Research Statement

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I am a roboticist, engineer, and educator interested in the **relationship between designs and the processes of building them**. My research develops **intelligent robotic systems** to simulate, quantify, and augment design and construction, aiming to transform how we conceive, plan, and execute building projects. At its core, my work integrates *automated planning*, *physics simulation*, and *computational design* to establish a forward–backward feedback loop: in the forward direction, planning algorithms empower robots to autonomously assemble structures across scales; in the backward direction, insights from planning and execution inform new design strategies that are both efficient and robot-compatible.

The long-term vision is to pioneer a new generation of construction automation where **planning serves as the backbone that links design intent, robotic capabilities, and site conditions**. By advancing this integration, I seek to address urgent challenges in Singapore and globally: labour shortages in construction, the need for rapid and high-quality housing and infrastructure delivery and renovation, and sustainability through resource-efficient design and reuse.

Previous and current work

<u>Planning for robotic prefabrication of structural components</u>

In the last three decades, robots deployed in factories to prefabricate structural components have shown promise in dramatically improving production efficiency and cost reduction. However, unlike their human counterparts who are capable of *implicit planning*, robots require *explicit planning* both on high-level **tasks** ("what to do") and on low-level **motions** ("how to do it"). Enabling the robots to do such planning automatically is the key to flexible manufacturing that can swiftly adapt to evolving design demands, novel fabrication processes, and irregular material stock from natural or reclaimed sources.

During my PhD, I developed a series of planning systems that **simultaneously reason in both task and motion levels**, while staying flexible to allow integration of motion, structural, and logistic constraints. In contrast to prior work that used robots to build shapes constrained in certain typologies, my planning systems have advanced the robotic system's capability to **build unconstrained design input**. Exemplary outcomes include robotic spatial extrusion of topology-optimized shapes [1-4] (fig.1-1), robotic assembly of bar structures [5] (fig.1-2), and large-scale robotic assembly of timber structures with integral joints [6] (fig.1-3).

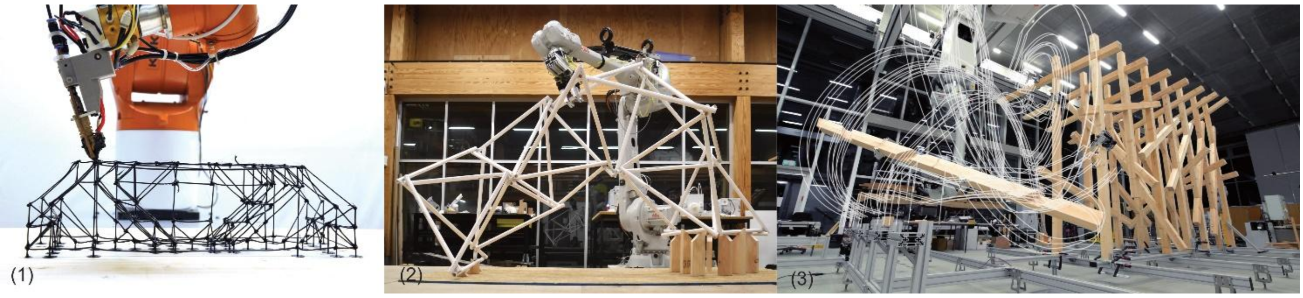

Figure 1. Research outputs enabled by my robotic planning algorithms: (1) robotic spatial extrusion [2]; (2) robotic bar assembly [5]; (3) integral timber assembly that involves beam placement and joint fixturing [6].

<u>Computational circular design</u>

Designing with reused materials requires a paradigm shift from the traditional design model, where infinite material supply is assumed, to an **availability-driven design** model, where limited quantity and irregularity of individual pieces are actively embraced. However, **balancing other objectives in structural design and availability requires planning** to decide the best way to assign and process our material inventory.

In this research featured on Dezeen, I developed an **optimal matching algorithm** to assign discarded tree branches as joints on load-bearing structures, exploring the structural potential that arises from the tree branches' inherent fiber direction and natural geometry [7] (fig.2-left). My recent work explores computational circular design from another angle: **how can we design infinitely reusable kits of parts from standardized elements and connectors**? Together with my Master's student at ETH, we developed an optimization algorithm to convert arbitrary line graphs to temporary structures that use bars with uniform lengths and swivel couplers [8]. Because no custom joints are required (e.g., cast or 3D printed), and bars stay uncut, no physical trace will be left on the material kit once disassembled, and the kit can be reused to build diverse structures (fig.2-right).

