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ORIGINAL PAPER

Roboticus tignarius: robotic reproduction of traditional timber joints for the reconstruction of the architectural heritage of Valparaíso

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Abstract The architectural heritage of Valparaíso, Chile is disappearing before our eyes while all the conventional resources to reverse this situation seem to have been exhausted. A large portion of the existing historic building substance consists of timber frames that succumb one after another to weathering, termites and structural fires. The acute shortage of traditional timber framers and a weak local heritage industry feed investors' disinterest in preserving the original structural conception of these timber-framed buildings when they need restoration or rehabilitation. There is a need for technological innovation enabling one-off production of complex-skilled joinery at competitive costs. Robotic machining emerges as a flexible and customizable alternative to the missing timber framers and the insensible substitution of original timber joints for metal fasteners. We present a proof-of-concept of parametric 3D modelling and robot path generation using a single visual scripting environment integrated to CAD software that requires no knowledge of robot programming and might encourage designers as well as small- and medium-sized manufacturers to develop a local heritage industry. Several classes of timber joints found in Valparaíso were parameterized and instances thereof manufactured by a six-axis industrial robot with a spindle mounted thereon to gain empirical knowledge of the entire process. Experimental results show that procedural modelling of parts, assemblies, and tool paths in the tested visual scripting environment is time-consuming and rather complicated for conventional architectural thinking, but is largely compensated by its software and hardware interaction potential.

Keywords Robotic milling · Visual robot programming · Visual scripting · Parametric milling models · Timber joints · Wooden architectural heritage

1 Introduction

A historic "area" or "site" comprises a variety of open spaces, structures and buildings, each with specific qualities to be preserved. The wooden architectural heritage of the historic quarter and the UNESCO world heritage site (inscribed in 2003) of the seaport city of Valparaíso, Chile consists of timber-framed buildings of which the original structural conception meet geometric, material and mechanical qualities to be preserved. Traditional timber framing differentiates itself from other wood construction methods by the use of heavy hardwood timbers interlocked by corresponding pairs of projections and recesses carved on each member and secured together with wooden pegs and wedges. Timber framing was commonly practiced in many parts of the world from ancient times until the beginning of the twentieth century when technological innovation and the demand for fast and cheap housing solutions favored the use of softwood dimensional lumber and metal fasteners. Technological innovation, at that time, brought to Chile the steam-powered sawmills and nail-cutting machines (Guarda 1995). We found timber frames

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Fig. 1 The roof of the National Maritime Museum of Chile

built in Valparaíso between the late-nineteenth century and the early twentieth century that use lighter timbers than traditionally with interlocking joints held together with nails, bolts or iron straps to prevent disassemblage in the out-of-plane direction (see Fig. 5). Valparaíso was then a thriving seaport that attracted immigrants from all over the world including carpenters and joiners mainly from Europe and North America. They built this cosmopolitan city applying traditional knowledge and copying the latest fashion back home. We found in Valparaíso and Santiago original copies of carpentry treatises and manuals that were most likely brought by them. The geometry of many interlocking joints is not visible to the naked eye and often cannot be identified on site by non-destructive methods; therefore, hypotheses about their form were validated by the exhaustive review of these documents (Barberot 1911; Gaztelu 1899; Oslet 1980; Cabanié 1864; Biston et al. 1842; Emy 1841). By now, we have identified twenty-seven classes of timber joints found in historic buildings of Valparaíso.

