AUTOMATIC ASSEMBLY OF JOINTED TIMBER STRUCTURE USING DISTRIBUTED ROBOTIC CLAMPS

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Abstract. This paper presents a novel robotic assembly method for timber structures with integral timber joints, specifically, crossed-half-lap joints. The proposed method uses a set of custom-built, remote-controlled, high-force robotic clamps to operate in collaboration with an industrial robotic arm to overcome challenges of robotic timber joint assembly, such as providing large assembly forces and correcting misalignments. This method enables automatic assembly of non-repetitive and spatially connected timber structures. We developed custom software for modelling, visualization and feasibility-checking for structures compatible with the proposed assembly method. As a proof of concept, we designed and robotically assembled a spatial frame structure (4.8 x 3.0m footprint, 3.4m tall) comprising 40 pieces of 100x100mm profile timber elements.

Keywords. Robotic Assembly; Spatial Timber Structure; Wood Joints; Distributed Robots.

1. Introduction

Robotic timber assembly concerns the use of easily-programmable robots for placing and joining timber elements. It is a rapidly advancing field in academia and industry that aims to construct timber components and structures through the use of programmable assembly robots. This paper focuses on the assembly of bespoke (aka. non-repetitive), spatial (aka. non-planar) timber structures with integral timber joints, in particular, crossed-half-lap joints.

Integral timber joints were used extensively in pre-industrial timber structures (Zwerger, 2015; Sobon 2002; Coaldrake et al 2006; Sato and Nakahara, 1998) and are still used today in large scale timber structures (SBA Tamedia, 2013). These connections are often spatially joined in different directions to create a stable structure. In the past few decades, industrial automatic joinery machines (Wieloch and Porankiewicz, 2010) had substantially lowered the cost of the otherwise labour intensive process of cutting intricate timber joints. These machines can be digitally programmed to cut different joint geometries at different locations along the length of the timber element. However, the assembly of these digitally machined timber components had so far been performed manually.

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Recent researches in robotic timber assembly often use robotic arms to manipulate timber elements to achieve spatial placement of timber elements (Thoma et al, 2018). The connections used in these precedence research tend to avoid form closure and instead use glue (Kohlhammer et al, 2017), screws (Thoma et al, 2018; Robotic Pavilion, 2016) and nails (Apolinarska et al, 2016). This research focuses on the assembly of integral timber joints without fasteners and addresses the following challenges:

1. **Large assembly force to overcome joint friction.** Timber joints are often designed to be tight-fitting to ensure structural rigidity. However, when the parallel faces of the lap joint rub against each other during joint closure, a large frictional resistance is created. This friction can vary widely due to surface roughness or misalignments, and can result in jamming. Traditional solutions to this problem include tapering the mating faces (avoid parallel faces) so that the contact on both sides is deferred to the very last moment.
2. **Simultaneous assembly of multiple joints.** The risk of jamming is particularly common when multiple tight-fit joints need to be inserted at the same time, e.g. one beam is joined to two or more others, in a kinematically constrained trajectory.
3. **Local and global accuracy.** The position of two mating elements have to be precisely aligned at the mating joint during assembly. Within a small range, this alignment can be guided by a chamfer at the expense of increased friction. However, in the case where multiple joints need to be aligned, the structure may have displaced or deformed in different directions, making large friction unavoidable.

2. State of the Art

Many researchers have demonstrated the versatility of a 6-axis robotic arm for spatial manipulation of long elements. Thoma et al. (2018) made use of two robotic arms mounted on linear axes for constructing modular timber houses. One arm can be used for temporarily supporting unstable elements, while another arm continues the assembly. Leder et al. (2019) used distributed robots to collaboratively transport and assemble timber elements, by attaching the robots to the partially-built structure, and using the timber elements as part of the robot's kinematic chain.

There have only been a few publications on robotically assembling tight-fitting joints. Robeller et al. (2017) used a 6-axis robotic arm to assemble tight-fitting tenon joints along the edge of cross-laminated wood veneer panels. However, they have only limited success using the robotic arm alone for the assembly and various external help (including a vibration device) was needed. They also experimented with a tapering angle and observed a reduction in assembly force. Apolinarska et al. (2020) applied reinforcement learning techniques to control robot arms for timber joint assembly based on contact forces. Their trained models allowed the controller to automatically adjust insertion movement strategy in reaction to collisions and friction.