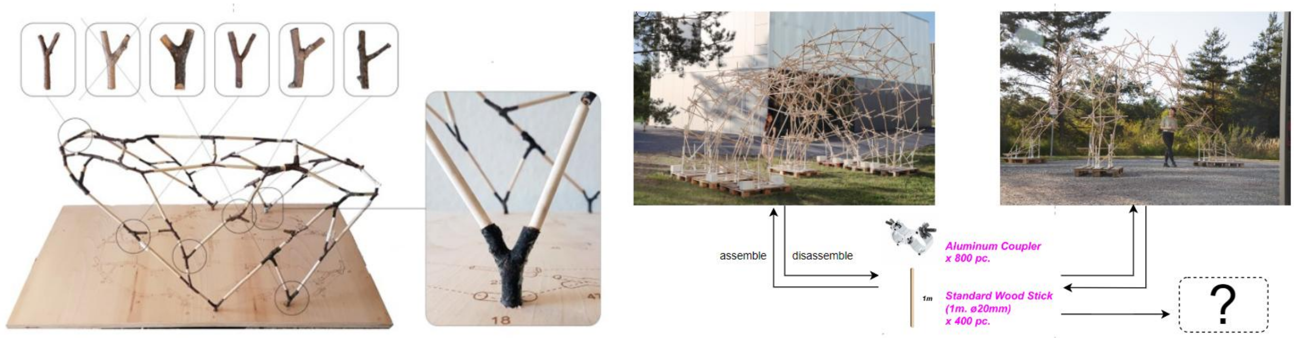

Figure 2. Left: optimal matching for utilizing waste tree forks as structural joints [7]. Right: infinitely reusable kit of parts by computing diverse structures from a standardized material kit [8].

Future directions

<u>Co-designing Tools, Behaviors, and Structures through TAMP</u>

My central thesis is that task-and-motion planning (TAMP) should not only plan robotic construction; it should shape the design ("what to build") and the process ("how to build them"). I will use TAMP as the backbone to co-design robotic behaviours, specialized tools, and robot-friendly structural systems so that assembly becomes both feasible and efficient on real platforms.

Prefab automation to full autonomy. Many planners I have developed transfer directly to controlled factory settings. I will leverage industry collaborations to push from "robot places elements" to full autonomy, where robots also perform **connection making**. Instead of forcing robots to struggle with human-centric connectors and tools, I am interested in co-designing robot-friendly joints, specialized end-effectors (e.g., the distributed robotic clamp in our previous timber assembly work [6]), and new robotic capabilities. TAMP remains the central validation tool: before hardware is built, the planner will **simulate feasibility, quantify throughput, and expose bottlenecks**—shortening iteration cycles and reducing integration risk. I am exploring this direction in ongoing work with Prof. Pok Yin Victor Leung at the City University of Hong Kong.

From prefab to on-site assembly. The next research frontier in the field is **mobile, on-site assembly** for tasks that make little sense off-site (e.g., scaffolding). I will progress material/structural systems one at a time, starting with wheeled mobile manipulators as a pragmatic intermediate step, while keeping the tools, processes, and planning-informed design patterns platform-agnostic. As capabilities mature, the same abstractions can extend to **humanoids** or **mixed teams (cranes + robots)**.

Towards foundation models. Each co-designed system will generate paired simulation-and-field traces: symbolic task graphs, geometric/physics states, actions, and outcomes. My long-term goal is to curate these as a construction assembly data corpus to train a **foundation model for robotic assembly** that captures cross-task regularities (tool use, bracing, sequencing) and supports few-shot skill adaptation.

