All Bent Out…

Adaptive Fabrication of Bent Wood Assembles

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Abstract All Bent Out… explores adaptive fabrication techniques for robotically constructing steam-bent wood assemblies. The following paper discusses a constellation of hardware and software tools that leverage the material constraints of steam bending (e.g. spring back, irregular grain) as opportunities to develop adaptive fabrication workflows where predetermined machine tasks can be informed by sensor-based events. In particular, research in coordinated motion control of two industrial robots and environmental sensing help to negotiate discrepancies between intended, digitally modeled geometries and actual, physically bent wood assemblies.

Keywords Adaptive fabrication · Real-time sensing · Computer vision · Steam bending

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1 Motivation

All Bent Out… reconsiders the traditional fabrication technique of steam bending natural hardwoods—a process pioneered by Michael Thonet (1796–1871)—using contemporary robotic technology. The focus of the workshop resides in a combined interest in material deformation, in particular the difficulties present in predictably free-form-bending natural hardwoods, and in the robotic assembly of bent components. To address material constraints in the process of bending and assembly, the workshop will develop an adaptive fabrication workflow, drawing from recent research by the authors in coordinated motion control of two industrial robots and real-time sensing. Adaptive fabrication is a responsive construction approach that allows a task to update based on data received from external sensors and events. This approach enables one to negotiate the translation from intended (digital) to actual (physical) material assemblies of bent wood.

2 Challenges Present in Bent Wood Assemblies

Steam bending is a traditional wood-working technique often used to construct furniture and other curvilinear industrial objects. As a proto-industrial technique, popularized by the iconic No. 14 Café Chair of Michael Thonet, steam bending has long captured the collective imagination of designers across many disciplines. The technique achieves curved material deformation in air-dried wood without the use of toxic adhesives. During the process, heat and moisture penetrate the wood's fibers and lower the elastic limit of the material. Bending stresses are introduced (beyond the elastic limit) resulting in a permanent set of the material and the resulting curved form (Hoadley 2000).

The constraints of applying robotic techniques to bent wood assemblies are a product of wood's unique material behavior during the process of steam bending. Many of the difficulties of free-form bending derive from the fact that wood is not a uniform material: "Steam bending has shortcomings. The most troublesome is accurately predicting springback… In steam bending the results depend upon the grain structure of each piece of wood. Local eccentricities—knots, checks, and cross grain—will affect the final curve… This disadvantage becomes critical when exact duplicates must be made" (Keyser 1985). Small changes in grain (e.g. runout or knots) can significantly alter the shape of a bend or sometimes result in material failure and careful handling/drying after bending is needed to minimize springback.

In addition, the nature and direction of forces applied during bending are important due to wood's anisotropic qualities. Often the limiting factor leading to material failure in bending is the introduction of axial tension on the outer, convex side of a bend. While steamed wood can compress up to 30 % of its original length it can elongate by a maximum of 2 % (Hoadley 2000). Industrial processes often deploy expensive, dedicated molds for repetitive parts to mitigate tension failure during bending. A steel tension strap can also be used but this often constrains bends to two dimensions and precludes free-form bending. One such example is the beautifully designed Timber Seasoning Shed from the Architectural Association's Design and Make graduate program where dimensionally unique parts are produced with a variable, table top formwork to form an undulating lattice shell (designandmake.aaschool.ac.uk/timber-seasoning-shelter/).

Wood's combined heterogeneous qualities introduce issues of unpredictable geometric translation from digitally modeled curvature to physical bending with repeatable robotic motion. This geometric error compounds when positioning multiple components into larger assemblies. Thus, despite the sub-millimeter accuracy of industrial robots, these combined factors lead to fabrication error beyond acceptable tolerances.

This workshop explores the potential to bend non-repetitive, three dimensional parts and aggregate them directly into architectural assemblies using robotic workflows. To achieve these aims wood's material behavior during steam bending can be addressed through adaptive fabrication techniques where bending irregularities can be analyzed during fabrication and digital models can be updated to respond in real-time. The following sections will discuss relevant precedent and the development of robotic software and sensing tools aimed toward this end.

