ROBOTIC MANIPULATORS AS ADVANCED MANUFACTURING AGENTS FOR LASER-CUT CONSTRUCTION SYSTEMS

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Robotic manipulators are transforming advanced manufacturing by allowing for the precise manufacture of intricate geometries and the direct transfer of digital data to physical materials. Recent work in the Architecture and Structures Lab (ASLab) of Politecnico di Milano has explored how these technologies can be integrated into laser-cut construction systems, particularly into workflows that connect digital design with robotic assembly. A series of methods are described to optimise designs for handling by manipulator arms, employing reachability analyses and assembly sequencing to ensure that construction is feasible. The stability of structures during scaffold-free assembly has been verified using R-funicularity and Coupled Rigid-Block analysis, with the goal to minimize reliance on temporary scaffolding during robotic assembly. Online control systems have been explored to improve on more widespread offline planners, utilizing fiducial markers and point cloud data to improve accuracy and robustness of automation. These workflows significantly enhance the fabrication and assembly of interlocking panelised structures, allowing for precise placement and a reduction in errors as well as providing early-stage design feedback. A case study with laser-cut timber sheets demonstrates cost-effective manufacture of contour crafted panels and their robotic assembly. This research pushes forward the integration of online planning for robotics in manufacture, providing a scalable workflow for automated assembly. With this, it is shown that through incorporating sensor feedback it is possible to improve manufacturing process precision and lessen the need for manual calibration.

INTRODUCTION

As architects and makers, robotic arms provide exciting opportunities in the realm of digital fabrication and manufacturing. The inherent precision of such digitally controlled systems allows high repeatability of tasks and enables the direct realisation of complex designed CAD forms. In the realm of additive manufacturing, they allow non-planar deposition which was previously infeasible with traditional cartesian printing machinery, providing benefits in layer adhesion, printed component strength and surface quality [1] and allowing sequential printing of multiple components. Recent work is also focusing on embedding components within conformal geometry [2] which is made possible through mounting 3D printing end-effectors to manipulators.

In assembly and subtractive manufacture, too, there are opportunities to be exploited with manipulator arms. Traditional assembly lines in the automotive industry have long made use of industrial arms for highly repetitive tasks, although typically such robotic cells are trained to function on a single task within the manufacture process. Better exploitation of the potential for arms allows their use as multi-functional agents able to complete multiple different tasks; for example, work of ICD Stuttgart constructed a multi-purpose manufacturing unit for the construction of the BUGA Wood Pavilion which was capable of manipulating cassettes, assembling them from plate components, milling and drilling [3].

Solutions integrating robot control into the CAD environment exist already (e.g. KUKA|prc [4] and HAL [5, 6]). As noted by Gandia et al. however [7], these tools work on input curves for the robot end-effector to follow, and these curves have to be created manually. With COMPAS FAB [8], the Gramazio Kohler research group allowed for connection between CAD and popular robotics middleware the Robotic Operating System (ROS) [9]. Using ROS, which is what many roboticists build hardware drivers and interfaces for, it then becomes possible to access sensor data and process feedback, something else which is lacking in the common workflows for CAD. In addition, tools such as MoveIt [10] provide capabilities for robot path planning and collision avoidance (shown being used for motion planning in Figure 1).

In this chapter, a series of software tools and pipelines are described which have been developed with the purpose of easing the digital design, fabrication, and robotic assembly of panel structures. Steps towards providing the designer with initial knowledge of robotic capabilities and translational freedom of designs are given, which allow the design of interlocking structures within the reach space of manipulator arms. Explorations in structural analysis are also described, such that structures may be constructed with minimal use of external scaffolding. Furthermore, a workflow has been developed based on the ROS middleware which allows for online planning and adaptation of motion planning for structural assembly. Finally, a series of experiments into this assembly process incorporating sensor feedback are discussed.

DESIGNING FEASIBLE STRUCTURES FOR ROBOTIC ASSEMBLY

Within the Architecture and Structures Lab (ASLab) at Politecnico di Milano, one stream of research has been focused on the development of CAD plugins and software to make design for robotic assembly simpler for the end users. While there exists a potentially infinite design space for a discrete panel structure typology which can be created within CAD, actual feasible designs which can be realistically manufactured and assembled by a robot arm represent a small subset. Indeed, the capabilities of the available robot arms (e.g. maximum reachability, carrying weight, ability to reposition the base), as well as geometrical design constraints (e.g. interlocking and interfacing between parts), and mechanical properties of the structural systems can limit the panel structure typologies that can be feasible for robotic assembly. In the following sections, pathways to overcome these limitations (or to work within these constraints) are discussed.

Reachability analyses

The working capabilities of manipulator arms are not necessarily intuitive for humans. Whilst many manipulators are based on human arms – with a set of joints, often a shoulder, elbow and wrist they are similar in many ways – however the configuration of a manipulator's joints is fundamentally different. The standard number of joints employed to be able to have a solution for any position and orientation within the reachable radius of the arm is 6, in order to cover cartesian poses, i.e. positions in X, Y, Z, and the respective rotations of roll, pitch and yaw. However, some arms have less joints than this, and many have an additional joint, to allow redundancy in having multiple solutions. Additionally, the physical structure of the arm can cause less reachable zones, where the arm cannot pass through itself. Further, singularities cause issues – where two or more of the joints are aligned in such a way that controlling the end effector to a local Cartesian pose can cause wild, dangerously fast motions.

