figure 1. First the wire frame of the geometry is created. Untrimmed surfaces are generated to create the branches of the structure. These are then trimmed at custom angles to create bespoke parts for fabrication. The assembly is evaluated for stability and structural integrity. The parts are checked to ensure they fit the stock material and robot gripper. The design part’s information is then processed into a robot movement that can be simulated with Kuka|prc, a plug in for the Rhino/Grasshopper 3D modeling environment. Constraints of the robot and tool workspace are analyzed so the user can see if changes to the tool path are required. Parameters that can be adjusted including robotic approach vectors and material orientations. When the design is fully optimized, the information is ready to be sent to the robot cell and metal fabricator. To ensure constructability, the design is broken down into parts, components and assembled structure.

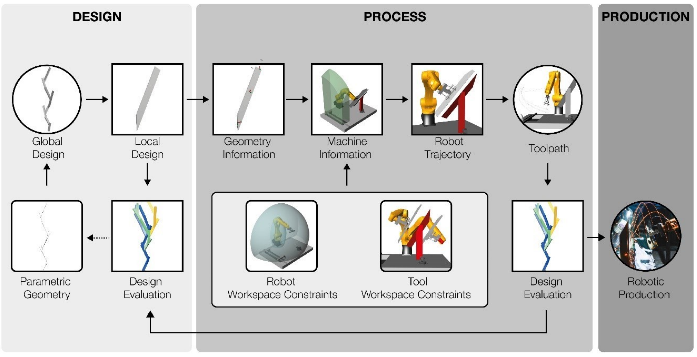

Figure 1. Process diagram of the optimization and automation workflow that was developed to build branching steel structures.

3. Design

The branching algorithm provides various parameters to generate a tree: the start point of the trunk, the vector orientation, the length of the trunk, the position of the next branch, the recursion of the pattern, and the number of branches in the system. This design logic is reflected in the creation of the steel branching structures built during this research. To mass customize these structures, a parametric model was developed which allows a user to iterate through a design landscape in search of optimal solutions. An initial point in space is used to define a vector along which a line is drawn as the trunk center-line of the trees. A second base point for the new branch is defined on the initial trunk center-line. The designer adjusts the direction, length and rotation of the branch vector, and determines the point on the curve to create other branches repeating this process to create the desired number of branches. The center lines are offset to create the flange and web surfaces of the T shaped steel structure. These are then trimmed to create the custom angles needed to cut the metal.

3.1. OPTIMIZATION

Parametric modeling and generative algorithms enable teams to rapidly explore design iterations in search of optimal solutions. The possible solutions for a design grow exponentially as the amount of input parameters increase. Design optimization leverages the power of computation to determine which of these many possible solutions best achieve the goals of the project. There are many methods for optimizing designs, ranging from early stage visualizations of information, to evolutionary algorithms which utilize single or multiple objective optimization algorithms to sort design solutions by fitness (Brown 2016).

For the design stage optimization of the branching steel structure the algorithm provides the user with early stage information to help guide their decisions. In the first phase of design optimization the user is provided with feedback on the stability and structural integrity of the tree as well as information regarding constructability. This allows for the designer to optimize the geometry and member sizes to find the a solution which will not tip over, which will have minimal deflections, and will be able to be fabricated from the material sizes available. The landscape of optimal design solutions must be explored by the designer. This approach is less automated than an evolutionary optimization strategy which automates the exploration the parametric possibilities of the design. A later second stage of optimization does use evolutionary single fitness optimization algorithms to determine the best position of the assembly part. The best solution in this case allows the robot to fully reach all necessary positions without collision.

3.1.1. Stability

The tree is anchored to the ground with a base plate. To calculate the ability of the tree to tip over, the construction is evaluated to determine the center of gravity. To calculate this the surfaces of the parametric model are extruded to custom thicknesses and their volume multiplied by the weight of material to calculate the overall mass of the object and it center of gravity. This center of gravity should remain in the lower third of the bounding area of the entire construction to ensure that lateral forces will not be able to tip over the structure. This common rule teaches the user that a wider base is more efficient than a smaller thicker base in securing a stable structure. This tip over check is visually indicated to the user in the modeling interface so they can see the stability for their design and adjust accordingly.

3.1.2. Structure

A deeper analysis into the structural nature of the model is provided to the user by connecting the parametric model to Karamba, a finite element analysis tool that plugs into the Rhino Grasshopper framework. This structural model provides feedback to the user regarding deflection, utilization and stress that results in the physical structure. This information can be compared to allowable deflection standards to determine if a structure will hold the weight of its own material as well as any additional load it must carry. The geometry of the branching structure and the thickness of the element parts can be optimized based on this information to balance design drivers of low weight low cost high strength to weight ratio elements for assembly.

