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Adaptive robotic manufacturing using higher order knowledge systems

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ABSTRACT

Despite a well-understood potential to increase productivity of the global construction industry and sustained, international research efforts in recent years, wide-scale adoption of robotic technology currently remains elusive in the industry. As part of a larger industrial research effort to increase the efficiency of automation technologies within construction, this paper proposes a novel multi-layered knowledge encapsulation model to enable low-cost development of highly diverse robotic control applications within a parametric manufacturing paradigm. The effectiveness of proposed theoretical framework has been validated by developing multiple industrial applications and resulted in almost 40% reduction in development time.

1. Introduction

Despite representing the 5th largest industry segment, the global construction industry has for a decade seen stagnant growth in productivity, while other sectors – such as the manufacturing industries – have enjoyed nearly a quadrupling within the same period [1]. Even in more recent works [2,3], it is mentioned that the problems related to low productivity is still prevalent in construction industry. The rising productivity in neighboring segments is widely attributed to the pervasive automation and digitization these sectors have been undergoing. Hence large scale adoption of robots in the construction sector is widely regarded as the primary enabler of potential productivity increase [4]. However, despite large research efforts, and the availability of mature automation technologies from tangential fields such as automotive, aeronautic, naval and energy industries, ubiquitous adoption of robotic processes within the industry still remains evasive. As a result, construction is one of the least automated of the leading industrial sectors, next only to agriculture [5]. Inside of a larger industrial research effort to establish a general purpose, cyber-physical technology platform for efficient automation of construction tasks, this paper reports on the developments relating to the establishment of a software framework for adaptive robotic control in construction manufacturing.

2. State of the art

A widely understood differentiating factor between construction and other manufacturing industries relying on large scale production is the circumstance, that while general manufacturing can benefit from deploying a mass manufacturing paradigm - in which multiple instances of identical products is repeatedly produced at high volume - such repetition is not feasible in construction, in which each building project is essentially unique [4]. Since automation technologies in general manufacturing is designed to support a repetitive mode of operation, they lack the flexibility to accommodate the variability experienced in construction. To overcome this shortfall, significant research efforts [6–8] have been directed towards establishing parametric manufacturing workflows, in which a production system relying on one or more standard industrial manipulators with associated machining end-effectors is driven by a parametric manufacturing model, which utilizes the inherent flexibility of a manipulator with *m* degrees of freedom to create shape-variant instances of a customizable part design within pre-defined ranges of variables. The establishment of construction scale parametric manufacturing workflows is complemented by additional research attention directed towards machine process innovation, investigating a plurality of avenues for achieving low cost, large scale production through mechanical end-effector engineering. Leading examples from this work entails robotic processes such as e.g. timber sawing [9,10]; hot-blade and wire-cutting [11,12]; brick assembly [13]; robotic concrete printing [14–16] and metal forming [17]. The combined developments in this strand of research have recently culminated in the realization of several experimental and commercial construction projects, such as Fjordenhus Kirk Kapital HQ, Vejle, Denmark (2018) [18], Opus Dubai, Dubai UAE (2020) [19], The Sequential Roof, Zürich, Switzerland (2016) [20], and DFAB House, Zürich, Switzerland (2019)

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[21], signifying the principal applicability of robotic manufacturing at construction scale. While the establishment of a robotic parametric manufacturing paradigm – complemented by aforementioned advances in process innovation – have successfully demonstrated a pathway for increasing flexibility of digital production to create shape variant parts at near cost-parity to standardized production schemes – two fundamental limitations remain largely unaddressed:

1. while parametric manufacturing workflows can be established for predefined typologies of component production, they are ill-suited to accommodate non-linear changes in fundamental parameters such as product typology, material composition or machining process. Since the variability of construction manufacturing entails exactly this across individual building projects, each non-linear change requires manual amendment of an existing or establishment of a new workflow;
2. establishment of such workflows rely on an emerging cross-disciplinary expertise spanning across previously isolated domains, including robotics, computational design and construction manufacturing. By contrast, the global construction workforce is overwhelmingly trained in craft based, manual processes with little to no exposure to robotic manufacturing.

Taken together, these limitations incur significant overhead in the establishment of project specific workflows, while inducing substantial inflexibility in applying them in a general regime across projects.