In order to gain a quantitative understanding of the workspace for manipulator arms, the concept of the reachability analysis was developed, as described by Bergerman and Xu for point reachability [11] and extended to include pose orientation [12]. This method has been implemented by the ASLab group for Grasshopper modelling. First, an inverse kinematics numerical solver was created to find joint angles given a cartesian pose using a popular software package IKFast [13]. With this analytical solver available, it becomes trivial to test whether a pose is reachable or not.

To provide a metric probability of a pose being reachable, the volume around the manipulator was divided into a regular grid of points. For each point, a series of orientations was tested, sampled regularly using a Fibonacci sphere, and the number of reachable orientations found for each point. Then, the reachability score (for each 3D point is:

(1) $$R = \frac{N}{D}\#\left(\ \text{SEQ (\textbackslash* ARABIC 1 }\right)$$

Where N is the number of reachable orientations, and D is the number of orientations tested. These reachability scores can then be stored and used to score a geometric design for its overall reachability. Figure 2 shows the analysis applied to a parametric brick wall, which was scored using a fitness function to completely disallow unreachable bricks and maximise both the reachability and number of bricks; green locations in the figure indicate highly reachable regions and bricks, whilst red regions are close to singularity with few reachable orientations. The fitness score could then be used with an evolutionary solver to find some highly performant designs within the workspace.

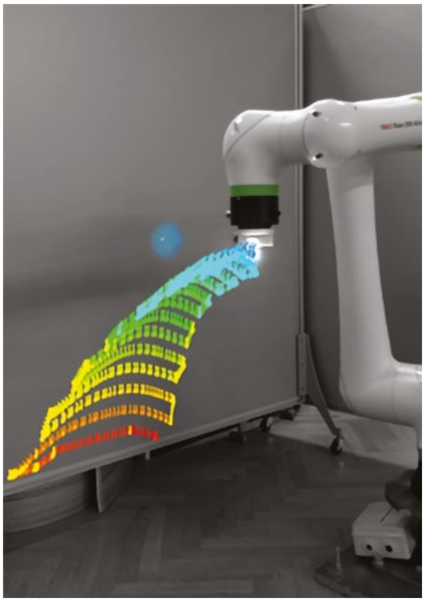

Figure 1: Control of a Fanuc manipulator arm to follow an example printing path, using online planning and control. An LED is attached to the end-effector, and a post-processing OpenCV script provides a long exposure light painting effect.

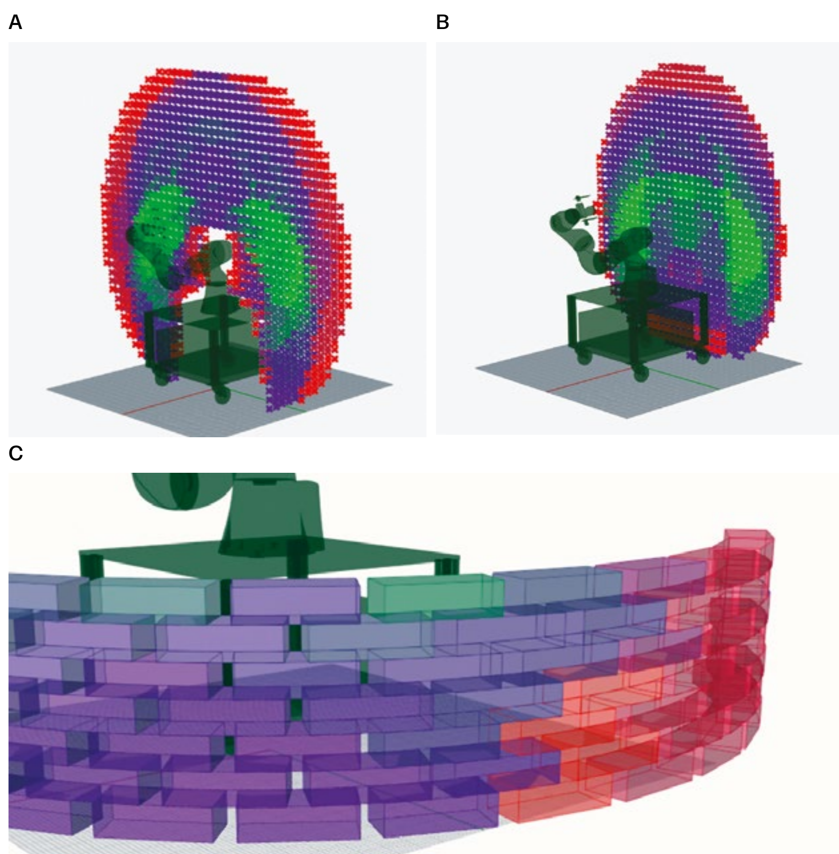

Figure 2: Reachability scoring for understanding construction feasibility, with green indicating high reachability and red, low reachability: (A) Reachability about a central slice in line with the manipulator base; (B) Reachability further out along the robot base's X-axis; (C) reachability metrics applied to a parametrically designed brick course.