3.1.3. Material Size

The material size of the parts is then processed for evaluation to ensure that the part fits within the material size. A warning red color will display on the plates to indicate to the user whether the plates are too long or too short to fabricate. As it is not possible to cut underneath the gripper, in this experiment the minimum length of the plate is 400 mm. The maximum plate length is 1000 mm to stay within the limits of the work range of the robot. By providing immediate user feedback as to the availability of material sizing appropriate for this robotic process, the user can easily understand whether the desired tree falls within fabrication constraints and adjust the model accordingly.

4. Robot Assisted Assembly

4.1. EXPERIMENT SETUP AND OPTIMIZATION OF ROBOTIC PROCESS

The experiment setup consists of a steel table for the robot positioning, material supply, plasma cut-ting, arc welding, a KUKA robot arm with vacuum gripper, a plasma cutter, an arc welder, pieces of 2mm x 1000mm x 100mm mild steel plates, a cutting jig and a mobile clamp for component assembly. The robotic process includes a collaboration between fabricator and machine.

To create the part, a robotic arm picks up a piece of metal with the vacuum gripper and moves it to a cutting jig according to the angles of the digital model. If necessary, the fabricator first marks the part for registration in place on the larger assembly. The robot positions the plates on the cutting jig, so that the user can always cut along the same line without having to measure the different angles on one plate. After the positioning, the user cuts the metal with a plasma cutter. This process is repeated until all the angles are cut, at which point the metal is moved by the robot into assembly position and welded manually by the user. The robot thereby becomes a design partner, helping the fabricator assemble complex angles without referencing blueprints or setting up complex clamping fixtures. The robot is utilized for its strengths of repetitive movements and accurate positioning according to digital data while the fabricator is utilizing their strengths of complex tasks such as cutting and welding. This combination provides a powerful workflow for the optimization and automation of steel structures.

The process can be described in the following diagram:

Figure 2. This diagram details the collaboration between machine and fabricator during the robot assisted assembly of the branching structures .

Figure 3. These images detail the robotic process of moving metal from pick up point to cutting jig and to assembly position for welding.

4.2. ASSEMBLY OF THE ELEMENTS

The robot has its own limits, such as reachability, collision and singularities. The tool-path planning process optimizes the movement of the robot to ensure the safe production of the design element. For the design to be roboticlly fabricated the assembly must be broken down into parts and tool-paths created to enable the creation of these parts ensuring reachability and collision free movement. Based on the reachability of the robot in use, the number of sheets that can be assembled as a component must be analyzed. A KUKA Agilus900 was used to create the prototypes of branching steel structures for this research. As this arm has limited reach the component can be made from 4 sheets of steel.

To create the robotic tool path, the designer creates key positions for the robotic process. These include the pickup point, position points on the jig for marking or cutting and the assembly place. Transition points are added in between key positions to define the safe path to approach or leave a point of reference and start moving to the next step in the process. The details of the key points are referenced as planes so that they contain data regarding x, y, z position and rotational information such as a, b and c orientation necessary for determining robot kinematics.

Before any robotic construction begins, the designer must simulate robotic movements to determine if the robotic arm can safely navigate the work environment. The robotic path is simulated to test for collision to ensure the material will not hit the robot, the work cell or the previously assembled pieces. The path is simulated for singularities to ensure the arm will not achieve a state where two axes of the robotic arm align, and the robot cannot solve for kinematic solutions. The robot path is simulated for reachability to ensure the metal can be laced in the proper position. The parametric model allows the user to optimize the robotic path by parametrically adjusting the approach vectors of the robotic movements. The model also allows for the movement of the assembly location in the robotic work cell so that if a different assembly point or rotation increases the chanced of success this can be easily adjusted.

4.3. AUTOMATION OF TOOL-PATH OPTIMIZATION

Even with the increased accessibility of parametric modeling the optimization of design and tool-path information can be a lengthy process with many potential solutions. Advanced computational processes be used to leverage the power of computers in search of optimal path planning solutions which take into account robot configuration and collision avoidance (Gandia et al 2019)

Evolutionary optimization algorithms like Galapagos (Rutten 2013), are used in this research, to automate this process and sort through the iterative design landscape in search of ideal solutions. In this case an optimal solution will find a location and rotation of the assembly position that the robot can fully reach without any collisions. The optimization of the tool path provides the user with additional adjustable parameters including; the orientation of material on the gripper, the height of the retraction, the sequence to key positions, and position of the metal on the cutting jig. In this research an evolutionary model was used to automate the location and rotation of the assembly and to determine the proper approach vectors for moving metal through the workspace. Every collision and limit to reachability in the simulation analysis output can be counted as value that determines the solutions fitness. The more collision points or unreachable positions a potential tool path creates the worse the robotic solution is. The sum of these numbers can be recorded as a fitness and ranked using the plug in Galapagos. The aim of the algorithm in this process is to iterate through parametric values to find a solution with a fitness value which indicates a robotic tool path without any collision or reachability problems. In this research, the robot will turn red and record a value of 1 when a problem is encountered. The sorted solutions are stored in the Galapagos solver.