3. Prototypical Setup

Our approach to solve the above mentioned challenges is to make use of distributed robotic clamps to apply a large clamping force at each mating joint in a synchronized motion. This approach separates the task of applying large assembly force from the task of manipulating timber elements in space. This allows the use of a low-payload robotic arm to perform spatial manipulation and in collaboration with as many robotic clamps as necessary to assemble an element with any number of joints. Below we explain our prototypical setup.

3.1. ROBOTIC CLAMPS

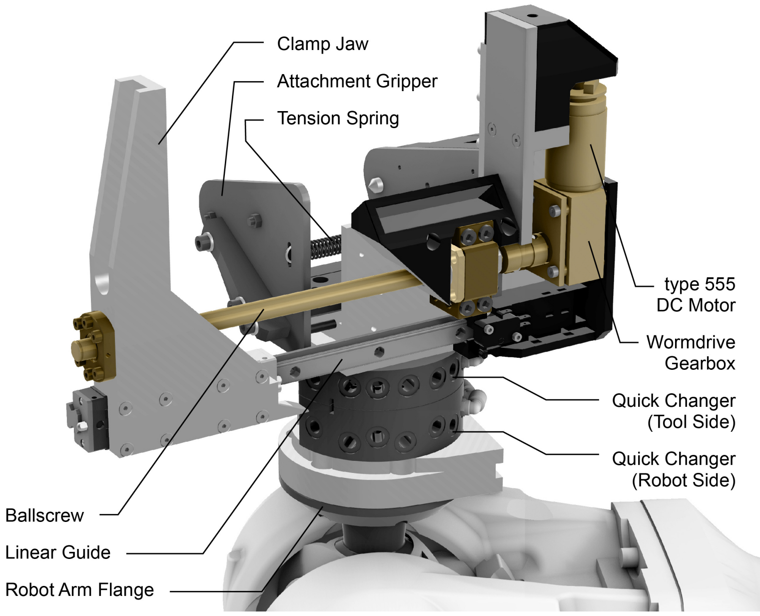

Figure 1. Major mechanical components of the clamp. The motion powertrain is highlighted in brown.

Each clamp is essentially a single-axis robot with a high force actuator that pushes a pair of lap joints together, and can be re-positioned by a robotic arm. Because different joints types (e.g. lap joints, tenon joints and splice joints) require very different clamping directions, they require different clamp designs. In this paper we focus on clamps for in-plane lap joints. The main features of the proposed clamps are wireless operation, ability to produce large force, synchronize to a motion profile, have a small size and low weight. In our demonstration, our clamps can produce 3kN force, move at 2mm/s and weight 4.9 kg.

The mechanical components of our demonstration clamp are shown in Fig.1. A spring-loaded mechanism allows the clamp to attach to the timber element by itself, allowing the robotic arm to detach from it (Fig.2a-b). The clamp jaw is positioned across the lap joint and pushes on the opposite element. To enable non-standard structures, the clamp can accommodate joint angles from 25° to 90°, a mirror copy of the clamp accommodates angles 90° to 155°.