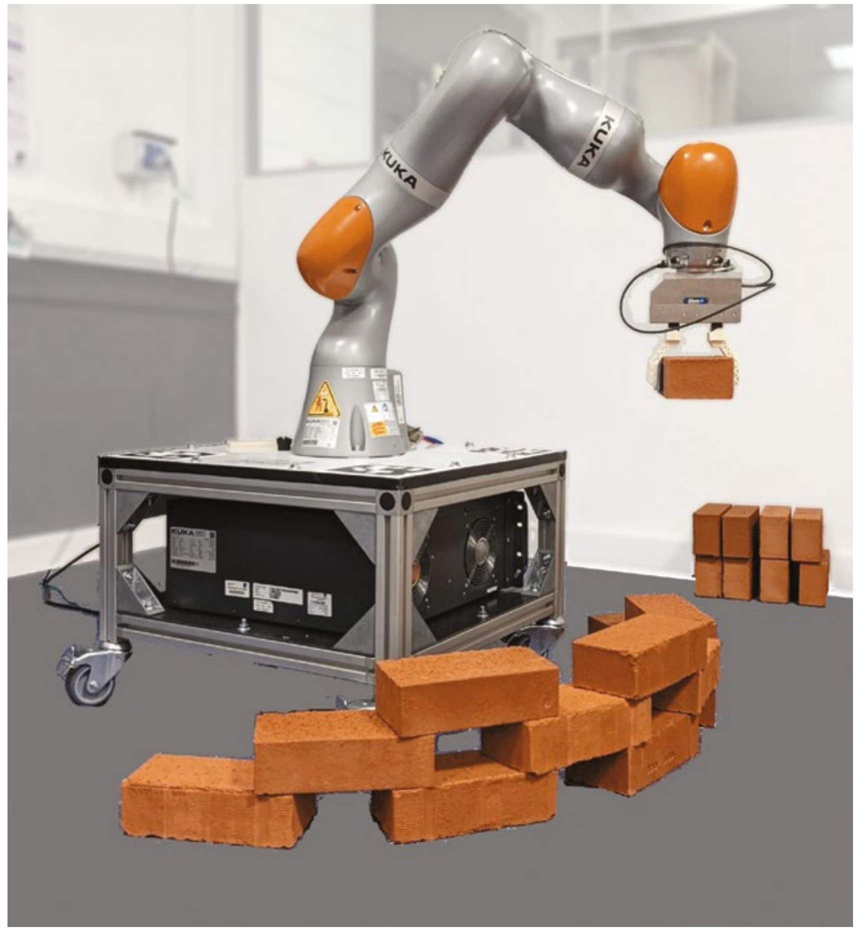

Figure 3: Brick wall construction with end pose data transferred from parametric CAD design.

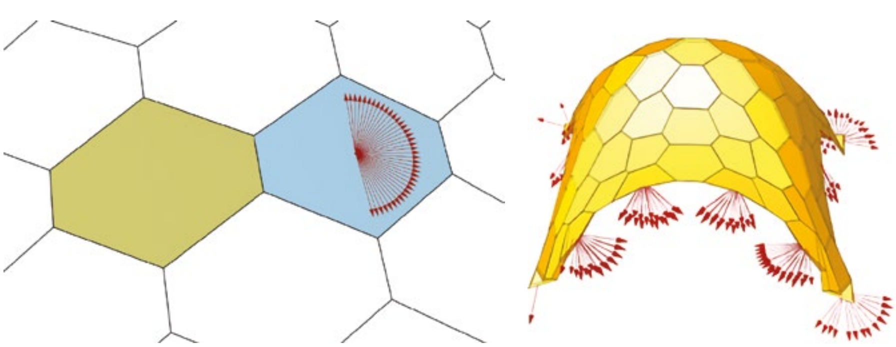

Figure 4: Kinematic analysis of a structure based on mating geometry: (A) The "free directions" of the clear blue panel are displayed relative to the opaque yellow panel; (B) The free directions within an example panel structure, accounting for all neighbouring panels.

Assembly sequencing

When designing interlocking panel components, there are two, contradictory goals. The first is that the panels should constrain each other in such a way that the structural integrity is guaranteed once assembled, for example preventing sliding motions, particularly those that could occur through gravity. When done correctly, it is possible to design structures without external fixtures, making disassembly much simpler at the structure's end of life [14]. On the other hand, it is also important that the designed structure is not over-constrained: it is perfectly possible to design a structure in CAD that is locked together in such a way that it could not realistically be assembled or disassembled, like a sliding puzzle with no solution.

One possible solution to this problem lies in Non-Directional Blocking Graphs (NDBG) [15]. First take a set of "free" or unblocked directions between a reference panel and one of its neighbours, which are vectors through which an infinitesimally small translational movement could be made without hitting anything (Figure 4A). If the set intersection of these vectors, and the similar sets describing free directions between the reference panel and all neighbours within the structure is found, it will describe the translational freedom of the reference panel, and thus possible directions through which it could be removed from the structure. If, at any given partial set of the structure's panels, we apply this to every element, we can locate the panels which are loosest, i.e. have the highest translational freedom (Figure 4B) [16]. Incorporating precedence constraints, i.e. ensuring that panels are only inserted if they have at least one neighbouring panel already within the structure, allows defining the possibility to insert each panel at any configuration of the partially assembled structure.