3. Research challenge

For clarity, aforementioned concerns may be expressed as:

$$\mathrm{C} = \mathrm{C_v} + \mathrm{C_f}/n \quad (1)$$

where C denotes the production cost of a shape-variant part or building component, $\mathrm{C_v}$ is the variable cost associated with producing each item unaffected by the number of produced items - typically entailing labor, material and machining time and $\mathrm{C_f}$ signifies the fixed, one-time costs of implementing the digital production workflow required to manufacture the shape variant family of parts, and n denotes the number of construction projects on which the particular workflow can be applied. Since global construction is generally characterized by a high number of sub-specialized trades, which operates interchangeably to construct topologically variant tasks, it stands to reason that the probability of $n = 1$ is high. In this case, only an extra-ordinary construction budget would be capable of sustaining the upfront cost of bespoke workflow establishment, limiting the application of such robotic schemes to high-profile building projects. The presented work assumes the hypothesis that:

1. full automation of the workflow creation process is not feasible, because the number of implied variables for constitutional parameters is too high;
2. this leads to high development costs which - in combination with the small niche markets resulting from the high level of trade-specialization – makes the development of project specific workflows economically non-viable in mainstream construction, and thus leaving the majority of construction disciplines technologically under served.

To overcome this challenge, we propose increasing the efficiency of custom workflow implementation through deploying a model of second order knowledge encapsulation, which enables semi-automatic application development and framework architecture generalization. The purpose of this effort would be to lower the development costs of implementing bespoke, project specific applications below the cost of manual production, hereby facilitating wide spread adoption of robotic manufacturing in construction. The presented work addresses the software related implication of this solution.

In other words, we are presenting a software framework that will enable someone to rapidly design, prototype and develop a robotic application. As a result, one can achieve cost parity even though the aforementioned application is not mass manufactured. This is specifically of interest in construction industry, as a building contractor usually orders only 1–2 robotic units supporting a given process. For any provider of such cells to the industry, it becomes important that a framework exists to develop applications quickly.

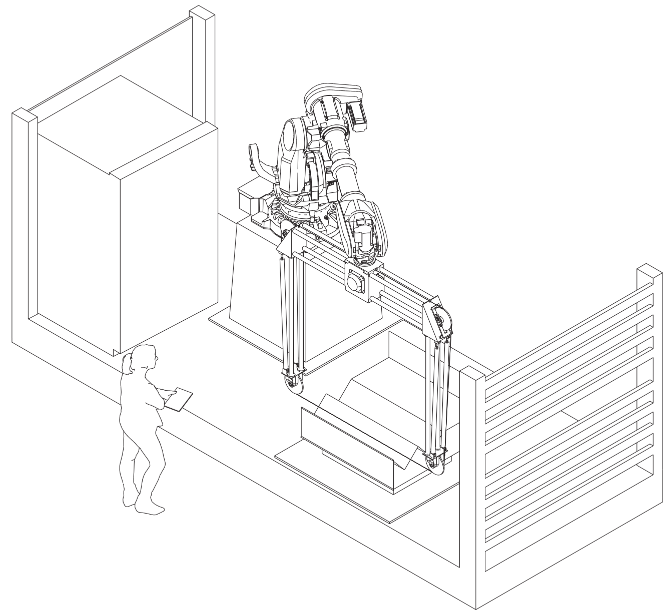


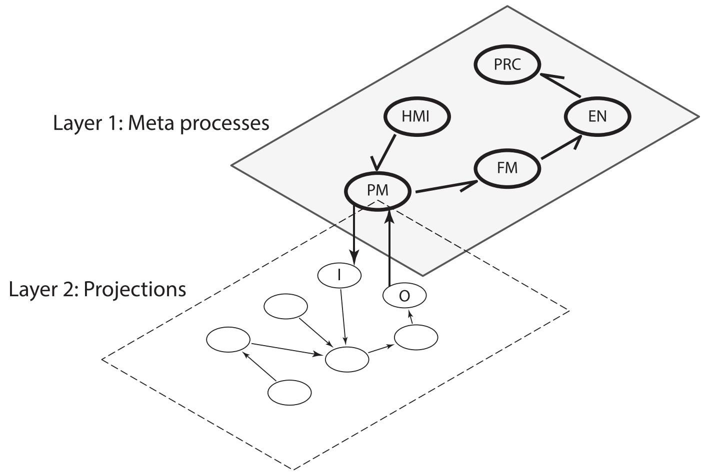
Fig. 1. An application is understood in the context of a software system operating on a cyber-physical production unit entailing a) one or more m-axis manipulators enclosed on b) a modular frame, equipped with c) custom processing end-effectors and d) operated from a tablet or mobile device by a non-specialist user.