Both historic and non-historic buildings of Valparaíso succumb one after another to weathering, termites and frequent fires. Timber-framed buildings found in Valparaíso hide their load-bearing structure behind inner and outer coatings, except for their roofs (see Fig. 1). Nevertheless, the evidence of former timber-framing practice in this city allow us to infer that there is a large and diverse stock of handcrafted timber joints yet to be discovered and preserved. The field survey showed that their location exceeds the limits of the "official" historic area. Fortunately, stripping the structure to reveal the skeleton of old buildings is fashionable in Valparaíso when it comes to convert them into boutique hotels or stylish restaurants. This type of projects is progressively attracting new investors to this city. However, renovators simply replace original timber joints with metal fasteners, sometimes with expensive purpose-built connectors and cheap softwood lumber. The main reasons include the nationwide shortage of timber framers, the absence of vocational education and training in timber framing, the absence of a national technical approval specific for timber joints (e.g., load-bearing capacity and seismic resistance), the lack of performance specifications, the high cost of workmanship deficiencies (especially when carving large members of high-quality hardwood), and the durable market-dominating position of metal fasteners in Chile.

2 Bringing creative robotics to Valparaíso

Industrial robots are automatically controlled, reprogrammable, multipurpose manipulators that exceed the functions of conventional CNC machine tools. The main barriers to robot diffusion have been so far high prices and the need for expert programming. While purchase prices are generally determined by integrators on a case-by-case basis, according to RobotWorx (2017), complete new industrial robotics with controllers and teach pendants may cost from USD $50,000 to $80,000. Used robot prices, on the other hand, can range between an estimated USD $25,000 and $40,000 (RobotWorx 2017). Introducing industrial robots to the architectural heritage sector of the construction industry

Fig. 2 Robot workcell (KUKA KR125/2 and 4.5KW HSD spindle)

in Chile requires first the availability of robots and designer-friendly means for programming them. According to Lohrmann (2016a), there are approximately 230 industrial robots installed in Chile today. They serve in the mining industry, the shipbuilding industry, the food and beverage industry, the pulp and paper industry, the glass industry, the energy industry, the medical devices industry, and the metal industry. There are four robot integrators in Chile so far. Except for one company using an industrial robot for cleaning formworks, there is no significant application of industrial robots in the Chilean construction industry and none in the woodworking industry yet. Paradoxically, advanced manufacturing, engineered wood products, high-rise wood construction, and the challenge of doubling the construction of wooden housing units top Chile's Sustainable Productivity and Construction agenda for 2025. As for the availability of robots in the region, Lohrmann (2016b) estimates the amount of industrial robots currently installed in Latin America to be around 40,040 units leading Brazil (20,000), Mexico (17,500) and Argentina (2000)—due mainly to their automotive industry—followed far behind by Chile (230), Colombia (140), Perú (70), Venezuela (70), Equator (20), and Uruguay (10). A growing number of competitive robot suppliers ready to offer increasingly tailored solutions to new customers, together with a growing secondhand robot market facilitate their diffusion in emerging economies.

The application of industrial robots to architecture started already in 2005 when Fabio Gramazio and Matthias Kohler (Gramazio and Kohler 2014) built the world's first robotic laboratory for the research of architectural design and fabrication processes at ETH Zürich in Switzerland. As for "designerly ways" of programming industrial robots, there was no significant development until Johannes Braumann and Sigrid Brell-Çokcan (2011) released in 2011 the first parametric robot control application called KUKA|prc, compatible with robots of the German brand KUKA. Shortly thereafter, Thibault Schwartz (2013) released a similar application called HAL extending compatibility with other robot brands. Both applications are plugged in David Rutten's graphical algorithm editor called Grasshopper, which in turn is a parametric design plug-in for the CAD/CAM software called Rhinoceros (Robert McNeel and Associates). Grasshopper is a free and very popular visual scripting environment that uses a graphical method based on node diagrams to create form generators by procedural modelling, sometimes also referred to as algorithmic modelling. A worldwide dynamic and ever-growing community continuously contributes diverse plug-ins including, i.a., dynamic simulations, physics, structural and environmental analysis, microcontroller programming, and industrial robot programming. Grasshopper supports real-time interaction between its algorithmic modelling environment and external software (Excel, Photoshop, Revit, Ecotect, etc.) and hardware (KUKA Robot Controller KRC, Arduino, Kinect, etc.). KUKA|prc benefits from Grasshopper's wide plug-in ecosystem and its software and hardware interaction potential. KUKA|prc allows free-form tool path generation for unique free-form shape manufacturing. It also encourages creative combinations, such as using form-finding strategies or physical sensing for tool path generation.

