Co-Design in Architecture: A Modular Material-Robot Kinematic Construction System

Samuel Leder[1], Ozgur S. Oguz[2,3], Hyun Gyu Kim[4], Valentin N. Hartmann[2]
Marc Toussaint[3,5], Achim Menges[1] and Metin Sitti[4]

***Abstract*— Modern developments of construction robotics generally utilize a robot-oriented design approach to develop viable systems for the building industry. This has led to highly sophisticated automation of conventional, but at best slightly altered construction processes. In this paper, we argue for a material-robot oriented design process for the creation of novel construction robotic systems, which can expand the repertoire of current building practice and architectural possibilities. The co-design of a modular material-robot kinematic chain construction system in which the material, robot, and process inform the overall system is introduced from the architectural design, robotic mechatronic development, and task and motion planning perspectives. We present initial research on how material-robot kinematic chains can work in parallel to assemble, disassemble and rearrange large structures.**

***Keywords*— construction robotics, architecture, task and motion planning, modular robotics**

I. INTRODUCTION

Construction robotics as a field has gone through a series of paradigm shifts since its emergence in Japan in the late 1970s due to developments in computational building design, robotics, and computer science. What began as a series of experiments in robotically prefabricated large-scale building of houses, gradually expanded towards applications of on-site automated heavy-duty construction equipment [1]. However, the complexity of installation of such equipment and lack of integration between different construction processes on-site led to a reorientation of the field by mid-1980s towards integrated on-site factories with highly structured construction environments. More recently, construction robotics is shifting away from chain-like organizations of on-site factories towards revisiting the concept of multiple single-task on-site robots, which allow for workshop-like flexibility for the automation of conventional construction processes originally designed for human workers [2].

The research has been supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2120/1 – 390831618, and the DAAD.

[1]Institute for Computational Design and Construction, University of Stuttgart, Germany {firstname}.{lastname}@icd.uni-stuttgart.de

[2]Machine Learning & Robotics Lab, University of Stuttgart, Germany {firstname}.{lastname}@ipvs.uni-stuttgart.de

[3]Max Planck Institute for Intelligent Systems, Germany

[4]Physical Intelligence Department, Max Planck Institute for Intelligent Systems, Germany

[5]Learning and Intelligent Systems Lab, TU Berlin, Germany

Although much of these advances in on-site construction robotics were achieved through a robot-oriented design approach, this paper introduces exploratory research into methods in which both the robotic manipulator and the building material play equal importance in the co-design of a complimentary robotic construction and architectural building system. The research presents a shift from the automation of large-scale machinery to custom built bespoke mobile machines. Furthermore, the research proposes a system that combines actuator hardware and building material into a modular robot-material kinematic chain that can reconfigure in order to enable the execution of construction processes. We assume that, by combining construction materials and robotic actuators into an integrated modular kinematic system, one could achieve a higher degree of adaptability of the construction process. Thus, rather than defining automation processes based on the capabilities of specific pre-existing machines as with the robot-oriented design approach, this research investigates the co-development of construction processes, material and robots into a single system.

In order to achieve this material-robot oriented design approach to construction robotics, the research involves the development of methods for designing architectural artefacts, creating robotic hardware and task and motion planning. This paper discusses the overall co-design workflow of a modular robot-material kinematic chain construction system.

We build on the previous research of one of the authors from [3] and [4] and develop a single degree of freedom robotic actuator that leverages timber struts, a readily available construction material, as the basis of a construction system (fig. 1). The building material forms part of the robotic body, serves as the locomotion base for the robot, and can be used to build the architectural artefact. Specifically, the contributions in this paper are:

- a new design of the mechatronic system,
- application of robust task and motion planning methods to plan the movement and the robot-strut interactions,
- initial exploration of feasible architectural design methods and building artefacts using the developed system.