4. Knowledge encapsulation strategy

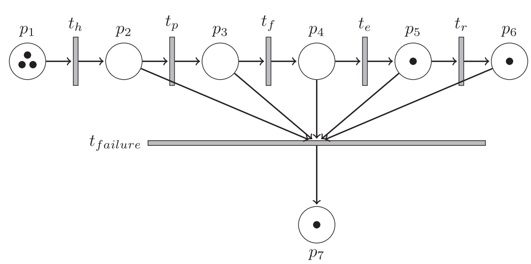
Our knowledge encapsulation is initialized with denoting an application to entail the following components:

1. a parametric template or product model (PM), which holds a customizable design of a component, part sub-assembly or entire building design;
2. a fabrication model (FM) which, as a function of PM generates the corresponding tool path targets;
3. an execution node (EN) entailing a digital representation of the robotic system with incorporated planning module to ensure motion safety;
4. a physical robotic cell (PRC) equipped with a set of predefined end-effectors for executing one or a combination of several processes. The robotic system is containerized or mounted on an autonomously moving base for modular deployment;
5. a human machine interface (HMI), which exposes key parameters of PM, FM and EN to the user through a Graphical User Interface (GUI).

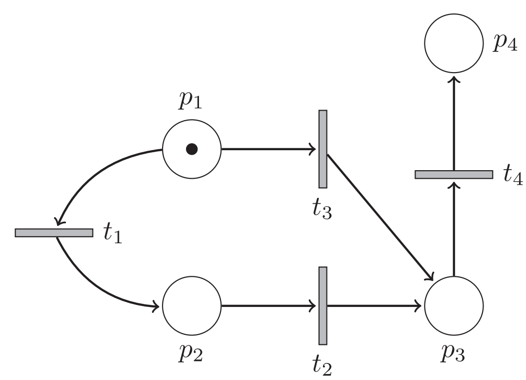
The entirety of the application is process or product specific, allowing for a simple expression of controls. Hereby the application enables a non-expert user, i.e. a construction worker trained in craft with no robotics experience, to.



(a) Bi-layered structure



(b) Petri net representation of the bi-layered structure. t_h, t_p, t_f, t_e and t_r are transitions (projections) associated with HMI, PM, FM, EN and PRC respectively. $t_{failure}$ is the error handling routine.



(c) t_h, t_p, t_f, t_e and t_r are further represented using individual Petri nets and resides in layer 2 of our bi-layered structure. For example, for a given application, the role of a Computational Design Specialist (CDS) is to model t_p and t_f whereas a robotic engineer will be able to build up t_e. A sample Petri net which can be used to model one of the projections is shown here. t_1, t_2, t_3 and t_4 are individual transitions which make up a function composition model.

Fig. 2. Knowledge encapsulation strategy.

1. customize a part design on the fly or retrieve an externally customized part design;
2. safely execute production of the customized instance of that part.

The concept of such a containerized set up with a tablet interface can be seen in Fig. 1 where a user can be seen interacting with PRC using a HMI. The containerized set up including the tablet is referred to as Factory on the Fly™.

4.1. Application model

Pursuant to the proposed encapsulation strategy, the robotic application can be visualized as a bi-layered structure (ref. Fig. 2a) and the corresponding Petri net models are shown in Fig. 2b and c. Petri nets have previously been shown useful for knowledge abstraction [22,23]. The first layer entails a meta-representation consisting of 5 components and the interactions between them.

The second layer corresponds to a topologically variable sub-system, which models the product or process specific aspects of the application (ref. Fig. 2a). Since these sub-systems may model any variability within the constitutional parameter space including product type, material combination, machining process, location or robot system configuration, the technical challenge becomes projecting a non-finite variety of sub-system topology to a finite meta representation (layer 1) under the constraint that model should remain valid. To solve this, we implement the following method as shown in Fig. 3.

4.2. Layer 1

Each component in the knowledge encapsulation strategy viz. PM, FM, EN, PRC and HMI finds a representation in this layer to completely define various robotic applications. Associated to the components, there are transitions or projections. Depending on the current state of the application, a particular route gets active. A route is an event handling

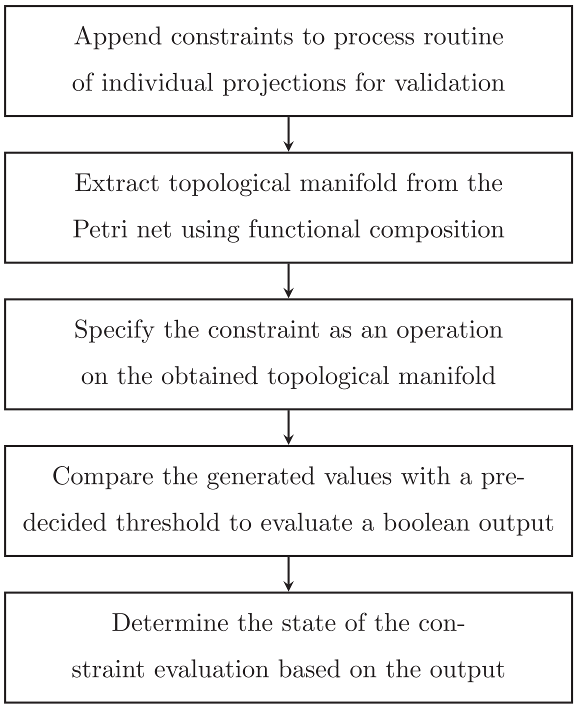


Fig. 3. Constraint checking workflow.