3 Previous Work

A number of recent projects exploring bent architectural assemblies illustrate the problem space the workshop seeks to investigate. In particular, the workshop is focused on the deformation of heterogeneous materials and the robotic assembly of volumetric framing systems.

Case Study I: Spring Back, a steam-bent gateway structure, is one such example where CNC fabrication and parametric modeling were used to generate geometrically unique bent wood components (Bard et al. 2012). Precise registration holes were cut near each member's endpoint with a CNC water jet cutter. These registration holes located components in a variable bending formwork and later became connection nodes in the final structure.

In this case, the problem of modeling the irregular behavior of bent wood was not solved; rather, the influence of compound error in the assembly was mitigated by making part-to-part connections at key indexed locations. While this approach did allow for the efficient production of geometrically unique bent wood components, one drawback of this approach was that materially intensive falsework was needed to position components to erect the final structure. Large plywood forms were cut to bundle components together in three sub-assemblies that were then erected using a separate set of scaffolding (Fig. 1).

Case Study II: High Wire a project developed during a robotic fabrication seminar at the University of Michigan in 2012 addressed issues of robotic

Fig. 1 *Left* water jet cut blank with registration holes, *center* materially intensive formwork for component assembly, *right* spring back installed

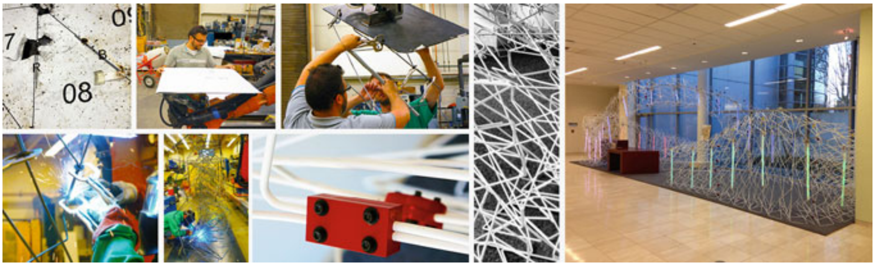


Fig. 2 High wire assembly using robotic formwork and final installation

assembly in bent steel rod frames. The project incorporated robotic bending workflows previously developed by research teams at the University of Michigan in projects such as the "Clouds of Venice" installation at the 2012 Venice Biennale (Pigram et al. 2012). One aspect of the bending workflow extended through the seminar was the development of re-positionable, robotic falsework for the assembly of a large number of uniquely bent members into a steel space frame. Students developed a mountable steel fixture with interchangeable templates that was robotically positioned to weld individual bent rods into larger sub-assemblies (Fig. 2).

This strategy enabled the fabrication of an inhabitable (3 m × 8 m × 3 m) volumetric assembly without the use of extra falsework during installation. Although High Wire shares an affinity for material deformation of linear members and the assembly of structural frames the project remains distinct from bent wood assemblies due to the differing material behavior of wood's anisotropic and steel's isotropic properties. As a result, falsework for welding modules could be positioned directly from offline data with little need to check physically bent pieces for fidelity to the intended assembly.

Fig. 3 HAL software architecture, in relation to external sensors and robot controllers

4 Software Development for Adaptive Fabrication Using HAL

4.1 Development Context

Adaptive control, as a technique for the manipulation of a predetermined machine task informed by external sensors and events, is a key topic of software research. Notwithstanding substantial development in many areas of robotics and computer science, adaptive control is still underutilized in the domains of architecture and construction, despite many promising applications (e.g. automated compensation of an existing part, real-time adaptation to deformable material behavior, interaction with dynamic environments, etc.). The following sections focus on the implementation strategies for HAL (Schwartz 2012) users to integrate feedback mechanisms—and thus adaptive control—into ABB robot programs (Fig. 3).