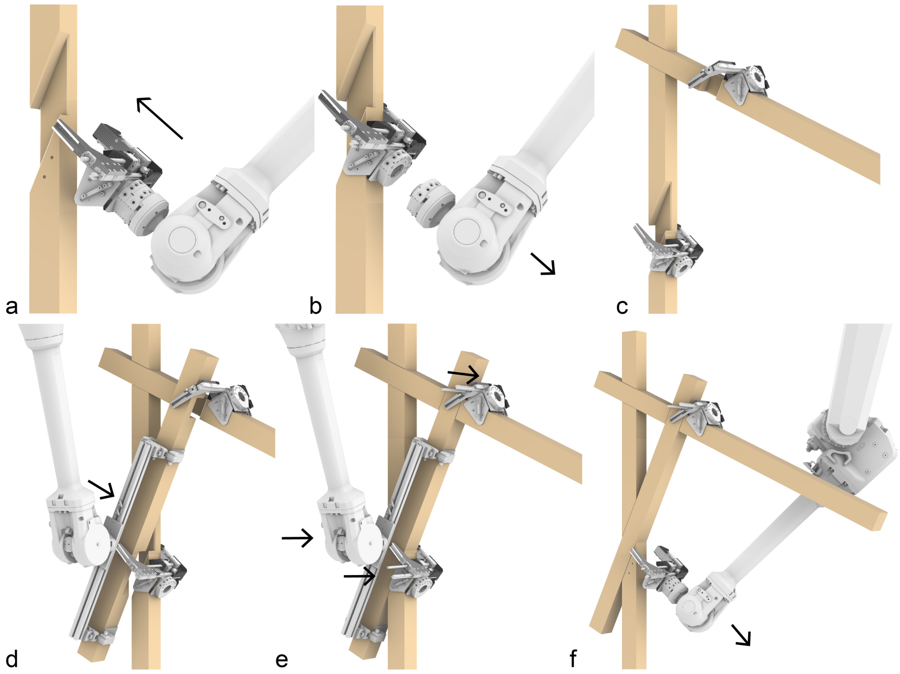

Figure 2. Robotic arm moving clamp to joint. (b) Clamp detach from arm. (c) As many clamps as necessary are placed. (d) Robotic arm brings a new element in the clamp jaw using a gripper. (c) Element assembled by arm and clamps. (e) Clamps removed by robot, one at a time.

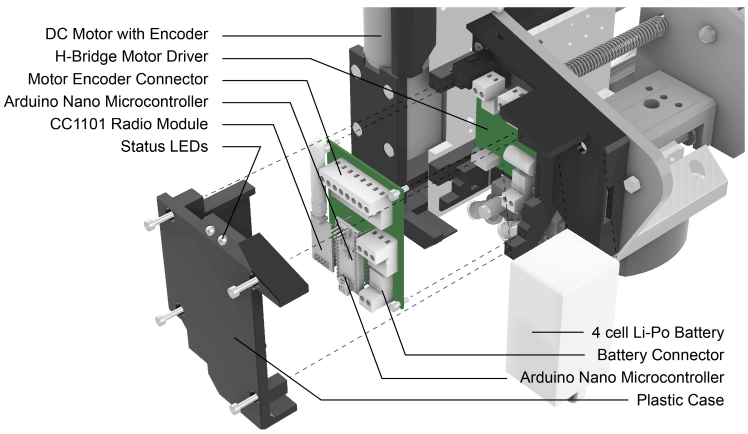

Figure 3. Major electrical components at the back side of the clamp.

In order to allow synchronized motion between multiple clamps and the robotic arm, the clamps are controlled by an Arduino Nano microcontroller (Fig.3). It drives a brushed DC motor with encoders for position feedback. To enable adaptive force output against variable resistance, the motor current is controlled by a 100Hz PID controller that minimizes instantaneous positional error to a motion profile. The wireless communication is based on a CC1101 digital radio transceiver operating in the 433MHz ISM band frequency for its ability to band around obstacles. All the clamps can be controlled from one computer equipped with the same transceiver to execute motions.

3.2. ROBOTIC ARM AND GRIPPER

The proposed assembly process requires a robotic arm with a reachability that covers the construction area (e.g. mounted on a gantry) and a tool changing system for changing between grippers and clamps. In our demonstration, we used an ABB IRB 4600 robotic arm, mounted on a custom 3-axis Güdel gantry system (operating within 8 x 8 x 6 meters envelope) and a Schunk SWS040 robotic tool changer. The robotic arm is programmed to be compliant in case of small misalignment. To pick and hold the timber elements, we used two grippers (500mm and 1m long), each containing two PGN-plus 100 parallel grippers with sandpaper lined fingers.

3.3. ASSEMBLY PROCESS

Elements are placed one at a time. For every element, the robotic arm places the clamps on the partially-built structure at every joint that needs to be connected to the next element (Fig.2c). After all the clamps are placed, the gripper is attached to the robotic arm, picks up the next timber element and places it into the jaws of the clamps (Fig.2d). The arm and the clamps then move synchronously to insert the element (Fig.2e). During this movement, the arm supports the weight of the element while following the assembly trajectory and the clamps provide the necessary force locally at each mating joint to overcome the resistance. This step repeats for all the subsequent elements after the arm relocates the clamps to the next joints (Fig.2f).