Hierarchical planning for entire construction operations

My mid-term goal is to develop a hierarchical planning stack that scales from **single-robot, single-manipulator skills** to **coordinated, multi-agent operations** (machines across different scales) and multiple tasks over an entire site. At the top, an **operations layer** schedules cranes, lifts, routes, and safety/exclusion zones; a **process layer** decomposes work into task networks with physical preconditions; and an **agent layer** uses task-and-motion planning (TAMP) to produce time-stamped, collision-free trajectories with reactive re-planning. This enables both small-scale cross-machine coordination, such as **a humanoid collaborating with a crane to guide the last-inch installation of a crane-lifted prefab module**, and a site-scale shift: replacing **experience-based Gantt charts** with a **4D simulation** that goes beyond a stationary spreadsheet to encode not only task assignment but also **kinematic trajectories** and spatial footprints, updating on the fly under uncertainty. Methodologically, I will **push the algorithmic frontier of multi-agent TAMP** and develop a **modeling interface** that formulates construction processes in a planning-friendly format. Such planning is especially useful in Singapore, where there is high demand for new housing, infrastructure, and repairs. In a country with land scarcity and dense urban conditions that constrain sites and make project planning complex, a live 4D plan helps minimize disruption and better control of risks.

Towards plannable, actionable BIM

My very long-term goal is to develop a new generation of **BIM that is planning- and execution-ready for human and robot workers**. Concretely, I will extend BIM with planning primitives (tasks, resources, affordances, contact surfaces, tolerances, assembly semantics, safety/exclusion zones, staging areas, lift points) so it can be planned by a TAMP solver to generate executable task-and-motion plans for a given robot team. My envisioned future BIM modelling workflow is: an AI assistant runs in the background to **auto-populate this metadata** from design intent and learned past experience; the TAMP engine then **validates feasibility, estimates 4D timelines**, and writes back trajectories and constraints, keeping the model live. When a task is not robot-feasible, the system **returns diagnostics** (why it fails) and **remedies** (edits to geometry, materials, or metadata) and **proposes alternative design options with quantified cost/time/risk deltas from the planner**. The end state is an actionable BIM that serves as both a compiler (BIM → executable plans for robots/humans) and a linter (design → buildability critique), closing the loop between design, planning, and site execution.

References

* indicates equal contributions.

[1] **Y. Huang**, J. Zhang, X. Hu, G. Song, Z. Liu, L. Yu, and L. Liu, "FrameFab: Robotic Fabrication of Frame Shapes," *ACM Trans. Graph.*, vol. 35, no. 6, p. 224:1-224:11, Nov. 2016, doi: 10/gctq9n.

[2] **Y. Huang**, J. Carstensen, and C. Mueller, "3D truss topology optimization for automated robotic spatial extrusion," in *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2018*, 2018.

[3] **Y. Huang**, C. R. Garrett, and C. T. Mueller, "Automated sequence and motion planning for robotic spatial extrusion of 3D trusses," *Constr Robot*, Dec. 2018, doi: 10.1007/s41693-018-0012-z.

[4] C. R. Garrett*, **Y. Huang***, T. Lozano-Pérez, and C. T. Mueller, "Scalable and Probabilistically Complete Planning for Robotic Spatial Extrusion," in *Robotics: Science and Systems (RSS)*, 2020.

[5] **Y. Huang**, C. R. Garrett, I. Ting, S. Parascho, and C. T. Mueller, "Robotic additive construction of bar structures: unified sequence and motion planning," *Constr Robot*, vol. 5, no. 2, pp. 115–130, Jun. 2021, doi: 10.1007/s41693-021-00062-z.

[6] **Y. Huang**, P. Y. V. Leung, C. Garrett, F. Gramazio, M. Kohler, and C. Mueller, "The new analog: A protocol for linking design and construction intent with algorithmic planning for robotic assembly of complex structures," in *Symposium on Computational Fabrication*, Virtual Event USA: ACM, Oct. 2021, pp. 1–17. doi: 10.1145/3485114.3485122.

[7] F. Amtsberg*, **Y. Huang***, D. Marshall, K. Gata, and C. Mueller, "Structural upcycling: Matching digital and natural geometry," in *Proceedings of Advances in Architectural Geometry*, 2020, p. 17.

[8] **Y. Huang***, Z. Wang*, Y.-H. Hung, C. Jiang, A. L. Gheyselinck, and S. Coros, "Computational design and fabrication of reusable multi-tangent bar structures,"*Computer Aided Design*, 2024.