4.2 Adaptive Control Scenarios

In order to understand the implementation logic we will depict, it is necessary to analyze several usage scenarios:

Scenario 1: The user wants to modify a single position, relative to a tool or reference axis system calibration procedure. In this case, the compensated position can directly be linked to a single frame variable, and will automatically impact any further movement instruction without additional computing efforts. An alternative is to use multiple search routines (using *SearchL* for example) to obtain an equivalent compensation by merging multiple local corrections (along any direction).

Scenario 2: The user wants to modify a single position in a set, in order to dynamically compensate for an imprecision detected during the execution of a toolpath. The compensation will only affect this position and will necessitate an update of its coordinates in the code. It will require an interruption of the execution in order to take the compensation into account every time a modification is required.

Scenario 3: The user wants to globally refine the positioning of a toolpath. The ABB correction generator feature can be used, and will allow the user to activate, deactivate, or update a global correction during the execution to make it local if necessary. Another solution is to modify the reference axis system of the toolpath and/or the active tool, by adjusting their declaration by the rotation and translation that needs to be compensated (Scenario 1). A third solution, involving more computation, is to apply compensation via a displacement frame. For this scenario, the compensation can be executed iteratively. These scenarios can then be merged and tweaked to create some automated toolpath teaching procedures, step-by-step compensated manufacturing processes, etc.

It is obvious that the organization of the communication routines channeling the compensation measures will have a strong impact during the execution of each of these scenarios. Multitasking is an option available in ABB controllers starting with the S4 versions, but requires some manual operations on the teach pendant unit and a reboot of the machine to create or a delete a parallel task. To eventually gain in performance on the communication latency, it could be useful to use a background task to constantly listen to communications with the computer, but due to the inability to administrate tasks automatically, the workshop will focus on a solution involving a single task, this solution allows one to switch instantaneously between traditional programs and interactive programs with minimal latency.

4.3 Implementation Logic

The implementation logic of adaptive tasks is handled in HAL by the automated inclusion of the programmed process/toolpath into a generic “feedback-friendly” RAPID module. This module embeds five different logic blocks (Fig. 4):

- Variable declarations, including positions, speeds, tools, work object and zone presets, and all the necessary variables to be accessed by the communication and correction routines.
- Main process/toolpath procedure, including the motion instructions. Depending on the selected compensation mechanism, one or multiple instructions can trigger the communication routines, using specific RAPID instructions (*TriggL*, *TriggJ*, *TriggIO*, etc.).
- Communication routines that can automatically select and parse the feedback values coming from an internal or external sensor. Different communication methods are available depending on the amount of data to be transferred: RMQ messages (for short instructions), TCP socket messages (for short or long instructions), or IO monitoring (for analogue sensing or digital switches).

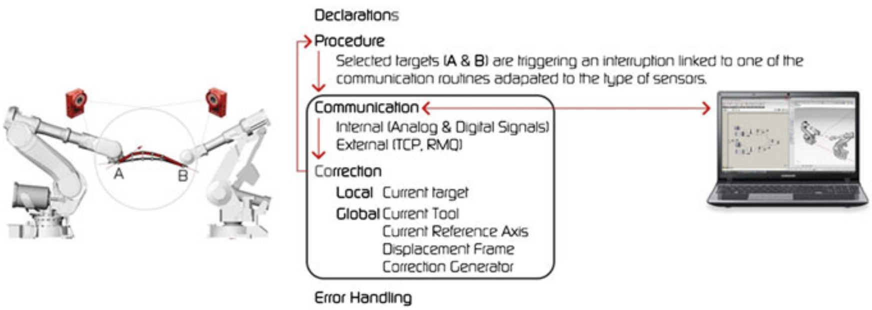


Fig. 4 HAL feedback implementation logic to be executed on the robot side

- Correction routines, applying compensation measures as explained in the list of scenarios. These correction routines can also be looped with the communication routines until an acceptable tolerance is reached.
- Error handling routines, allow one to continue the process or propose additional communication options on the teach pendant unit when a compensation operation or the communication with external devices failed.