Table 1
Associated projections.

Projection (transition) name	Associated meta node	Input	Output
PPM (t_p)	PM	Numeric/ Boolean	Fabrication task
PFM (t_f)	FM	Fabrication Task	Robot task
PEN (t_e)	EN	Robot Task	Configuration task
PPRC (t_r)	PRC	Configuration task	Physical motion
PHMI (t_h)	HMI	Human gestures	System action

pipeline (ref. Fig. 2b) comprising of a subset of components. At any given time, there will always be only one active route. For example, when a production user is initiating a request to fabricate a piece to the robot, the active route is shown in Fig. 2a and b.

Due to the simple nature of interaction possible, it is suitable for a low skilled production user to work with this layer. He or she can tweak input parameters to achieve a specific valid product configuration and further instruct the robotic system to manufacture the product confirming to the specified parameter values.

4.3. Layer 2

As mentioned, there is a transition associated with each one of the components in layer 1. They encapsulate the complex nature of computations required to achieve the functionality of a meta node. For example, PFM (ref. Table 1) is primarily tasked with the computation of tool path to service the fabrication request from the user.

Expert user knowledge is required to model projections. A CDS will be able to define the transitions for PM and FM whereas a CAM operator or a robotic engineer is required for EN.

Every transition has a predefined input/output type. Since it's most of the times difficult to describe the relationship between the output and input with a single function, it is expressed using function composition which is an operation that takes two functions f and g and produces a function h such that h(x) = g(f(x)) (see, Figs. 4a and 2c).

The details of projections is provided in Table 1. A fabrication task contains a NURBS model, tool data and other process parameters whereas a robot task comprises of a tool path, process speed along with other specifications including Robot Model (RM), Environment Model (EM), Tool Model (TM), Work Piece (WP) and Operation Sequence (OS). The configuration task includes the position, velocities and accelerations of all the robot joints as a function of time.

Projections are further represented via Petri net. They are also composed of places and transitions just like any other Petri net. They involve a special set of transitions called constraints. An evaluation of a projection is said to be valid, if and only if all the constraints attached to the projection are satisfied.

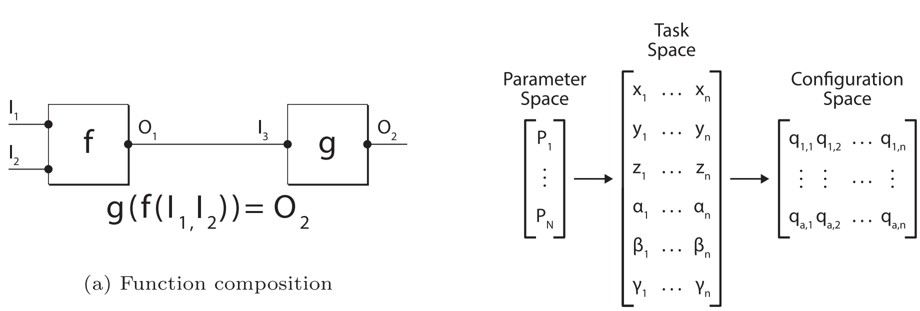
5. Constraints

In Fig. 3, a constraint is expressed as an operation on a topological manifold otherwise referred to as a manifold. Let an arbitrary set M represent the point cloud which resides either in task or configuration space (ref. Fig. 4b) and O be the chosen topology on M. For robotic manufacturing, it's a necessary condition that the topological space (M, O) forms a manifold. A topological space is called a d-dimensional manifold if $\forall \mathbf{p} \in$ M there exists an open set U containing $\mathbf{p}$ where the following continuous maps exist:

1. $x : \mathrm{U} \mapsto \mathrm{R}$: $\mathrm{R} \subseteq \mathbb{R}^d$
2. x^{-1}

This is called the charting condition.