Fig. 3 A knot composed of T-bridle jointed post and top plate with notched tie beam and oblique mortise on top

It was KUKA|prc that encouraged us in 2013 to introduce for the first time in Chile robot programming to an architectural studio at UTFSM (Chiarella et al. 2013). Despite the required use of procedural modelling which is more familiar to programmers than to designers, KUKA|prc provides a high level of abstraction from the robot's specific language, allowing designers to interact fluently with an industrial robot. It also offers the possibility to specify tasks without the need to heavily rely on well-calibrated world models (i.e., the workcell) for fast results. These types of advantages sowed the field of the so-called "creative robotics". In the last four years, there have been impressive research contributions from roboticists with creative backgrounds to the use of industrial robots in the manufacture of wooden structures (Williams and Cherrey 2016; Søndergaard et al. 2016; Robeller and Weinand 2016; Robeller et al. 2014; Johns and Foley 2014; Schwinn et al. 2013; Dank and Freißling 2013), although none is devoted specifically to traditional timber joints. Tamke and Thomsen (2008, 2009) had previously explored the application of parametric design methods to the one-off production of a series of differentiated timber joints for a single structure, but using the HSB CAD/CAM software and a CNC joinery machine. Accuracy of gantry and joinery machines is superior to that of industrial robots at machining. This is mainly because industrial robots are constructed as a cantilever in which each link is supported by motors, brakes, and reduction gears (Pandremenos et al. 2011). Robot stiffness and system natural frequencies produce deflections and vibrations of the tool center point (of the milling cutter) during the machining process (Iglesias et al. 2015). Industrial robots are therefore not the first choice for machining tasks, especially of hard materials. To us, however, high accuracy and high work speed of conventional 5-axis gantry milling machines and CNC joinery machines—most suitable for high-volume production—are less important than the flexibility of make-to-order manufacturing of unique pieces to replace the whole or part of a damaged structural or ornamental member such as a single rafter or handrail with double curvature. Default toolpath strategies of conventional CAM software as well as file formats and default timber joint classes delivered by proprietary software of CNC joinery machines limit such flexibility. On the other hand, a 50–55 kg small robot from the series KR AGILUS sixx (plus the 33 kg KR C4 compact controller) allows onsite manufacturing, which is impossible for any CNC joinery machine offering similar workspace size.

3 Starting from scratch

The aim of our research is to demonstrate at the proof-of-concept level the feasibility of using visual scripting to control a standard industrial robot to machine instances of different classes of timber joints of an existing building that needs restoration or rehabilitation. Our strategy to penetrate the architecture and construction industries is to deliver a catalog of associative geometry and tool paths enabling the designer to specify the required timber joint by simply assigning values to pre-existing parameters, and immediately get an updated robot-machining path. Naturally, the modification of tooling information and machining parameters are also considered. In practice, users may also add, remove or modify parameters and constraints due to the free access to the parametric diagram. We decided to assess the use of a single visual scripting environment for the whole process from design intent to machining to explore its full potential. The fact that this is a pioneering attempt in our specific context allowed us to simulate the start-up situation of an architectural or design firm using the same application to create their own catalog of parametric timber joints. We started with a borrowed KUKA KR125/2 robot, then bought a secondhand KUKA Agilus KR6 R900 sixx robot. We used first a 900 W METABO die grinder, then a 4.5KW HSD spindle. Ad hoc mounting devices were manufactured in-house, likewise a steady