Given the free directions of the panels within the fully assembled design, it is possible to search for assembly sequences through iteratively removing elements from the structure and recalculating the free directions. This "backwards assembly planning" is a common search method [17] as it works from the most constrained state to the least, reducing the potential amount of sequences to test. This is important as the number of potential sequences to brute force test would otherwise be , where is the number of panels – for a realistic number of elements this number is extremely high and hence computationally expensive.

Different selection strategies can be chosen for selecting the next panel to remove, which gradually frees more panels in its neighbourhood. Successful full assembly sequences were found for the design in Figure 4 based on simply selecting the panel with the largest number of free directions. However, for other designs with realistic constraints found in the later integrally joined designs in this chapter, disassembly testing found many "dead ends" where the panels were interlocked and the search required restarting. In these cases, a semi-stochastic approach (giving some random choice to the next panel to remove) more quickly found a feasible sequence for the disassembly, and hence assembly of the geometry.

The utility of such a tool is not simply limited to panels, but it can be applied to any assembly of volumetric geometries which are connected through matched surfaces between neighbours. For example, one possible use case would be to combine such tools with structural analyses, to additionally select assembly sequences by those which most improve the structural integrity [18].

STRUCTURAL ANALYSES FOR SCAFFOLD-FREE ASSEMBLY

In addition to the robotic assembly feasibility of structures, their stability should also be considered. Panel or shell structures tend to require temporary falsework during construction to prevent their collapse, since they are often designed for global stability (ability to self-support once fully assembled) but not for local stability (self-supporting when partially assembled). This can be problematic when pursuing robotic assembly, as the supports will often obstruct and reduce the possible motions.

A number of different solutions to the falsework issue have been explored in the literature. One approach explored by Parascho is the use of a secondary arm to provide temporary support to the structure whilst adhesive or fixtures are placed [19]. This however creates its own set of issue; besides requiring additional expensive hardware, motion planning for multi-arm systems is more complex than for a single arm if they are moving at the same time. Others have created collaborative situations where a human operative takes the place of the secondary robot as temporary support or works to apply permanent fixing during the robots holding phase [20]. However, this type of human robot collaboration can be more prone to the accumulation of errors.

An alternative approach has been taken within the ASLab, where the focus has been on creating dry-stacked structures, i.e. without fixtures or adhesives to create structures that can be more easily disassembled. In order to do this, structural mechanics has been leveraged to solve the local stability issue through 2 methods, with one approach focusing on flexural and material effects, and the other focusing on contact and friction effects [21].

R-funicularity as post-processing tool for FEA

Gabriele et al. [22] introduced the use of an eccentricity metric for shell structures, as an indicator of how close the structure is to funicularity in different locations. By taking the ratio of bending moments to tensile forces and comparing to a factor of the material thickness, it can be shown whether the structure is dominated by compression effects (in which case the load is directed through the structure and is stable) or bending effects (in which case the structure will need external support). An initial finite element elastic analysis is undertaken on the design, before a postprocessing step is undertaken to calculate eccentricities. Additionally, the use of joints between panels can infer a tensile limit force [23], which has been calculated for dovetail joints and used to predict the stability of test arches and shells [21].

In recent work from the ASLab, the formulation was modified slightly to give a simplified visual representation of this eccentricity, also showing regions of contraflexure and where compression changes into tension, allowing a fast visual inspection to show expected failure regions to focus on adding additional support. Models were manually exported in FEA software for analysis, before being reimported back into Grasshopper for post-processing (see Figure 5A).

Due to the use of the elastic FEA, the R-funicularity approach works well for predicting the deflection of panels caused by flexural rigidity and could be well applied to a variety of materials and manufacturing processes where the material properties can be estimated. It is primarily defined for the fully assembled case, as the concept of funicularity makes little sense where there is no membrane through which to distribute the load acting on the material. Additionally, it relies on the assumption that the structure acts similar under load to a continuous geometry, as setting up an elastic analysis factoring in joint interactions is not a trivial task.

Coupled Rigid-Block Analysis (CRA)

In an attempt to account for the mechanics of the discretised panel typology of structure, an alternative approach has also been utilised. The coupled rigid-block analysis (CRA) of Kao et al. [24] is a methodology where masses are assigned to the discrete elements, in addition to friction coefficients at element interfaces. In a simplified form, based on a classical rigid-body mechanics formulation, it is possible to apply equilibrium conditions with friction constraints into an optimisation problem (Figure 6). If a solution to the optimisation problem can be found where there are no tensile forces, the structure can be assumed stable. In the original article by Kao et al. introducing CRA, the rigid block formulation was extended to include rigid body displacements, allowing for more realistic constraints to be added, such as removing friction constraints and normal forces when part surfaces move too far apart.