3.4. LAP JOINT DETAIL

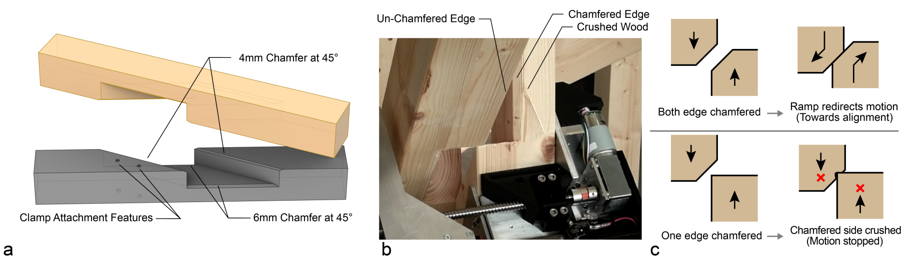

Figure 4. (a) Joint chamfer details used in our demonstration. (b) Photo showing failed attempt with crushed wood when only one side is chamfered. (c) Diagram showing misaligned edges being clamped together, highlighting the undesirable crushing behaviour.

To guide insertion in the event of misalignments, we chamfer the edges of first contact by 4mm and 6mm at 45° (Fig.4a), this amount is determined empirically to correct up to 6mm of misalignment. Note that it is not sufficient to chamfer only one side, as the “sharper” un-chamfered corner can crush the wood on the opposite side (Fig.4b-c).

4. Process Constraints and Computer-Aided Design

4.1. ELEMENTS, JOINTS AND SEQUENCE

In order to design structures that can capitalize on the proposed assembly method, considerations have to be made for (1) joint angles, (2) assembly sequence, (3) insertion direction (includes the orientation of the lap joint) and (4) room for collision-free robotic manipulation of clamps and timber elements. These decisions are interdependent problems and two approaches can be taken to ensure agreement between assembly sequence and the joints’ design. The first approach (”Auto-sequence”, Fig.5a) is to first design the structure with all joint geometry, and then derive feasible assembly sequence. The second approach (”Auto-joint”, Fig.5b) is to design the structure by specifying the assembly sequence, and the insertion direction and then derive the joint geometry.

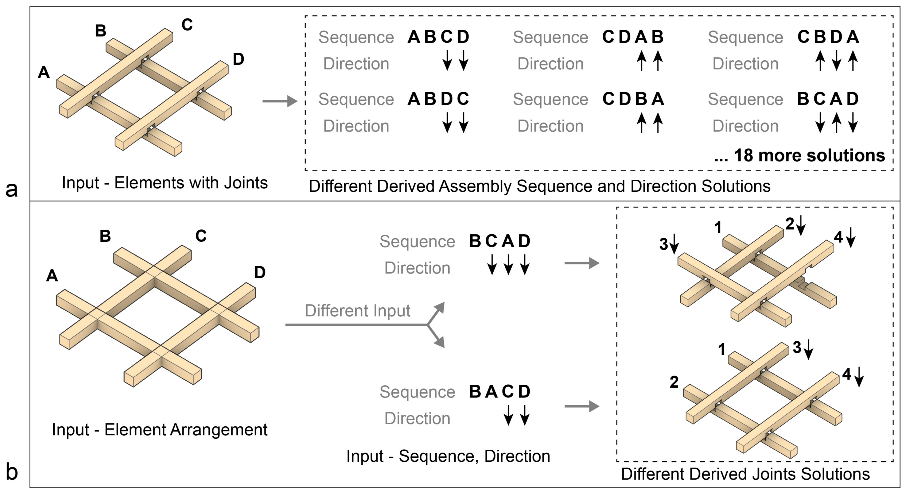

Figure 5. (a) Auto-sequence approach: Given elements arrangement and joints, different assembly-sequence-and-direction are possible. (b) Auto-joint approach: Given the same elements arrangement but different assembly sequence and direction, resulting in different joint geometry.

We opted to use the second approach for our demonstration because we find it more intuitive. In either method, there might be either none or multiple solutions. In case of no solution, the sequence or member arrangement have to be changed. In case of multiple solutions, one can be chosen based on structural requirements and robot accessibility.