4.4 Current Limitations and Further Development

While this approach of generic feedback loop integration has numerous benefits especially concerning the usage flexibility, it is true that a multi-threaded application could bring several improvements in certain scenarios. One main limitation of the current single threaded feedback comes from the temporary interruption of the initial process triggering the correction routines, as it disables smooth process during the compensation. If the communication and correction routines were executed in parallel tasks, it could diminish this small inactivity time, and eventually lead to better overall precision for intrinsically continuous applications. Another limitation comes from interruption and communication latency, which exceed real-time (<10 ms) latency requirements, even if acceptable response can be measured with this system (100 < 250 ms).

5 Sensing Tools for Adaptive Fabrication in Wood Assemblies

The following section describes open-source toolsets developed by research groups at Carnegie Mellon University. These toolsets combine techniques in proximity sensing, computer vision (CV), lo-fidelity force feedback, and motion capture (MOCAP) to augment standard industrial robot configurations with real-time control. Each custom tool encodes a contextual awareness of the immediate physical environment within the robot's work cell. When these tools are layered together, they demonstrate how live control of an industrial robot can be safely driven by environmental stimuli, to augment standard on-line programming. These toolsets can play an important role in making fabrication and assembly processes for robotic steam-bending more adaptive to the material constraints of natural wood.

5.1 Vision Capture

Computer vision provides environmental awareness and can generate motion paths from visual cues in a robot's immediate context. For example, *Stroke*—a program used to dynamically draw tool paths for an industrial robot on a physical 2D work surface—incorporates computer vision to capture and translate hand sketches into robot position targets. With robotic steam bending, these same techniques can be adapted for checking physical bends in wood members against an idealized digital model (Fig. 5). During the coordinated bending process, a camera can capture and extract a trace of the physical curvature of the deforming wood. Once captured, the deviation between a projection of the desired digital curvature and actual physical curvature can be used to adapt the robots' bending motion. Projecting the digital curvature onto the physical component offers another layer of visual error checking during bending.

5.2 Force Feedback

RoboMasseuse is a project that modifies a light payload industrial robot with a force feedback end-effector. Force feedback is an important component in adaptive fabrication, as it has the potential to detect *when* and *how* a robot engages a particular surface. Pressure sensors embedded within the therapeutic end-effector enable the robot to safely give back massages to its human operator. Streaming sensory data is used to map tactile feedback from the operator to initiate robot commands for pushing harder or softer against the user's back. This force feedback end-effector can be directly applied to control and coordinate the variable pressure needed to stress the wood during the robotic steam-bending process (Fig. 6). Whereas the forces controlling *RoboMasseuse* were based on human limits, *All Bent Out*… will modify robot movement based on measured forces approaching the minimum stress to failure point of the bent wood. Therefore, through simple recalibration, this force feedback tool can become a device for adaptive forming in robotic steam bending.

5.3 Motion Capture

Motion capture is a vision strategy for tracking and collecting long periods of position/orientation data of a subject or rigid body. For example, *Pose*, uses rigid body tracking to capture the motion of handheld tools for collaborative construction tasks. MOCAP Camera arrays positioned within a work cell can aid in the adaptive assembly of bent wood members (Fig. 7). Placing tracking markers

