A Robotic Fabrication Methodology for Dovetail and Finger Jointing

An Accessible & Bespoke Digital Fabrication Process for Robotically-Milled Dovetail & Finger Joints

ABSTRACT

Since the advent of industrialized processes in modern construction industries, the development of and relationship between computer-aided tools of design and computer-controlled tools of fabrication has steadily yielded new and innovative construction methodologies. Whilst industry has adopted many of these innovations for use by highly efficient machines and flexible processes, their operation is often highly dependent on industrial scales of production, and thus often inaccessible for small-scale, bespoke and affordable application.

The prototype integrated joint milling methodology, case study and open-source software plugin ‘Dove’ presented in this paper, explores the efficacy of algorithmic processes in dynamically generating complex tooling paths and machine code for fabrication of bespoke dovetail and finger joints on a 6-axis industrial robot. The versatility, speed and precision of 6-axis robotic milling, allows us to liberate the efficiency, integrity and aesthetic of the dovetail and finger joint types from traditional application, and apply them to new architectures involving mass-customisation, complex form, and diverse materialities. In the development of full-immersion milling toolpaths and back-face filleting techniques that drastically reduce cutting times, tool path complexity and material waste, this study seeks to build upon past and current research by proposing a comparatively simple, efficient and more intuitive approach to robotically-fabricated integrated jointing for application at a variety of scales.
INTRODUCTION

Motivation
Recent studies concerning robotic-manufactured jointing, such as the 2011 “ICD/ITKE Research Pavilion” (Menges 2012), the 2013 EPFL IBIOS Pavilion (Robeller, Nabaei, and Weinand 2012) and more recently, the 2014 Landesgartenschau Exhibition Hall (Menges, Schwinn, and Kreig 2015) have demonstrated the advantages of 6-axis robotic manufacturing methodologies in the readaptation and fabrication of traditionally inspired, high-performance integrated jointing. Citing specific inefficiencies and limitations of state-of-the-art connectors prevalent in the construction industry, these projects have sought, through use of 6-axis industrial robots, to explore traditional finger-type and dovetail-type integrated jointing as a means of increasing overall structural performance, improving material efficiency and a reduction in construction process complexity (Menges 2012; Robeller, Nabaei and Weinand 2014).

The dovetail/finger-jointing algorithm and case study presented in this report seeks to build upon this research by proposing a new, more efficient and flexible approach to robotically facilitated joint fabrication, applicable across a variety of materials and at a range of scales (Figures 1 and 2). Utilizing the flexibility and precision of an industrial KUKA KR60 6-axis robot and milling spindle endeffector, our prototype algorithm explores full-immersion milling as a means to drastically reduce cutting times, toolpath complexity and material waste in subtractive joint fabrication.

Additionally, our process addresses the common inability of many CNC technologies to accurately mill sharp inner joint edges (Simek and Sebera 2010). Currently, this limitation is often addressed by boring a hole in place of the demanded inner edge, resulting in what is known as “Mickey Mouse ears” (Simek and Sebera 2010). Our algorithm substitutes this with a cleaner and more effective process of “back-face filleting”—an additional milling operation that fillets the corresponding demanded edge to the same radius as the filleted internal edge for clean connection (Figure 3).

Further, in the packaging of this scripted process into an approachable and customizable plugin component, named “Dove,” for the popular visual scripting interface Grasshopper for Rhinoceros, we demonstrate a potential means for bringing mass-customizable robotic joint fabrication to architectural academia and industry in an accessible and efficient manner.

Limitations of Current CNC Processes in Joint Milling
Historically, NC (numerically-controlled) and CNC (computer-numerically-controlled) manufacturing technologies have been
largely confined to repetitive-production processes (Gramazio, Kohler, and Willman 2014). Following the proliferation of low-cost CNC machines, and developments in early CAD/CAM (computer-aided design/manufacturing) software in the 1960s, more complex manufacturing briefs have become feasible. Indeed, the benchmark of complexity continued to be raised over successive decades with the development of multi-axis CNC machines, which utilize multi-axis movement of the tool, the base, or both.3 This allows for greater flexibility in the way parts are held and machined in the manufacturing process, increasing the diversity of applications of the tool.

Despite the development and adoption of multi-function, 6-axis articulated-arm robots in many automated manufacturing processes, industrial fabrication approaches concerning articulation and connection of building elements remain heavily dependent upon expensive and highly specialized industrial 3-axis and 5-axis CNC machines (Gramazio, Kohler, and Willman 2014). Whilst these machines and processes are capable of bespoke production, they generally depend on large production runs to remain operationally feasible and thus are mostly beyond the reach of small-scale construction or bespoke fabrication applications.