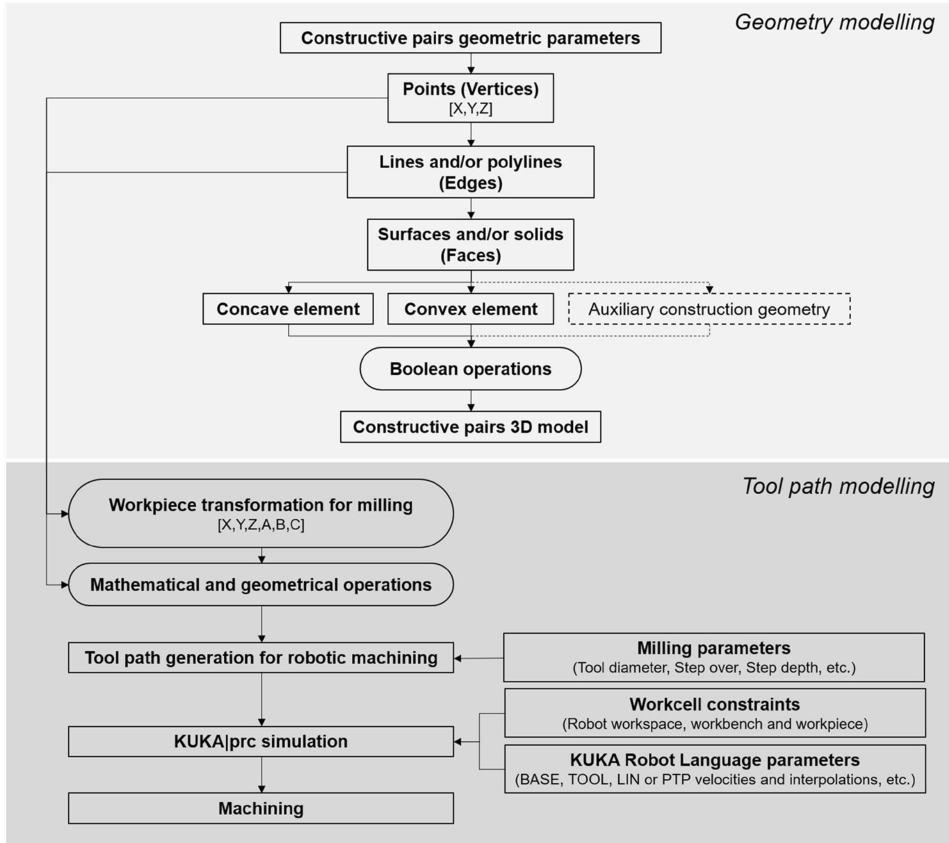


Fig. 4 Milling-focused geometric modelling workflow

workbench for long workpieces (see Fig. 2). Large-sized cutting tools were obtained from a local manufacturer.

The self-imposed restriction of using the same visual scripting application for every stage of the process led us to develop an ad hoc strategy for part and assembly modelling—something solved long ago by mechanical design software. A timber joint consists of interlocking protrusions and depressions carved on either one or both of a pair of solid timber members such as posts, beams and rafters. Gerner (1992) provides probably the largest catalog depicting the descriptive geometric parameters of over 250 traditional timber joints developed throughout history in the German-speaking area. These single geometric features commonly known in the field of CAD/CAM manufacturing by names such as "boss", "pocket", "hole" and "slot", in timber framing are called "tenon", "mortise", "through mortise" and "trench," respectively. Complex timber joints combine several features, therefore, they adopt longer detailed names such as "bridle joint" or "bevel-shouldered through mortise and tenon joint". Inspired by Reuleaux's Kinematics of Machinery (Reuleaux 1876), we agreed to consider every timber joint as a "constructive pair" (i.e., instead of a "kinematic pair") consisting of two coincident regions of two rigid bodies whose shape correspond, pairwise, reciprocally. Put in mechanical terms is just a two-part assembly. If a third or nth timber member joins a member of a constructive pair, either within or very close to that same connecting region, we call this multiple-part assembly a "knot" (see Fig. 3).

For modelling purposes, however, we treat timber joints always in pairs. It was necessary for us to first develop this simple theory to understand the modelling process with KUKA|prc. In fact, the process resembles mechanical design more than architectural design. Figure 4 shows the workflow we carried out.