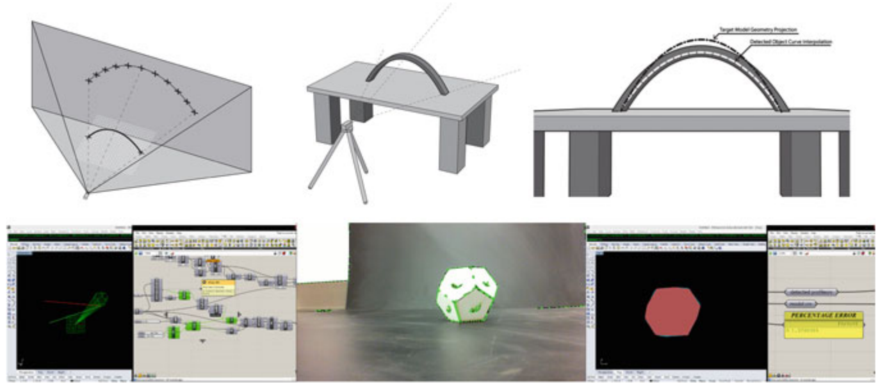


Fig. 5 *Left* digitally project desired curve. *Center* capture outline of physical bend. *Right* compare desired curve with physical bend and update motion

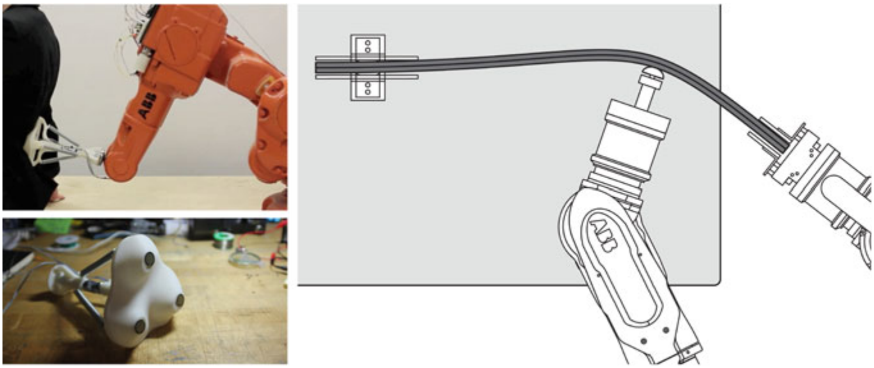


Fig. 6 Custom forming tool gauges pressure feedback from stressed wood

onto bent components and known registration points in the assembly area will enable each bent piece to be dynamically positioned into the overall configuration. After each component is placed in the assembly motion tracking positions can be checked against reference points in the digital model and be used to update the digital description of each successive component in the remaining assembly.

6 Workshop Outlook

All Bent Out… will stage three areas for material preparation and steam, material deformation, and assembly (Fig. 8). After wood is pre-soaked and steamed it will be moved to a coordinated bending cell within the overlapping work envelopes of an IRB 4400 and an IRB 6640. While in the bending cell the steamed wood's endpoints will be captured by a table gripper and the end of arm gripper of the IRB 6640. A third, force sensitive, end-effector on the IRB 4400 will engage the material at

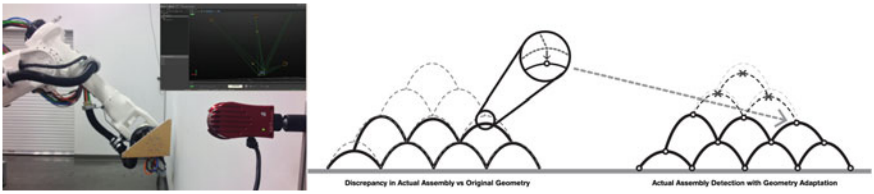


Fig. 7 *Left* calibrating motion capture and robot path. *Right* markers placed on physical components map the deviation between digital model and physical assembly