II. BACKGROUND

Despite on-site construction robotics research currently relying on robot-oriented design approaches, there are various research projects exploring task-specific robotics for

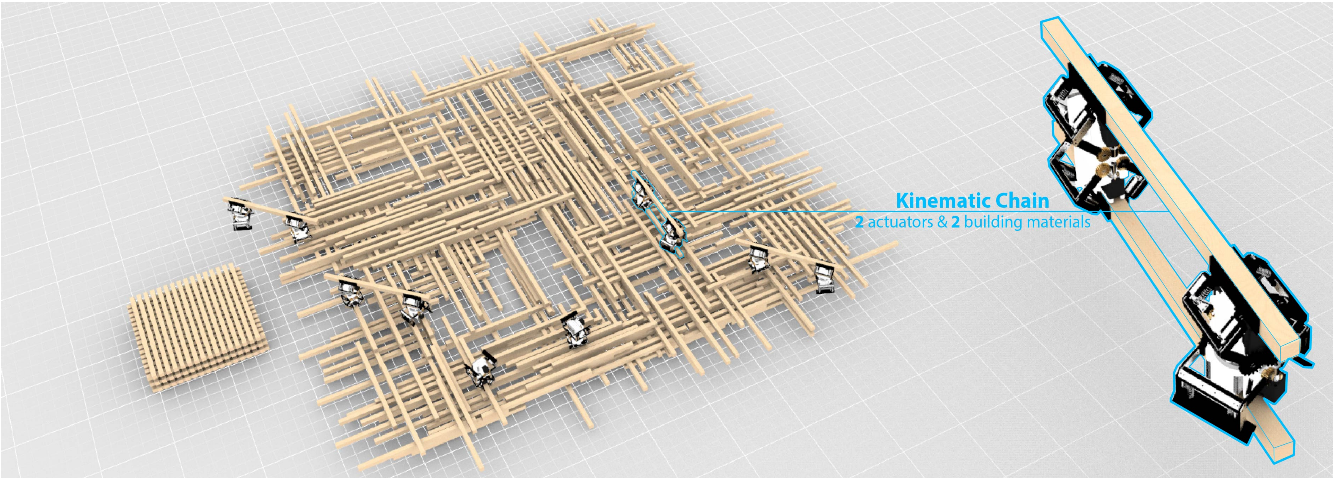

Fig. 1: Modular material robot kinematic chain construction system, composed of many single axis actuator robots which collaborate in parallel with timber struts to form kinematic chains and in turn construct architectural artefacts

architectural construction in which the material and robot influence the overall construction system. These projects can be broken down into three categories: *i)* machines designed to operate with off-the-shelf material, *ii)* off-the-shelf machines augmented to assemble designed materials, and *iii)* co-designed machine and materials.

Although the first category depends on existing construction material, in each case the robots are designed specifically in relation to a chosen material, which can either be discrete (i.e. bricks, struts) or continuous (i.e. fibers, concrete) [5]. Robots are equipped with the ability to manipulate material and often locomote on the material itself [6]. In [7], the material not only serves to inform the design of the robot but further influence the process and design space. In such cases, the material, robot and process are continuously informing the generation of the robotic construction system.

Unmanned aerial vehicles (UAV) have also been customized for the assembly of structures. Despite their highly unrestricted working area, UAVs have very low payloads and therefore require the creation of custom materials for their application in construction. Custom end-effectors were developed for UAVs in order to assemble plastic struts into cuboid truss structures as well as custom carbon fiber building blocks into canopies [8], [9].

The final category involves the design of machines and building materials for the creation of completely novel construction systems. This research includes systems where the machine is using the current state of the built artifact as its base, iteratively relocating itself along the structure for every next step of the construction process [10]. Some researchers within modular robotics are investigating the use of passive modules for the assembly of furniture scaled objects [11]. However, most of this research generally ignores, or relies on weak connection between elements [12]. Thus when scaled up to an architectural application, they run into challenges of structural stability, geometric variation and applicability.

III. Method

Reducing the manipulator to a robotic actuator with minimal degrees of freedom and leveraging the construction material itself as a link between two actuators allows for a highly modular robotic system capable of forming a variety of robotic configurations, which we refer to as kinematic chains. Timber struts and robotic actuators can be added to a kinematic chain throughout the construction process, as more complexity of movement is required, which allows maintaining the agility of the overall system with a minimum number of actuators. Furthermore, discretizing the robot into a modular system implies possibilities for parallel construction, where a fleet of robotic entities can simultaneously work on various parts of the architectural artifact.