Kao et al. demonstrated that their analysis was suitable for shell forms including the well-known Armadillo shell from the Block Research Group [25] and for concave interface geometries, making it ideal for the integral dovetail joints being experimented on in the ASLab. The analysis was implemented through Python to be easily run from within Grasshopper (Figure 5B), allowing fast stability analysis of partially assembled structures.

A CALL FOR PROCESS FEEDBACK AND ADAPTIVE CONTROL

While manipulator arms tend to be highly repeatable – also called precise, meaning that they will repeatedly move close to the same location when given the same command. They are often not, however, accurate, meaning that the position they go to is not necessarily the requested one. This can have many causes, such as inaccuracies in the kinematics calibration, nonlinear effects in motors and operating temperatures to name a few.

As previously mentioned, a majority of the available CAD plugins for robot control are based on offline planners – a set of instructions is generated to complete a task, and then often generated to a robot manufacturer specific list of instructions to be executed similarly to how G-code works for traditional printing devices. While this works well for these Cartesian devices, there is a widespread issue of how to continue a print (or in this case, an assembly) if something goes wrong or needs recalibrating during the program's runtime. Additionally, due to the repeatability/precision issue, it is not guaranteed that the end effector is actually in the specified location. The ASLab has tackled this issue through two related aspects: implementing real-time, online motion planning with adaptive logic, and adding sensor feedback in connection with CAD for process monitoring.

Online control

To make use of the ROS software and to move away from offline control, a software pipeline has been built to connect manipulators directly to Grasshopper. Using the roslibpy software bridge [26], the CAD software can interact with ROS services and topics, and in particular with custom nodes specific to the task at hand. For example, for the brick wall assembly in Figure 3, brick poses were transferred to ROS for controlling a Kuka IIWA7, where custom logic was as follows:

1. Wait for the brick picking pose to be calibrated by hand-guiding of the robot,
2. Wait for user verification that brick is in the picking location,
3. Pick up brick,
4. Place in location at low speed, using constrained motions,
5. Repeat steps 2-5 until completion.

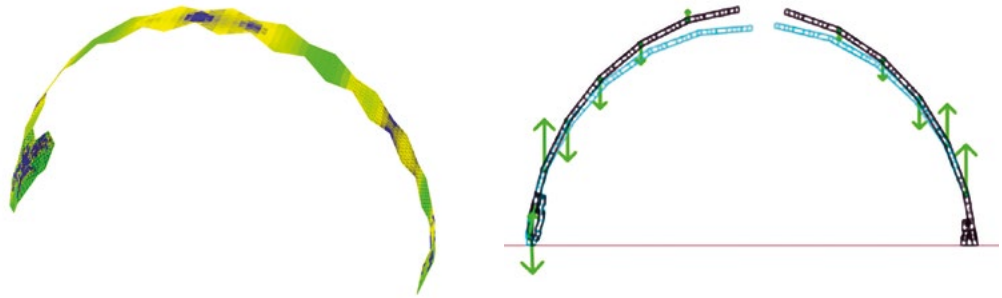

Figure 5: Structural analyses integrations within Grasshopper: (A) The R-funicularity analysis for a fully assembled arch, with blue regions showing high bending moments prone to failure; (B) CRA analysis for a partially assembled subset of the arch, showing potential deflection (blue) and interaction forces (green).

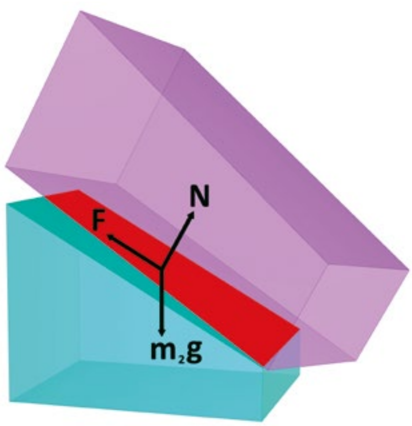

Figure 6: Base simplified rigid block equilibrium method, balancing the mass force of blocks mg, friction forces F and normal reaction forces N. Increasing number of blocks complexifies the analysis; and in CRA, virtual displacements are allowed, "activating" friction and normal forces only when there is a contact area between blocks (highlighted in red).