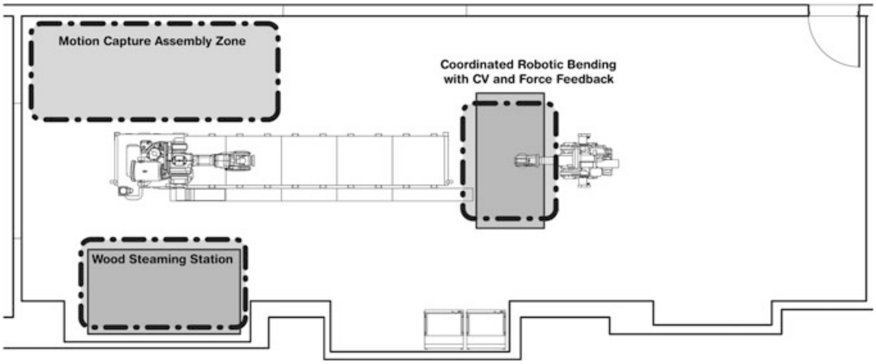
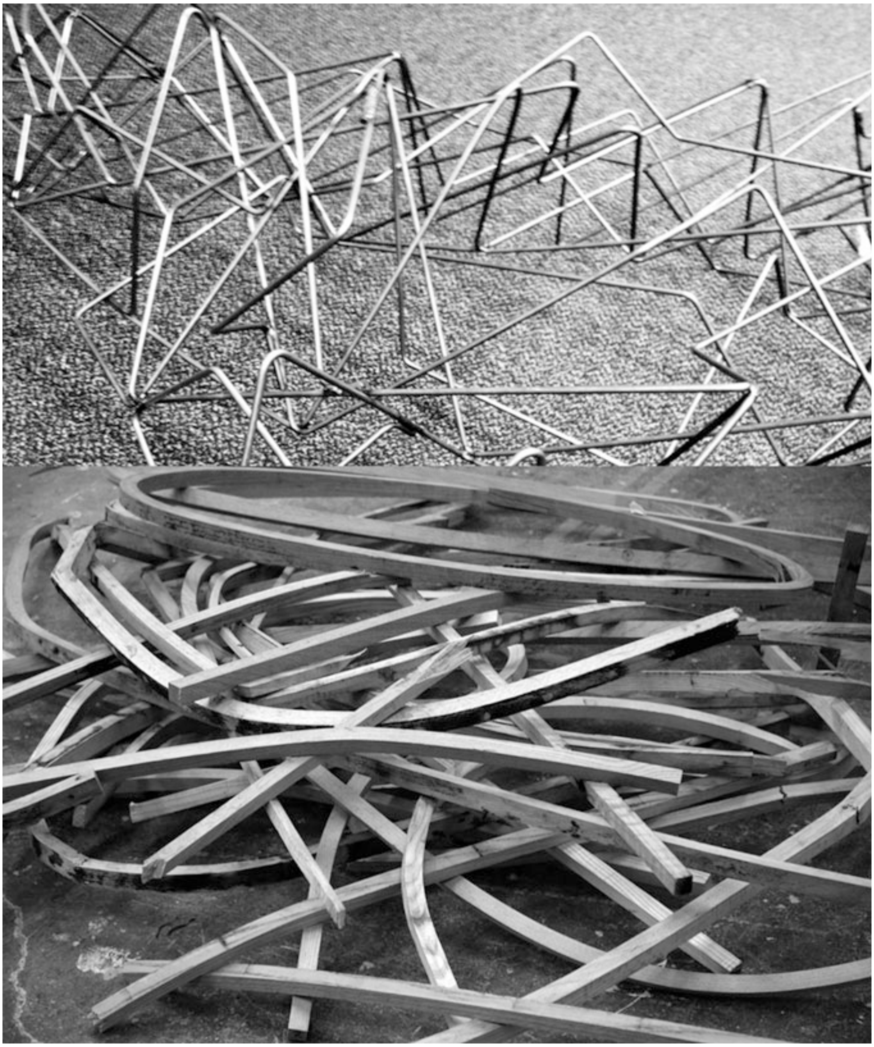