Automated manufacturing of bespoke integrated joints, such as the dovetail joint and finger joint, is fast and accurate on smaller, 3-axis CNC machines, but specific drawbacks limit the applicability of this fabrication methodology in construction (Simek and Sebera 2010). Such shortcomings include restrictions in material size (limited by CNC bed size), restriction to right-angled connections (acute or obtuse joints would require 4 or more axes), and the aforementioned inability to produce sharp inner edges (Simek and Sebera 2010).

Joint Types And Fabrication Approaches

Recent architectural research projects, such as the 2011 ICD/ITKE Research Pavilion (Menges 2012) and 2014 ICD/ITKE Landesgartenschau Exhibition Hall (Menges, Schwinn, and Krieg 2015) have explored the use of 6-axis, articulated-arm robotics and parametric algorithmic design in fabricating bespoke, multi-angled finger jointing in wood (Figure 6). In “Morphospaces of Robotic Fabrication,” Menges recognizes that existing industrial processes of fabricating integrated wood joints are highly restrictive compared to the flexibility of articulated-arm robotic milling, and suggests the potential for robotics to extend traditional wood-jointing techniques as a means for extracting the significant structural and economic advantages of form-fitting, mono-material connections (Menges 2012).

In order to overcome the aforementioned existing limitations in CNC dovetail/finger jointing milling, the fabrication methodology of the ICD/ITKE pavilion incorporates a 7th axis rotating base for increased toolpath access (Figure 4) and a spot-facing milling routine in order to produce a sharp inner edge.4 However, this methodology is only applicable to finger jointing and not dovetail jointing, since the acute nature of a dovetail geometry conflicts with a spot-facing toolpath of an end-mill tool bit.
Similarly, the 2013 EPFL IBIOS pavilion has also explored the possibilities of using robotic fabrication methodologies in wood joining, more specifically as a means to address particular limitations of state-of-the-art internal and/or external metal connectors in the alignment and connection of large-scale sheet materials at precise, non-orthogonal angles (Robeller, Nabaei, and Weinand 2014).

In contrast to the more complex spot-facing approach of the ICD/ITKE pavilion, the EPFL IBIOS pavilion utilizes a more common Mickey Mouse ear approach to the “sharp inner edge” problem by boring a hole in place of the inner demanded edge (Figure 5). Whilst simple and effective, it has been suggested that the remnant cylindrical cavity creates a partial weakening of its geometry (Simek and Sebera 2010). Further, it can be suggested the Mickey Mouse ear detracts from the aesthetic qualities of an expressed joint, particularly in a design context.

METHODOLOGY
Full Immersion Path Logic

The fabrication methodology and toolpath logic we propose in our prototype algorithm is composed of two separate milling operations. The first and primary operation explores full-immersion milling as a means of eliminating "roughing" passes from the milling sequence, thereby drastically reducing cutting time, toolpath complexity, and material waste in subtractive finger and dovetail joint fabrication (Figure 7). The second process seeks to resolve the "sharp inner edge issue" via the detection and application of a "back-edge filleting" milling operation, thereby removing need for the Mickey Mouse ear approach.

Unlike both the ICD/ITKE and EPFL IBIOS pavilions, the surfaces to be joined are milled upright in the XZ plane, with the connecting face oriented upwards (Z positive). This arrangement increases the degree of access for the robot for circumstances where a rotating base is unavailable, and enables use of a common table vice and simple bracing jig to secure each surface for milling. Similar to the milling methodology of the ICD/ITKE pavilion, acute/obtuse capability for joint angle is achieved via rotation of the milling tool in the plane perpendicular to that of the upright surface (Figure 8).

As illustrated in Figures 8–10, the notations AM\(^1\) and BM\(^1\) through to AM\(^n\) and BM\(^n\) specify both the initial sequence of the tool trajectory and the \(n\)th sequence of the tool trajectory for milling on each of the connecting surfaces A and B. The number of milling passes (n) for each surface are a function of the surface depth (\(D_A\) and \(D_B\)), the tool bit radius (\(R\)), and surface material type. The tool bit face type (flat-face, ball-end, etc.) is irrelevant for toolpath calculations.

"Dove" Plugin Interface

A key motivation throughout the development of this fabrication methodology was the aim of being able to disseminate the process in a way that was both approachable and accessible to designers of relatively low CAD/CAM literacy. As such, the development and writing of the fabrication script has been consistently approached with regards to flexible applicability, as
8 Isometric: Surface A, primary full-immersion milling toolpath
9 Isometric: Surface B, primary full-immersion milling toolpath
10 Isometric: Surface A, secondary back-face filleting toolpath
opposed to user-specificity.

An open-source, singular plugin component for Grasshopper, entitled "Dove" has been developed in response to these issues (Figure 10). Provided the referencing of two planar adjoining surfaces in the Rhinoceros workspace environment, and with the input of the specified variables, the KRL commands for fabrication and preview geometry are generated. Customizable variable inputs include (in order); Surface A Thickness, Surface B Thickness, Number of Dovetails, Dovetail Angle Factor, Dovetail Tolerance, Material Width, Material Height, Number of Milling Passes, Tool Diameter, Tool Rotation Direction, Spindle RPM, Number of Tool Bit Flutes, and the X, Y and Z location of the surface in space.