In order to develop such a novel construction system, the research implies the development of the architectural design methods, mechatronic design of the robotic actuator, and task and motion planning, which entails deploying co-design strategies where all three areas have to progress in parallel, continuously influencing each other.

A. Mechatronic Design

The design process for the robotic actuator is based on two mechanisms: rotating and gripping. It consists of 2 grippers that are connected by a geared slewing bearing (fig. 2).

The torque required for rotation is defined by the length and configuration of a kinematic chain; kinematic chains with more actuators or longer pieces of building material increase the required torque for rotation. In the case of a standard industrial robotic manipulator, the location of each actuator in the kinematic chain is static and the mechanisms for each axis can be designed based on its location.

In the proposed system, the configuration of the kinematic chain is dynamic and the location of the actuator within it

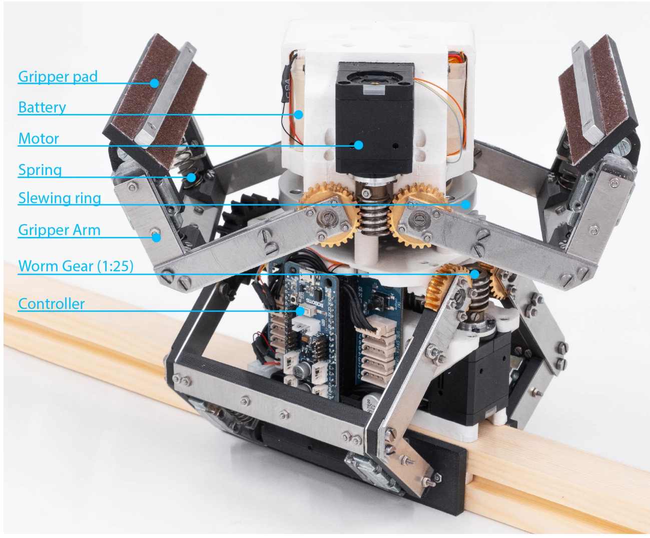

Fig. 2: Physical prototype with accompanying diagram of the single axis double gripper robotic actuator.

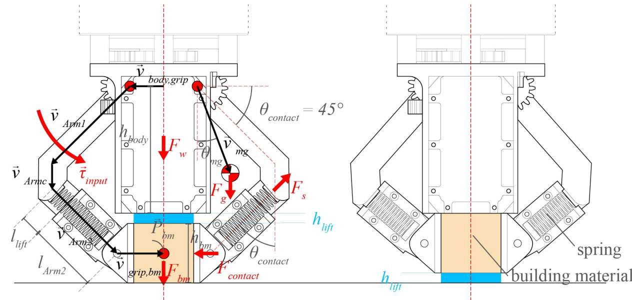

Fig. 3: Free-body-diagram of the gripping mechanism. $F_{\mathrm{w}} = g(2m_{\mathrm{bm}}+2m_{\mathrm{r}})$ is the weight from two robots and struts. The blue area indicates the free-space before and after the lifting motion.

is unknown. For initial experiments, the maximum torque of any actuator in the chain is thus calculated in order to allow it to occupy any location within the kinematic chain. This directly affects both the architectural design, and the task and motion planning process. The maximum static torque τ_{required} occurs when a kinematic chain is fully stretched in the horizontal plane and can be calculated as

$$\tau_{\mathrm{required}} = g l_{\mathrm{bm}} \left(\sum_{i=2}^{n_{\mathrm{r}}} (i-1) m_{\mathrm{r}} + \sum_{i=1}^{n_{\mathrm{bm}}} (i-0.5) m_{\mathrm{bm}} \right), \quad (1)$$

where n_{r} and n_{bm} are the number of robots and struts in the kinematic chain respectively, g is the gravitational acceleration, l_{bm} is the length of the building material, and m_{r} and m_{bm} are the mass of the building material and robot respectively. Although static torque provides an initial estimate for the design of the robotic actuator, further amplification of the torque must be considered for the acceleration of a kinematic chain.

The gripping mechanism is designed to grip and lift the building material. Lifting is required to move the material to a different plane in order to avoid friction with the building plane (fig. 3). This is achieved through the incorporation of a spring in the gripper arm which allows for its change in length depending on the force exerting on the gripper. In order to achieve both gripping and lifting, the problem is broken down to three sub-problems: *i)* the design of the gripper arms as relating to lifting distance, *ii)* the required spring compression, and *iii)* the required gripping torque.