4 Experimental results

As far as architectural heritage conservation is concerned, the task in our case is to preserve the original timber joint system of historic buildings of Valparaíso rather than make exact replicas of timber joints that are neither native nor unique (Fig. 5). However, this kind of task not only concerns heritage conservation, but also seismic retrofitting criteria.

Preserving the original structural conception of traditional timber frames without inappropriate increase of stiffness and weight, and possibly reducing costs in retrofitting of timber joints has long been the focus of research

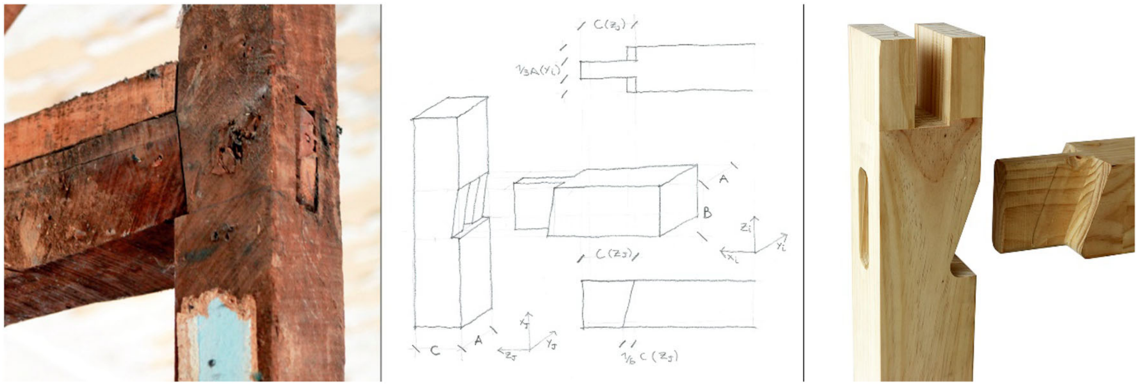


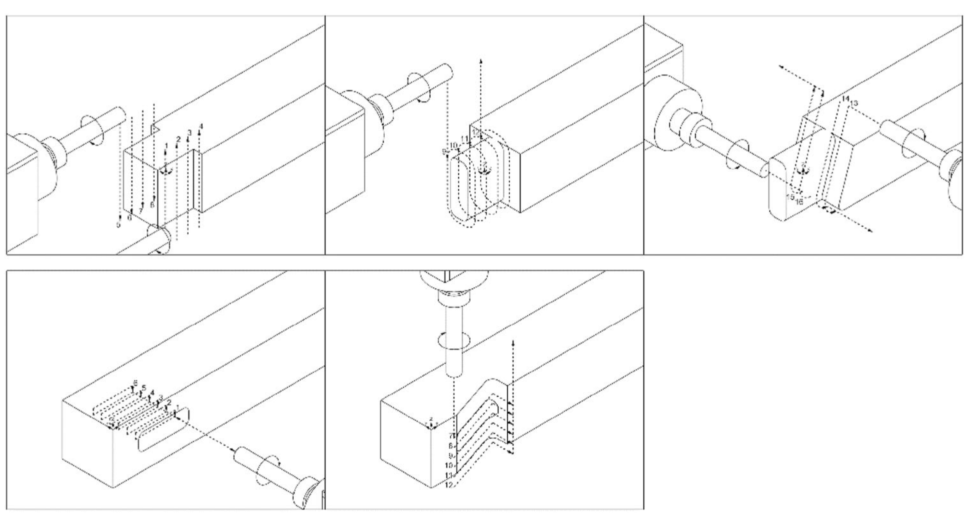
Fig. 5 Original bevel-shouldered through mortise and tenon jointed post and lintel (*left*). Field-survey sketch (*middle*). Robotically milled bevel-shouldered through mortise and tenon jointed post and lintel (*right*)

(Parisi and Piazza 2002). Gerner (1992) stresses that the geometry of traditional timber joints was the direct result of the available tools. We adopted this principle of "form follows tool" ignoring the substitution of the mortise chisel for the milling cutter; hence the sharp edges instead of rounded edges (see Figs. 6, 7, 8). The alternative is to try different cutting tools like oscillating tools, but we decided not to follow this route. We built instead a prototype (León and Cubillos 2016) of timber frame showing traditional timber joints found in historic buildings of Valparaíso.