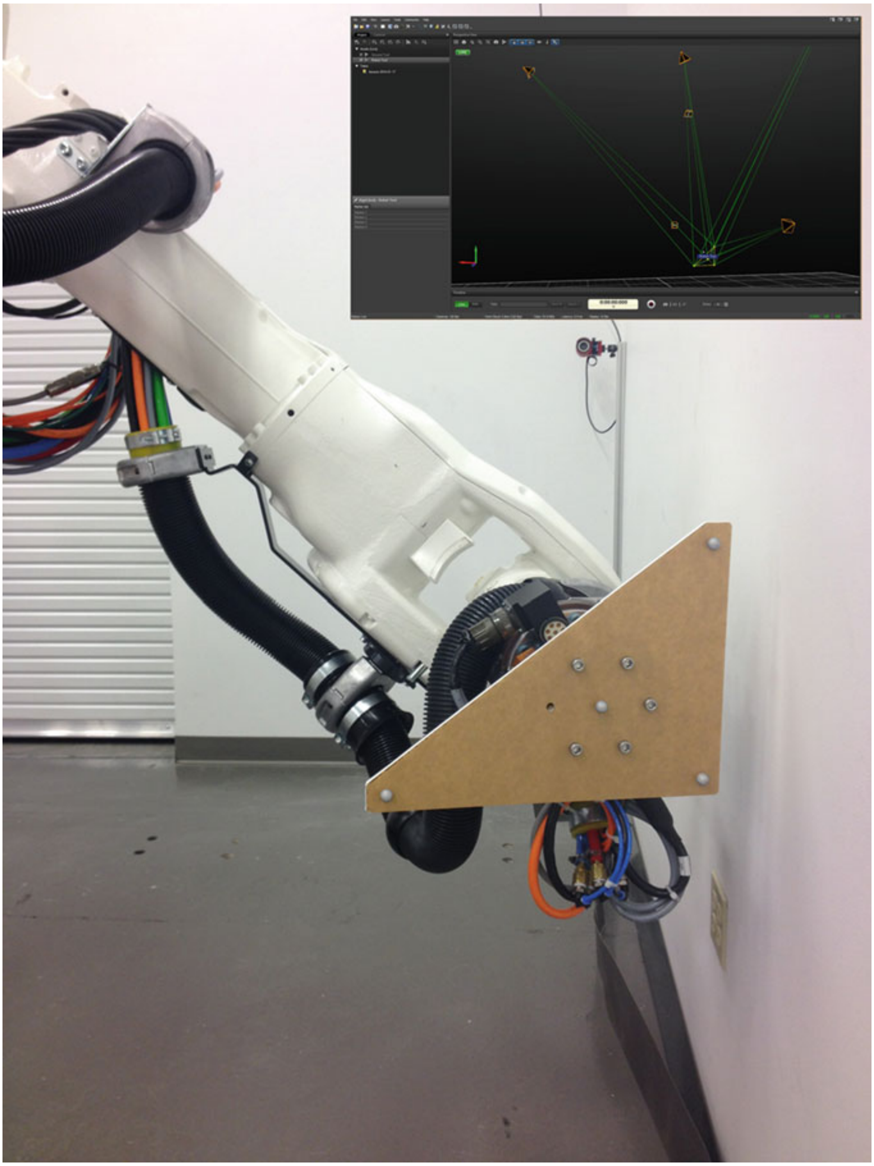
Fig. 8 Coordinated bending with an ABB IRB 4400, IRB 6640, and table fixtures. The IRB 6640 will position each component in the MOCAP assembly area

mid-span and deform the material into a desired shape. After each component is bent it will be checked with a digital camera and tagged with infrared reflectors. The component will then be repositioned along the 6640's 6 m linear axis in the MOCAP work cell and tracked in its final location. Tracking data will be compared against digital models of the assembly and discrepancies will be mitigated by generating new target positions for subsequent components. Participants of the workshop can anticipate testing this workflow through the fabrication of a bent wooden space frame with 30–50 members. Specific geometries will be refined through open-ended explorations in possible bent forms at the outset of the workshop.

7 Conclusion

The authors look forward to developing adaptive fabrication techniques in response to the unique challenges of robotically steam bending natural wood and anticipate that the synthesis of custom hardware and software tools developed for the workshop will extend the architectural designer's abilities to imaginatively utilize contemporary technology in fabrication settings. In particular the hope is that new opportunities to work with heterogeneous materials will drive further advancements in adaptive fabrication relative to the means and methods of constructing the built environment.





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