For the target lifting distance, we can design the gripper arm by solving equation (2) with some conditions about the gripper's lifting states (i.e. before or after lifting):

$$\vec{P}_{\mathrm{bm}} = \vec{v}_{\mathrm{body,grip}} + \vec{v}_{\mathrm{Arm1}} + \vec{v}_{\mathrm{Armc}} + \vec{v}_{\mathrm{Arm2}} + \vec{v}_{\mathrm{grip,bm}}. \quad (2)$$

In order to calculate the compressed length $l_{\mathrm{initial,comp}}$ of the spring μ used within the gripper for lifting, we compute

$$\begin{aligned} l_{\mathrm{initial}} &= l_{\mathrm{initial,comp}} + l_{\mathrm{Arm2}} + l_{\mathrm{lift}} \\ l_{\mathrm{initial,comp}} &= \frac{F_{\mathrm{w}}}{4\mu} \cos(\theta_{\mathrm{contact}}). \end{aligned} \quad (3)$$

The maximum torque is applied when the spring is fully compressed and the building material is lifted. The free-body-diagram in fig. 3 shows the forces acting on the gripper. The total torque is computed by summing three torques applied to the gripper: $\vec{\tau}_{\mathrm{g}}$ from the weight of the gripper structure, $\vec{\tau}_{\mathrm{bm}}$ from the weight of the building material, and $\vec{\tau}_{\mathrm{s,max}}$ from the fully compressed spring.

Power, although currently addressed using an on-board power supply, will be analyzed in the future using existing research methods such as wireless transfer or scavenge power from the operation environment [13].

B. Task and Motion Planning

Current research in task and motion planning (TAMP) is focussed on complex agents that are able to fulfill goals on its own, or with relatively little cooperation. Hence, the difficulty in planning for a swarm of simple agents is the explicit incorporation of the cooperation between the single DoF robots to achieve even simple goals.

We build on the TAMP formulation called Logic Geometric Programming (LGP) in [14], where the problem is formulated as a path optimization problem with switching conditions that impose a successions of logical states. These successions of logical states imply an action skeleton, where the actions fulfill the pre- and post-conditions of the switches. This allows for an explicit optimization over the switching states in the optimization problem, which can be exploited when solving the problem.

We solve the resulting mathematical program with the approach presented in [15], and the sampling-based path planning in the LGP framework introduced in [16] to improve robustness of the solver. This allows to satisfy the complex constraints arising from torque, force and friction limits directly in the planning process.

C. Architectural Design

Construction robotic systems currently rely heavily on a top-down building design methodology. Such a methodology involves a designer creating a blueprint, outlining the designed architectural artifact and any necessary construction instructions. This approach gives full agency to the architect, in order to derive a single fixed design.

With enhanced computational practices, bespoke robotic autonomous machines, and high level task and motion planners, bottom up methodologies for architectural design are becoming feasible. Bottom up methodologies are decentralized and generate designs through the emergence of collective material, robotic and other behaviors or constraints of the construction system without global coordination. However with no explicit expression of the final architectural form, complete bottom up methods give less agency to architects and designers.

As both methods are viable, the research on architectural design is interested in developing design methods in which both top down and bottom up methodologies can be implemented. This implies a direct influence and relationship to the task and motion planning for construction. In allowing for both methodologies, the design of architectural artefacts becomes an informed negotiation between designer intent and system affordances and constraints in which processes work in both directions, implying constant feedback between the various developments on the construction system.

IV. Experiments

The supplementary material shows a video of the initial experiments, and the simulated movement of the paths form the TAMP framework.

With the proposed planning method, we are able to explore possible construction sequences, and get some initial ideas about the design space. However, it is currently still too computationally expensive to form a full feedback loop, and inform the designers in real time.

For initial experiments, prototypes of two robotic actuators were assembled in order to test the functionality of the system to work on two-dimensional planes. The experiments show the viability of the mechatronic system, and further demonstrate early stage success in the co-designing from architectural, robotic, and computer science perspectives of the proposed construction.