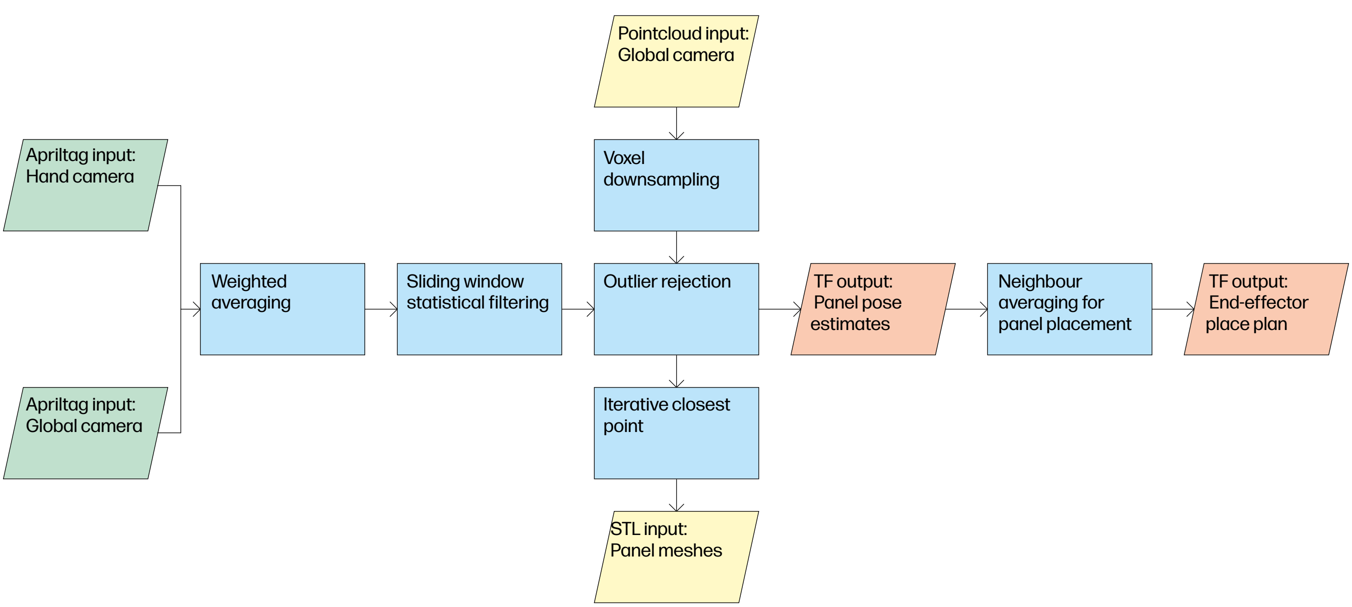

Figure 7: Sensor-based tracking used for pick/placing of panels.

Whilst for the printing simulation in Figure 1, the bridge was migrated to connect to the updated ROS2 software to run on a Fanuc CRX10iA/L arm to plan a series of motions to track a curve generated in CAD. The benefits here over offline plugin planning were that, in the case of occasional brick picking failures, the software could be told to replan and reattempt without restarting; the initial brick picking zone could be easily recalibrated during the process; and at all times, the progress of the robot could be monitored live within CAD along with a simulated representation of the assembly state. This move towards creating a manufacturing digital twin provides higher assurance of successful, robust processes.

Fiducial tags for camera feedback

A common approach to solving the issue of low accuracy in robotics is to provide a form of feedback or monitoring of the state of the environment. Through monitoring the actual state of the robot itself, it is possible to refine the state estimate provided by the robot's kinematic model. By additionally monitoring manufacturing components, they can be handled more successfully and the manufacturing state can be assessed.

Computer vision plays a key role in the current state of the art for robot process monitoring. Using machine learning (particularly neural networks) it is possible to observe using cameras, to label objects, and to estimate states. Such AI models however tend to be computationally expensive to run, dampening their utility for real-time monitoring. A faster solution is instead to encode data within objects so that it can be more easily read by a computer from an image. Fiducial markers such as AprilTags are a popular method for this. AprilTags are grid images of black and white squares which can be detected within an image, similar to a QR code [27]. Unobscured tags can be quickly detected in black and white images, with built in error metrics to prevent accidental false positives. Each tag is associated with an ID number, meaning that distinct parts can be given separate tags so that the robot control software can understand which parts are within a camera's field of view. Additionally, provided that the camera is well calibrated and the real dimensions of the tag are known a priori, the position and orientation of the tag relative to the camera can be calculated through matrix mathematics.

Initial tests were conducted in the ASLab on the use of AprilTags laser-engraved into wooden materials, to determine their effectiveness with different cameras and image resolutions, including low-cost computer webcams. Through varying light conditions and comparisons to similar black and white inkjet printed tags, a lower range of distances was reported for detection, particularly in extreme lighting conditions. It was also found that pre- and post-processing was important for tag detectability. By using masking tape on the area before laser engraving, scorch marks on white pixel regions of tags which would affect detection were reduced; while sanding could be used to clean remaining scorch marks.

Importantly, even the low-cost, readily available webcams provided high accuracy for pose estimation and tag identification on the wooden tags, as shown in Figure 8. The initial AprilTag algorithm from Olson [27] was reimplemented as part of a Grasshopper plugin, allowing real-time access to part locations for both the robot controller and the CAD model (see Figure 9B).

Such fiducial tags are of benefit here for the monitoring of parts for the digital twin model, and can help the manipulator arm to ensure correct picking and placement of parts. For manufacturing too, the use of tags as reference markers would allow the repositioning of workpieces, for example for the reorientation of printing beds in additive manufacture or for the locating of embedded components.

Point cloud data

Whilst the use of fiducial markers allows structured data to be encoded into manufacturing elements, they are restricted to use where they can a) be visible without obstruction, and b) on solid, planar surfaces. For the more general monitoring of manufacturing processes, recent work at the ASLab has approached the addition of point cloud data, observed using depth cameras.