5 Discussion and further work

The presented research is a pioneering attempt in Chile to introduce industrial robots for architectural heritage conservation. It is also the first attempt to catalog the variety of timber joints hiding inside walls, floors and roofs of existing historic buildings in Valparaíso. The feasibility of using a visual scripting tool like KUKA|prc to create a catalog of associative geometry and robot tool paths for machining instances of original timber joint classes found in timber-framed buildings of Valparaíso has been demonstrated at a proof-of-concept level. Our experimental results suggest several new competitive opportunities, e.g., no need to create new parameters only value assignment due to pre-existing parameters delivered within the catalog, extensible catalog, automatic real-time tool path updates associated to design (i.e., parameter value) changes, no post-process of geometric data required, fluent workflow between parameter value assignment and robot path simulation, onsite woodworking potential with lightweight robots like the 50-kg Agilus, less workmanship deficiencies, no shop drawings required. Timber joints, i.e., wood-to-wood joinery are regaining part of its former position and scientific attention due to their environmental sustainability potential. Our future work is aimed at creating metal-free, demountable timber frames for affordable housing for the poor tailored to family composition and geographic location.

Fig. 6 Tenoned lintel milling strategy (*top*). Mortised-and-bevel-shouldered post milling strategy (*bottom*)



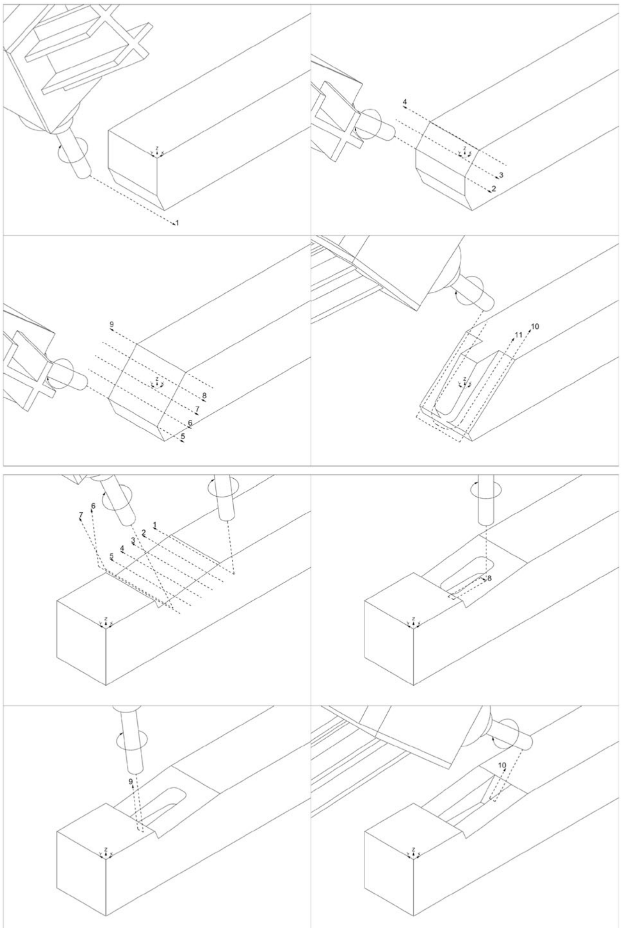


Fig. 7 Oblique tenoned rafter milling strategy (*top*). Oblique tenoned tie beam milling strategy (*bottom*)

Fig. 8 Robotically milled oblique tenon joint

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