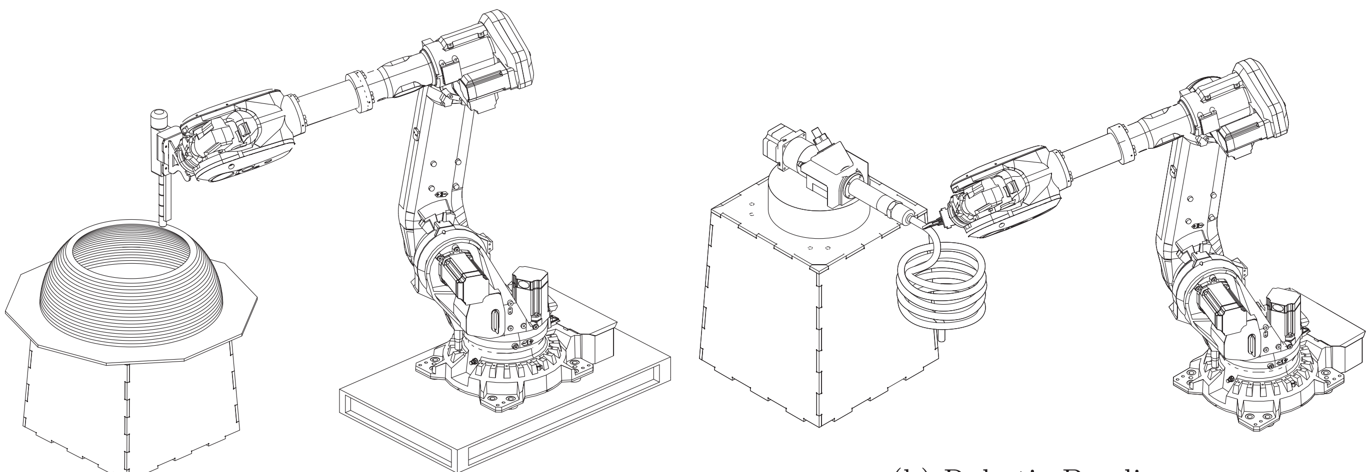
For example, consider the surface of a torus as the NURBS model included in the fabrication task, let the points in this model be M where $\mathrm{M} \subseteq \mathbb{R}^3$. We can choose standard topology as O. For any $\mathbf{p}$ in this model, we can find a U which is nothing but the open neighbourhood around



(a) Function composition

(b) Topological spaces

Fig. 4. Graph operations.



(a) Additive Manufacturing (b) Robotic Bending

Fig. 5. Robotic processes.

the point. Since U ⊆ M, it can be represented as a NURBS surface, following which it can easily be verified that there exists a x which maps every point on U to R embedded in $\mathbb{R}^2$ in a continuous invertible manner where R forms the parameter space for U. Hence we can say that (M, O) is a manifold as it satisfies the charting condition.

There are many artifacts whose presence will convert the model into a non-manifold geometry, viz. a curve that bifurcates at a point, a set of surfaces forming an open volume or an edge shared by more than 2 surfaces, because around such artifacts the continuity of x gets broken.

A robotic arm ζ having an m dimensional configuration space C is used to process the tool path specified in the robot task. Since ζ is made of several objects connected by joints, it is subjected to kinematic constraints. These are constraints which restricts an object or a collection of objects from rotating or translating freely in the workspace. There are two types of kinematic constraints viz. holonomic and non-holonomic.

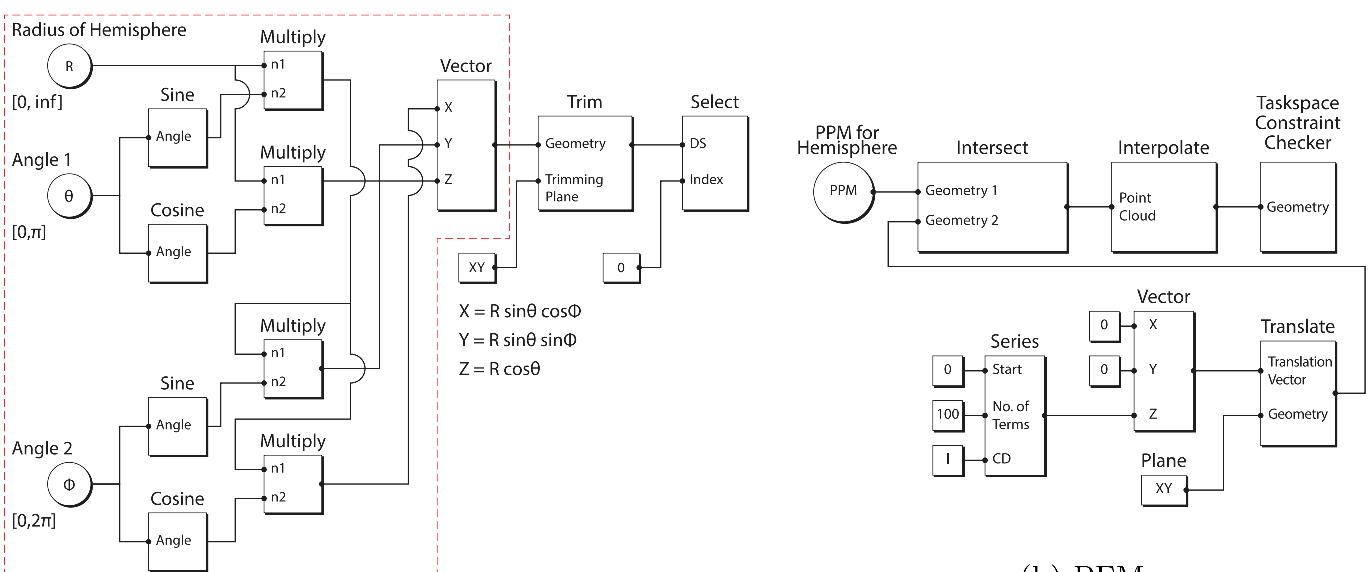
An atlas has been defined on C and any configuration $\mathbf{q}$ of ζ is represented by a list of m coordinates $(q_1, q_2, \ldots, q_{m-1}, q_m)$ in some chart of the atlas. A scalar constraint of the form:

$$F(\mathbf{q}, t) = 0 \tag{2}$$

where F is a smooth function with non-zero derivative, is called a holonomic equality constraint. More generally, there may be k such constraints where k ≤ m. Typically, such equality constraints allow us to map a manifold from task space to C. Undesirable collisions as well as out of reach scenarios could be modelled as holonomic inequality constraints of the form:

$$F(\mathbf{q}, t) \leq 0 \tag{3}$$

and can be expressed as an operation on the manifold in task space. Constraints can be modelled either in task space or C. As manifolds are inherently differentiable, constraints involving velocities or accelerations can be plugged in.



(a) PPM

Fig. 6. Additive manufacturing.

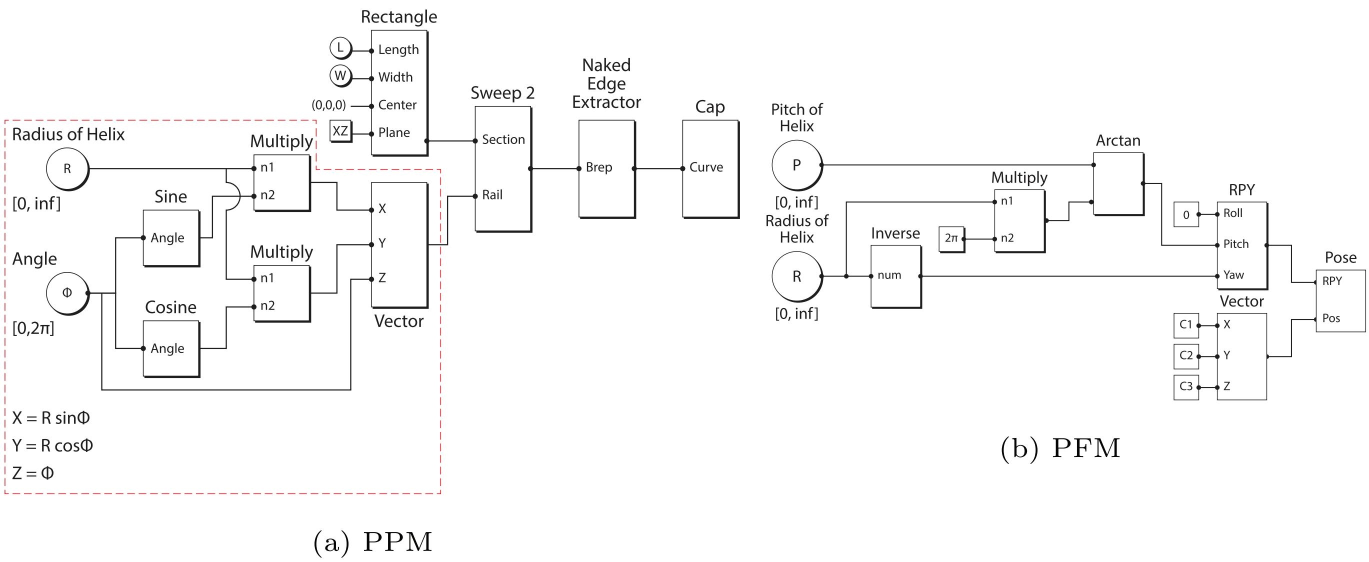


Fig. 7. Robotic bending.

Fig. 8. (top left) Robot sawing tablet interface; (top right) Robot sawing unit and (bottom) Wire-cutting unit.