V. Discussion & Outlook

This paper introduces a modular material-robot kinematic construction system that is derived for the components of the system rather than from the design of the robot. Specifically, small scale robotic actuators leverage timber struts for the construction of structures much larger than the machines themselves. Robotic actuators and building material can form kinematic chains of varying complexity, thus providing a higher degree of task flexibility and efficiency for construction. In order to achieve this vision, the research is beginning to address all related challenges that arise from this novel approach, which intrinsically requires co-design strategies for robot hardware design, building system design, robot control system design, and the computational design software tool.

Further experiments to improve the hardware of the robotic actuator, to increase the complexity in planning and to integrate more aspects of the system into the design methods will be conducted in order to further validate the proposed modular material-robot kinematic construction system as well as the overall co-design strategy.

References

[1] T. Bock and T. Linner, *Site Automation: Automated/Robotic On-Site Factories*. Cambridge: Cambridge University Press, 2016.

[2] ——, *Construction Robots: Elementary Technologies and Single-Task Construction Robots*. Cambridge: Cambridge University Press, 2016.

[3] S. Leder, R. Weber, O. Bucklin, D. Wood, and A. Menges, "Towards Distributed In Situ Robotic Timber Construction," in *Research Culture in Architecture: Cross-Disciplinary Collaboration*. Berlin, Boston: De Gruyter, Dec. 2019.

[4] S. Leder, R. Weber, D. Wood, O. Bucklin, and A. Menges, "Distributed Robotic Timber Construction," in *ACADIA – Ubiquity and Autonomy*, Austin, TX, USA, 2019, p. 10.

[5] K. H. Petersen, N. Napp, R. Stuart-Smith, D. Rus, and M. Kovac, "A review of collective robotic construction," *Science Robotics*, vol. 4, no. 28, p. eaau8479, Mar. 2019.

[6] D. Hjelle and H. Lipson, "A robotically reconfigurable truss," London, UK, 2009, p. 6.

[7] M. Yablonina and A. Menges, "Distributed Fabrication: Cooperative Making with Larger Groups of Smaller Machines," *Architectural Design*, vol. 89, no. 2, pp. 62–69, Mar. 2019.

[8] Q. Lindsey, D. Mellinger, and V. Kumar, "Construction of Cubic Structures with Quadrotor Teams," in *Robotics: Science and Systems VII*. Robotics: Science and Systems Foundation, Jun. 2011.

[9] D. Wood, M. Yablonina, M. Aflalo, J. Chen, B. Tahanzadeh, and A. Menges, "Cyber Physical Macro Material as a UAV [re]Configurable Architectural System," in *Robotic Fabrication in Architecture, Art and Design 2018*, J. Willmann, P. Block, M. Hutter, K. Byrne, and T. Schork, Eds. Cham: Springer International Publishing, 2019, pp. 320–335.

[10] K. Petersen, R. Nagpal, and J. Werfel, "TERMES: An Autonomous Robotic System for Three-Dimensional Collective Construction," in *Robotics: Science and Systems VII*. Robotics: Science and Systems Foundation, Jun. 2011.

[11] A. Sproewitz, A. Billard, P. Dillenbourg, and A. J. Ijspeert, "Roombots-mechanical design of self-reconfiguring modular robots for adaptive furniture," in *2009 IEEE International Conference on Robotics and Automation*. Kobe: IEEE, May 2009, pp. 4259–4264.

[12] B. Jenett, A. Abdel-Rahman, K. Cheung, and N. Gershenfeld, "Material–Robot System for Assembly of Discrete Cellular Structures," *IEEE Robotics and Automation Letters*, vol. 4, no. 4, pp. 4019–4026, Oct. 2019.

[13] M. Sitti, *Mobile microrobotics*. The MIT Press, 2017.

[14] M. Toussaint, K. Allen, K. A. Smith, and J. B. Tenenbaum, "Differentiable physics and stable modes for tool-use and manipulation planning."

[15] M. Toussaint and M. Lopes, "Multi-bound tree search for logic-geometric programming in cooperative manipulation domains," in *2017 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2017, pp. 4044–4051.

[16] V. N. Hartmann, O. S. Oguz, D. Driess, M. Toussaint, and A. Menges, "Robust task and motion planning for long-horizon architectural construction planning," 2020.