Point cloud data gives 3D locations of points on the first surface that can be seen by depth cameras. This can be compared to as-designed mesh models for the monitoring of processes without planar surfaces, and from any angle, which makes them more applicable to a wider range of manufacturing techniques including additive manufacture. Further, point cloud data from multiple orientations can be stitched together using registration techniques to better constitute a 3D model, which is made easier in combination with fiducial tags as reference points for a moving camera frame. This was again integrated into both CAD and the robot controller to avoid collisions and improve ongoing state estimates of assembly processes. The process is a highly viable candidate for ongoing monitoring of a range of manufacture processes.

CASE STUDY USING LASER CUT CONTOUR-CRAFTED TIMBER

As a study into the various aspects explored in this chapter, an end-to-end workflow from design to fabrication to assembly was conducted. Applying reachability metrics and assembly sequencing alongside mechanics modelling,

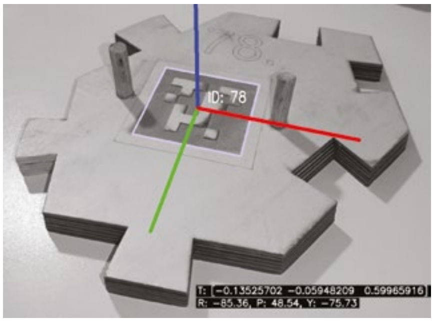

Figure 8: A laser-cut AprilTag for pose estimation on the surface of a panel, with output pose estimation data overlayed onto the image.

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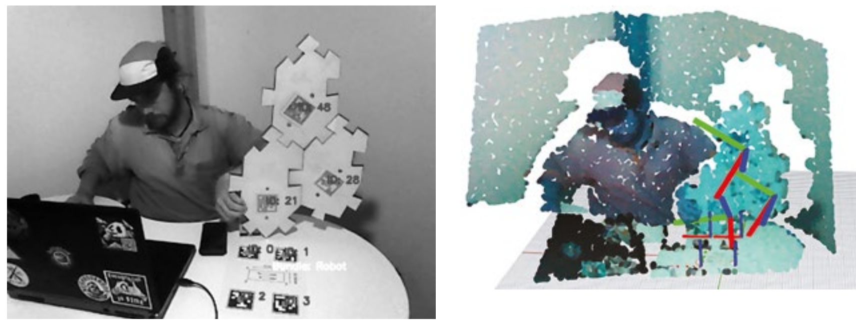

Figure 9: Direct real-time visualization of camera data within CAD software Rhino using a low resolution camera: (A) The original RGB image; (B) Visualisation of tag poses (as red/green/blue Cartesian axes markers) and point cloud data.

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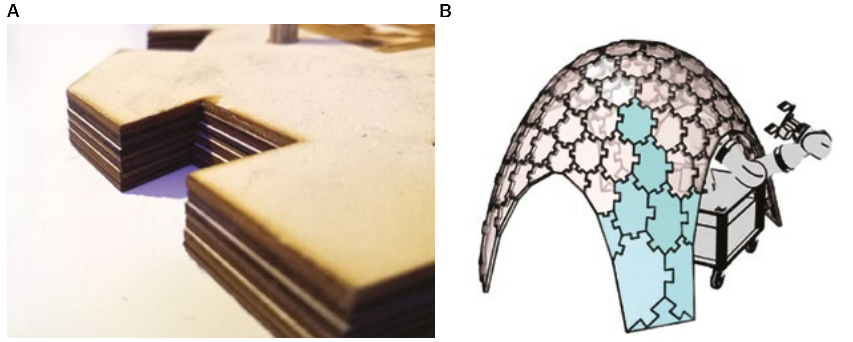

Figure 10: Stacked layers of laser cut materials allow complex geometry to form with low-cost manufacturing: (A) A sample panel, showing laminar layers; (B) A test set of panels from a designed structure, manufactured for robotic assembly.

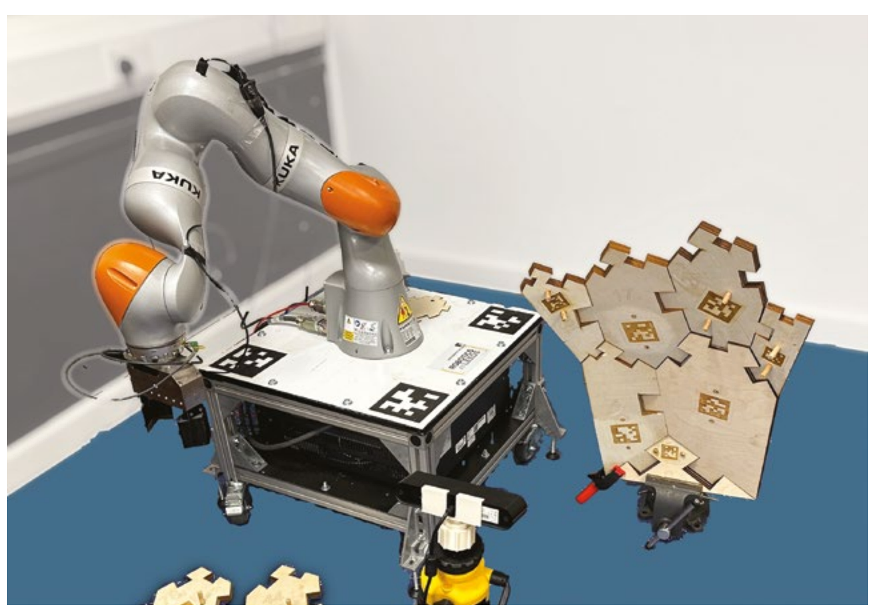

Figure 11: Successful pick and place assembly of timber panel system.

a panel structure was developed where every panel position was within the Kuka IIWA7 arm's functional workspace whilst maximising height and span (Figure 10B).