6. Exemplification

The generality of the proposed framework has been validated using two robotic applications viz. additive manufacturing and bending. For additive manufacturing, we will use the target product as a hemispherical bowl whereas for bending, the product is in the form of a coil or spring with a rectangular cross section. A serial chain robotic arm fitted with the corresponding tool will be used for physical realization of the process (ref. Fig. 5a and b).

In both the cases, the schematic representations of corresponding PPM and PFM are shown in Fig. 6a, b, Fig. 7a and b respectively. PEN, PPRC and PHMI are not shown for brevity. The various functions shown in the representation denotes the parametric operations performed in sequential form to arrive at the target geometry or tool path. Constraint nodes are not shown for clarity but are explained briefly below.

For a better understanding of constraints explained before, we will try to apply a well known reachability analysis to check the validity of the motion. A given $\mathbf{p} = (X, Y, Z)$, in the tool path contained in the robot task needs to satisfy the holonomic inequality constraint introduced before. If R (ref. Fig. 6a), increases beyond a threshold, $\mathbf{p}$ will breach (3). Similarly, any non-allowed collision between the given RM, EM, TM and WP can also be expressed in the form of (3).

7. Industrial applications

The presented knowledge encapsulation model has been utilized in the development of a novel framework for robotic control and product customization, Sculptor™, for high-efficiency development of new applications within the Factory on the Fly concept for modular, containerized robotic pop-up manufacturing stations, developed by Danish technology innovator Odico Construction Robotics. The framework has enabled CDS employed in the company with no prior training in software development to develop a plurality of functionally non-related applications such as.

1. sawing of concrete tiles (ref. Fig. 8) - objective of this portable robotic cell, is to be able to support cutting of tiles to various shapes so that they can be laid on pavements;
2. wire-cutting of custom EPS formwork (ref. Fig. 8) - the goal is to manufacture formwork for concrete casting of a given product geometry. Our modular robotic cell can be shipped to the customer site and production user can operate the same using our easy to use tablet interface to customize the formwork design and generate the robot instructions for wire-cutting EPS blocks to create the bespoke formwork. In this particular instance, product geometry was a staircase;
3. CNC milling of custom sewage and water pipe junctions - a contractor had approached Odico to build a robotic application which is easy to use and assists them in creating formwork for custom pipe junctions. As opposed to the staircase application, we had to use milling since the target geometry involved doubly curved surfaces.

For application 1, a mobile product has been launched as of August 2020. Early commercial tests have demonstrated that non-specialized pavers with no prior education in robotics can operate the unit and create advanced custom tile designs within a 10 min training window.

8. Discussion

Based on current implementation work, we project that any application in the field of construction can be modelled by the same set of five nodes in the meta layer. The variation which exists between applications can be accomplished by changing the contents of the corresponding projections (see, Fig. 2a) by respecting the desired input-output relationship between them. For example, as long as the NURBS model contained in the fabrication task is a d-dimensional manifold where $d \in (1, 2)$, PFM can accept it for further processing. Further constraints can be wired into individual projections to model various system limitations. In most cases, these constraints could be generalized to a degree that they could be used across applications. For example, the reachability or collision constraint in PEN can be applied to any robotic application.

Furthermore, in this work, we validated our framework by applying our model to examples belonging to entirely different realms as well as with some industrial applications. A closer inspection of Fig. 6a and Fig. 7a (refer, the components inside the red coloured region), reveals that many components could be rearranged and reused to build PPM and PFM for two applications. As a result, our original goal of keeping C_f low by distributing it over a plethora of applications has been achieved.

9. Conclusion

A novel model for second order knowledge encapsulation in the development of adaptive robotic applications for construction tasks has been presented. The model enables a single, 5-node meta layer as a uniform control scheme for a non-finite variability of applications, hereby greatly increasing the efficiency of development of bespoke applications for construction processes. It entails two layers of encapsulation in which.

1. complex machining processes for adaptive manufacturing of on-the-fly customized, shape-variant part designs can be operated by non-specialist construction personnel in the form of an application;
2. people from 5 specialist domains, viz. computational design, UI/UX development, manufacturing, robotic and process engineering are able to contribute within their domain in isolation through provision of constitutive sub-systems in a larger network.

Declaration of Competing Interest

There are no conflict of interests in our knowledge.