RESULTS
Preliminary Structural Analysis
As a means of testing the structural efficacy of the proposed filleted dovetail joint, preliminary finite element simulations were performed upon traditional-type, Mickey-Mouse-type, and filleted-type dovetail geometries in order to ascertain and compare indicative von Mises stress distributions across each dovetail jointing type. For each simulation, a uniform, positive-vertical (Z+) 2000 N load has been applied to the rear edge of Surface B (Figure 12), while the lower-bottom face of Surface A has been fixed (constrained in all possible degrees of freedom). In order to reduce the complexity of simulation, the material properties of each surface were defined as isotropic as opposed to anisotropic (this assumption would need be reconsidered in the event of a timber material stock). The number of dovetails and angle of dovetail is consistent across all simulations.

In comparing Figures 12a and 12b, we can see that the distribution of forces becomes focused around the bored-hole geometries at each inner edge, suggesting that a concentration yet overall reduction in von Mises stress is taking place in Figure 12b. This observation is consistent with finite element analysis undertaken by Simek and Sebera 2010) who suggest that while the Mickey Mouse ear dovetail joint reduces the probability of crack initiation, it also creates a partial weakening of the geometry. Further, in the comparison of Figures 12b and 12c, there is the suggestion that an even more optimal distribution of stresses could be achieved with a filleted dovetail type joint.

CONCLUSION
The dovetail and finger jointing methodology presented in this report seeks to build upon current research by developing a more flexible, efficient, and accessible approach to robotic joint fabrication; an approach that is applicable for a variety of material types and at a range of scales.
The scope of possible applications for robotically facilitated jointing is significant. At a larger scale, applications could include bespoke jointing articulation in prefabricated housing and large-scale material assembly in building construction, and at the smaller scale, user-designed and assembled furniture and joinery. In these applications, great potential exists for the joining of used, non-standard, readapted or found materials of diverse thicknesses, materiality and aesthetic styles.

This research additionally addresses some common limitations of current CNC technologies, most notably the inability to accurately mill sharp inner edges in integrated jointing systems. Where the aforementioned Mickey Mouse ear approach side-steps the issue, a filleted dovetail approach produces a clean, secure, and potentially more structurally effective solution through a back-face filleting technique. Importantly, this technique and the full-immersion milling procedure proposed are both applicable to wood and other more dense materials. It is however important to note that if a chosen material stock has anisotropic properties (such as timber), these will need to be taken into account when specifying material orientation, tooling, and spindle properties.

Finally, it is through the development of "Dove," an open-source plugin for Grasshopper, that this work further seeks to reduce the complexities of robotic milling operations into an approachable, accurate, and mass-customizable process. In this, we hope to expand and encourage a greater scope of feasible application for integrated jointing to the wider design and fabrication field.

ACKNOWLEDGEMENTS
This research was supported largely by the University of Sydney, Faculty of Architecture, Design and Planning, in particular, by the staff from DMaF whose insight, expertise and time were invaluable in producing the research.

NOTES
1. Full-immersion milling is the subtractive process of completely submerging a revolving tool bit in the milled material.
2. 'Rhinoceros 5.0', Robert McNeel & Associates
3. Multi-axis machining is defined by 4 or more axes of movement
4. A spot face is a machined feature in which a certain region of the work piece (a spot) is faced, providing a smooth, flat, accurately located surface.
5. Roughing mills or milling is a milling process by which removal of a large volume of material takes place. As a consequence of the aggressive subtractive process, a roughened surface finish is often left.
6. A jig is a device that holds a piece of work and guides the tool operating on it.
7. The Dovetail Angle factor refers to a value between 0 and 1 that maps the dovetail angle between 0° (finger-joint) and 12°.
8. Anisotropic is an object or substance having a physical property, which has a different value when measured in different directions.

REFERENCES


IMAGE CREDITS

Figure 4: ICD, University of Stuttgart. 2011. Photo retrieved from http://icd.uni-stuttgart.de/?p=6553

Figure 5: Photo by Fred Hatt, 2013, IBIOS Ecole Polytechnique Fédérale de Lausanne. Photo retrieved from https://actu.epfl.ch/image/17761/original/7104x3883.jpg


All other drawings and images by the authors.

**Mitchell Page** is a Graduate Architect and Computational Design and Fabrication Specialist at Cox Architecture, and a Research Assistant at the University of Sydney, Faculty of Architecture, Design and Planning. Mitchell received his Bachelor of Design in Architecture (2012), and Master of Architecture (2016) at the University of Sydney, Australia.