The panels were comprised of hexagonal, planar intrados and extrados, with the addition of integral dovetail joints between neighbours to withstand bending moments and support the structure through cantilevering during assembly, which the authors have previously demonstrated [21]. Due to the curvature of the structure, to maintain the planar panels, the edge surfaces require both positive and negative bevel angles. To manufacture these surfaces exactly in timber would require the use of 5-axis CNC machining rather than a less expensive Cartesian 3-axis process. As an alternative, a manufacturing method was devised using thin sheets of plywood and laser cutting. A selected subset of panels were sliced into layers at heights corresponding to the sheet material stock thickness, then border outlines were exported as vectors to instruct the laser cutting. AprilTags were additionally added to the top surfaces for rastering, whilst a pair of reference holes was cut through each panel. Once cut, the panel layers were glued and assembled by hand, with dowels inserted into the reference holes (Figure 10A). Taking quotes from CNC suppliers, the effective cost of this manufacture was reduced by a factor of 10x, and the use of thinner sheet layers showed an excellent fit with minimal post-processing between neighbouring panels, despite the stepped edges that form due to the layering process.

For robotic assembly testing, a series of AprilTags were placed around the robot base as a reference bundle. By doing this, the relative position of a camera to the robot could be found whenever the robot was within the camera's field of view. A RGB-Depth camera was placed on a tripod such that it could see both the robot base and the structure's base element (Figure 11). Due to the use of the robot base tags, the tripod could be moved freely within the environment so long as it could still see at least one robot tag and one structural tag, and provide data to the robot control software to comprehend where the next panel should be placed.

In addition to the depth cloud camera, which was calibrated to work in a range of between 1 and 3 metres, a low-cost webcam was also calibrated to work in a range of 5-30cm and attached to a known location on the manipulator's gripper, allowing better grasping of components by minimising the accuracy errors as the gripper approached parts. By combining these two input streams of AprilTag pose data, the controller gains information on both the global state of the assembly process and the local state of parts close to the end effector.

By continuous comparison of the construction to the designed structure, in particular comparing the relative pose transformations between panels, the arm was able to insert parts which it was not able to do without the process monitoring due to small errors. Particularly, deflection of the structure caused large enough changes in the structure at even this scale that the arm was unable to insert parts without the feedback AprilTag data due to the fine insertion tolerances. Planning of the arm movements was undertaken live before each form of motion (free movement, movement holding a component, slow linear motions for picking and insertion), meaning that the arm or the panel could be repositioned to get a better view or larger effective workspace. Due to this, the actual constructable workspace could have potentially much larger span than initially found in reachability analyses.

Future work on this topic will improve the digital twin aspect of the assembly by making use of the available point cloud data, to shift towards digital manufacture outside of assembly processes. For example, adaptive online planning of additive manufacturing processes could conceivably allow the generation of procedural printing paths and adaptive print speeds, augmenting the models of 3D manufacturing processes to improve print quality and size constraints.

CONCLUSIONS

A series of steps have been described for the end-to-end workflow of creating a digitally designed, manufactured and assembled panel structure. Through the development of software tools for robot workspace analysis and assembly sequencing, the designer can receive early-stage feedback to understand the feasibility of using manipulator arms for manufacturing processes. These are important factors when working with the often unintuitive kinematic capabilities of manipulators as well as to understand whether designs can be realistically assembled without potentially damaging collisions.

Structural aspects have been explored and describe the use of mechanical models for the assessment of not only the finished component, but also intermediate manufacturing stages. Such modelling of the full-process is here vital for assembly without scaffolding, and similar techniques should be implemented into complex geometry additive manufacturing processes to understand the stability of workpieces throughout the manufacturing process, whether that be through empirical models or more computationally expensive finite element methods.

The addition of sensors and online planning which is generated on-the-fly allows for dealing with non-deterministic, changing environments and aids in dealing with tolerances and calibration errors. The use of fiducial reference tags is shown to allow the movement of sensors, workpieces or robot manipulators without negatively affecting calibration, as automated calibration can be continuously reapplied to find the relative poses between the work materials and robot. In combination with point cloud data for taking 3D measurements, it should be possible to improve printing quality in manipulator assisted additive manufacture by constantly monitoring output geometry and adapting print parameters. Further, reference tagging and automated calibration shows promise for being able to work in larger span workspaces than the robot could reach on its own, through repositioning of the robot base. Ultimately, 6 degree of freedom kinematic devices like manipulator arms provide notable opportunities for the improvement of advanced manufacturing, and future research should continue to focus on moving away from offline planning in favour of augmented, feedback driven processes to generate improved end artifacts.

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