4.4. ASSEMBLY OF COMPONENTS

The components are produced by the robot arm, however, putting together the components requires manual placement and assembly. The robot assists the user in marking metal for future assembly registration thereby assisting the user in transferring digital information to the object for informing manual fabrication. The user must then align registration marks between components when fitting up the components into the full assembly. Future research seeks to integrate the assembly of components into the final configuration through the use of larger robots with greater reach or the use of mobile robotics. This will require further developments and a more robust tool path optimization strategy capable of navigating the complexity of a greater number of assembled parts.

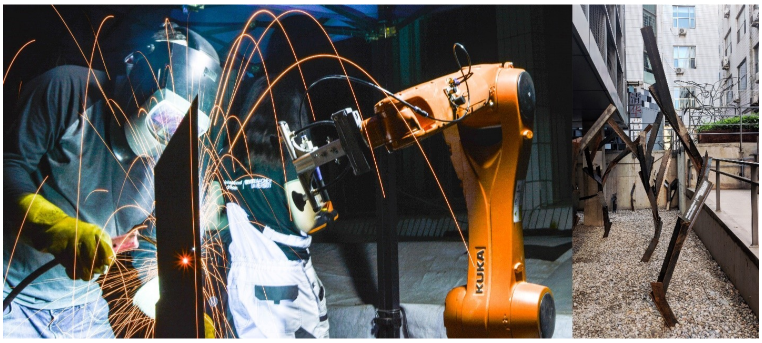

Figure 4. The above image (left) shows a fabricator collaborating with a robot to build branching steel structures (right).

5. Increasing Automation

There are many aspects of the plasma cutting process that a human operator can do easily which prove challenging to program into a robot. The plasma cutter must be held a proper distance from the surface of the material to ensure a proper cut. This distance changes as the metal is not always perfectly flat and may even deform during the cutting procedure. The human operator can easily adjust this distance by feeling the pressure of the torch against the metal and watching the cutting arc to estimate the voltage and proper speed of the cut. The robot is challenged to sense pressure or monitor the cutting arc.

To overcome this challenge this research is developing an automated cutting process built around an adaptive linear axis which connects the robot to the plasma cutter. The linear axis incorporates ohmic sensing to determine the position of the metal and set the start height for the cut. The end-effector then sends a communication to the robot to signal the cut is ready. The robot signals the plasma cutter to turn on and starts its movement to create the cut geometry. The plasma cutter outputs the arc volt-age at a reduced range so that the values can be monitored by Arduino and the position of the linear axis can be adapted utilizing PID controls to maintain a consistent and appropriate cut height (Yudin et al 2017). This process requires optimization to calibrate the amount of motion that the linear axis should take based on the sensitivity to the plasma arc output voltage.

The use of the external linear axis allows a fast reaction time, however, the small linear axis used in initial experiments produces some deflection and adds a waver to the straight line of the cut. Later experiments utilize the ability of KUKA|prc mxA features to directly update the robot movement during the plasma cutting process. This allows for the robotic path to be dynamic, adjusting the robot to changing conditions instead of the linear axis. By integrating the sensor data and adaptability directly into the robotic movement the linear axis can be removed, and the cut quality improved.

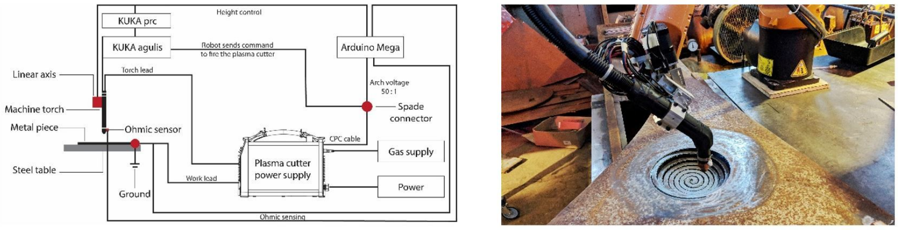

Figure 5. The above diagram (left) details the connection between robot, Arduino and plasma cutter. This setup is used to plasma cut the complex spiral shape (right).

6. Outlook

The goal of this research is advance the ability of designers to optimize and automate the robotic fabrication of steel structures. This includes the creation of early stage interfaces to assist users in creating, analyzing and optimizing the robotic process. This also includes the use of algorithmic optimization of robotic parameters to assist the user in exploring the many possible configurations of location and approach angles possible to achieve a reachable solution free from collision.

To accomplish this goal this research developed information cycles that communicate data from design to fabrication in order to create robotic processes which assist the human in the creation of complex parts and assemblies. As a result, smart hardware and software setups for human-robot-collaboration were developed.

Further future developments include the collaboration of multiple robots and mobile platforms to in-crease the range of assembly work area. This would allow for complex cuts of hollow steel sections beyond flat sheets and will allow for the development of robotically fabricated, structurally optimized trusses and space frames as developments of the work presented here in branching steel structures.

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