4.2. PATH PLANNING

The timber elements can be grasped by the gripper from all four sides and at many possible locations along the element's length. These two decisions affect the pose of the robot when holding the element for assembly. Furthermore, each clamp can be attached to a joint in two possible orientations. For every joint and element that needs to be clamped, the robot arm requires a continuous path that goes through the following key waypoints without collision between the robot arm, the tools, the already-placed timber elements and the element in motion.

- **Attach each clamp:** (1) Clamp storage approach, (2) target, (3) retract, (4) Clamp attachment location approach, (5) target and (6) retract.
- **Attach timber element:** (1) timber pickup approach, (2) target, (3) retract, (4) timber approaching clamp, (5) placement inside clamp jaw, (6) assembled, (7) empty gripper retract.
- **Detach each clamp:** Reverse sequence of attaching clamp.

4.3. SOFTWARE SETUP FOR DESIGN AND FABRICATION

To assist the design process, we developed custom software to run in Rhinoceros 6 using the COMPAS 0.16 framework (Van Mele 2021). A designer can model timber elements with the Rhino user interface and specify their assembly sequence, assembly direction, attachment position of clamps and grasp pose for grippers. It allows designers to visualize different steps of the assembly process by displaying the partially assembled structure, the active element being assembled and tools involved. The software checks at design-stage if assembly is feasible (all parts are insertable without collisions, given the sequence and joint geometry). Next, it calculates continuous motion paths for the robotic arm by using the path planning functionality of the COMPAS FAB (2018) library. If no valid path is found, the designer can then choose to modify the location of timber elements, the assembly sequence, selecting a different clamp attachment orientation or a different grasp pose.

5. Demonstration

As a proof of concept, we designed a spatial frame structure (4.8 x 3.0m footprint, 3.4m tall), featuring lap joints at different angles (25°-155°). It comprises 40 pieces of 100x100mm profile elements, ranging from 1.7 to 3.4m in length, made of GL24h grade glue-laminated spruce (Fig.6), produced by a Hundegger ROBOT-Drive joinery machine.

5.1. STRUCTURAL DESIGN

The structure consists of seven structural frames (in parallel, vertical planes) that are 700mm apart, each consisting of five elements, and cross-braced in the opposite direction. All joints are modelled as stiff connections and supports can only transfer compression to the ground. We applied self-weight and lateral (e.g. wind) load from 24 different horizontal directions. The joints are assumed to withstand bending moments up to 1kN.

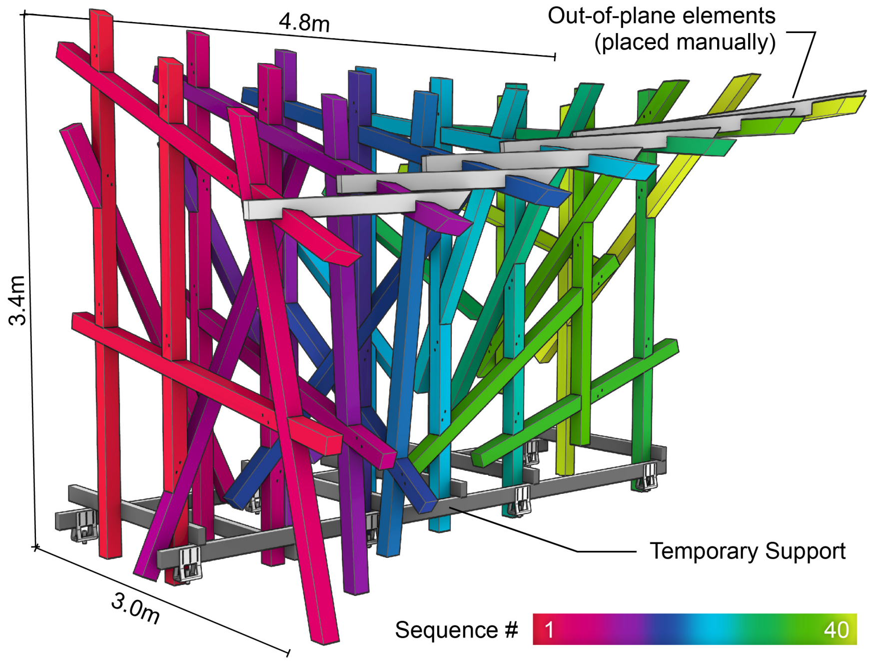

Figure 6. Diagram showing the demonstration pavilion, the colours represent the sequence of assembly; Six non-structural elements that are not robotically assembled (light grey); Temporary foundation during assembly (dark grey).

5.2. EXECUTION

The assembly process is executed by a desktop computer streaming pre-computed movement waypoints to the robotic arm, the gantry system and the clamps over a ROS network created by COMPAS FAB. For the joint closure movement that requires synchronization between the robotic arm and the clamps, the computer schedules the movements commands at the same time and constantly monitors the position of the two systems.

We manually placed the timber into the gripper, performed the tool change and attached carpentry clamps between the structure and the temporary foundation. This allowed us to reduce our experiment setup time. At the current stage, we also placed the clamps manually, with the aim to robotize this process in near future. The entire structure was assembled in a total of 24 work hours (Fig.7a), 4 hours of which involved machine operation (approximately 6 minutes per element).

5.3. OBSERVATION AND DISCUSSIONS

During the execution, we have recorded the power output of the clamp (proportional to the force output) and the instantaneous position error. As an example, Fig.7b shows the recorded data for three clamps during the assembly of one element. The small error (<0.1mm) yet high spike in output power (>2 times) shows the adaptive power control is able to keep the clamps in sync despite changes in friction.

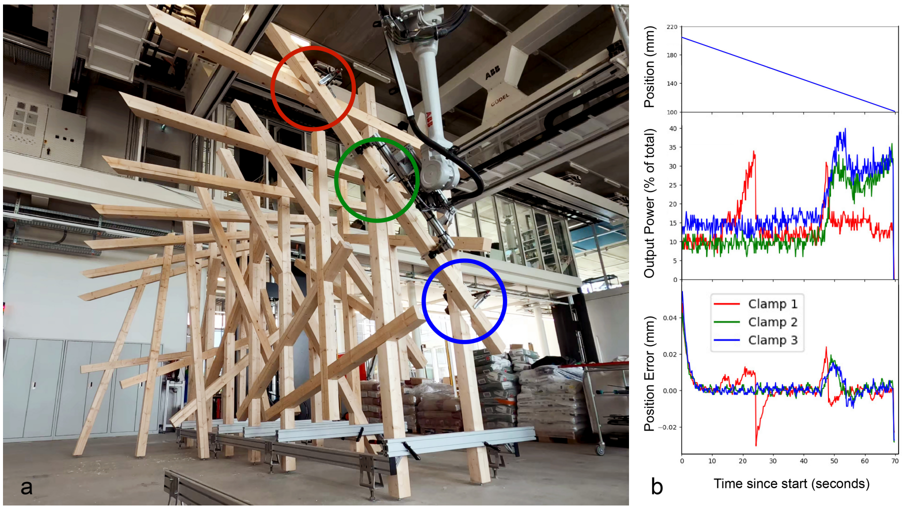

Figure 7. (a) Photo showing the final (40th) element being assembled. (b) Corresponding graph showing the clamp jaw position (left), power output (middle) and instantaneous error (right) during joint insertion.

The misalignment errors were larger than expected (> 6mm) at the beginning of the assembly. We believe this is caused by low joint stiffness, weak connection to the temporary foundation and insufficient cross-bracing. After the first two frames (12 elements) were assembled, misalignment amount falls within the ±6mm as predicted. Future work should attempt to improve the initial stiffness.

We have encountered a few collisions during assembly. Some are caused by a discrepancy between the real world and the digital model, specifically the temporary platform and the temporary clamps. Future work should be more diligent about their correct representation in the digital space. One collision is caused by an insufficiently high resolution setting in the motion planner. Two collisions are caused by the cable of the robot tangling with the structure.

6. Conclusion

We have demonstrated for the first time robotic assembly of spatial timber structures with tight-fitting joints using distributed robotic clamps, and showed that automated construction can extend to complex, non-standard structures. We have illustrated the decisions that need to be considered during the design stage and showed how it can be assisted by computational tools.

The concept of distributed, synchronized robotic clamps effectively addressed the problems of assembling integral, tight-fitting joints. In future works, the clamp design can be further developed to make them more universal and the remaining manual tasks can be automated. This allows a designer to design, plan and execute an entire timber structure in a digitally streamlined process.

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