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References

[1] H. Park, S. Thomas, R. Tucker, Benchmarking of construction productivity, J. Constr. Eng. Manag. 131 (2005) 772–778, https://doi.org/10.1061/(ASCE)0733-9364(2005)131:7(772).
[2] J. Berlak, S. Hafner, V.G. Kuppelwieser, Digitalization's impacts on productivity: a model based approach and evaluation in germany's building construction industry, Prod. Plan. Control 32 (2021) 335–345, https://doi.org/10.1080/09537287.2020.1740815.
[3] M. Bragliaa, P. Dallasegab, L. Marrazzinia, Overall construction productivity: a new lean metric to identify construction losses and analyse their causes in engineer-to-order construction supply chains, Prod. Plan. Control 1 (2020) 1–18, https://doi.org/10.1080/09537287.2020.1837931.
[4] J. Delgado, L. Oyedele, A. Ajayi, L. Akanbi, O. Akinade, M. Bilal, H. Owolabi, Robotics and automated systems in construction: understanding industry-specific challenges for adoption, J. Build. Eng. 26 (2019) 1–11, https://doi.org/10.1016/j.jobe.2019.100868.
[5] M. Rohana, An Investigation into the Barriers to the Implementation of Automation and Robotics Technologies in the Construction Industry. https://eprints.qut.edu.au/26377/1/Rohana_Mahbub_Thesis.pdf, 2008 (visited: 2021-03-29).
[6] J. Willmann, M. Knauss, T. Bonwetsch, A.A. Apolinarska, F. Gramazio, M. Kohler, Robotic timber construction — Expanding additive fabrication to new dimensions, Autom. Constr. 61 (2016) 16–23, https://doi.org/10.1016/j.autcon.2015.09.011.
[7] F. Gramazio, M. Kohler, Made by Robots: Challenging Architecture at a Larger Scale 1, 2014, pp. 66–68.
[8] A. Menges, Morphospaces of robotic fabrication, in: Robotic Fabrication in Architecture, Art, and Design, 2012, pp. 28–47, https://doi.org/10.1007/978-3-7091-1465-0_3.
[9] P. Eversmann, F. Gramazio, M. Kohler, Robotic prefabrication of timber structures: towards automated large-scale spatial assembly, Construct. Robotics 1 (2017) 49–60, https://doi.org/10.1007/s41693-017-0006-2.
[10] O. Krieg, T. Schwinn, A. Menges, J.M. Li, J. Knippers, A. Schmitt, V. Schwieger, Biomimetic lightweight timber plate shells: computational integration of robotic fabrication, architectural geometry and structural design, Adv. Architect. Geometry (2014) 109–125, https://doi.org/10.1007/978-3-319-11418-7_8.
[11] J. Feringa, A. Søndergaard, Fabricating Architectural Volume: Stereotomic Investigations in Robotic Craft, Fabricate: Negotiating Design and Making 2, 2014, pp. 44–51.
[12] A. Søndergaard, et al., Robotic hot-blade cutting, in: Robotic Fabrication in Architecture, Art and Design, 2016, pp. 150–164, https://doi.org/10.1007/978-3-319-26378-6_11.
[13] T. Bonwetsch, Robotically Assembled Brickwork: Manipulating Assembly Processes of Discrete Elements, Doctoral dissertation, ETH Zurich, 2015, https://doi.org/10.3929/ethz-a-010602028.
[14] S. Paul, G. van Zijl, M. Tan, I. Gibson, A review of 3d concrete printing systems and materials properties: current status and future research prospects, Rapid Prototyping 24 (2018) 784–798, https://doi.org/10.1108/RPJ-09-2016-0154.
[15] S. Ghaffar, P. Mullett, Commentary: 3d printing set to transform the construction industry, Proc. Inst. Civil Eng. Struct. Build. 171 (2018) 737–738, https://doi.org/10.1680/jstbu.18.00136.
[16] S. Ghaffar, J. Corker, M. Fana, Additive manufacturing technology and its implementation in construction as an eco-innovative solution, Autom. Constr. 93 (2018) 1–11, https://doi.org/10.1016/j.autcon.2018.05.005.
[17] M. Tamke, N. Paul, Z. Mateusz, Machine learning for architectural design: practices and infrastructure, Int. J. Archit. Comput. 16 (2018) 123–143, https://doi.org/10.1177/1478077118778580.
[18] A. Søndergaard, J. Feringa, Scaling architectural robotics: construction of the kirk kapital headquarters, Proc. Fabricate 1 (2017) 264–271, https://doi.org/10.2307/j.ctt1n7qkg7.40.
[19] S. Bhooshan, Parametric design thinking: a case-study of practice-embedded architectural research, Des. Stud. 52 (2017) 115–143, https://doi.org/10.1016/j.destud.2017.05.003.
[20] A. Apolinarska, R. Bärtschi, R. Furrer, F. Gramazio, M. Kohler, Mastering the sequential roof, Adv. Architect. Geometry (2016) 240–258, https://doi.org/10.3218/3778-4_17.
[21] K. Dörfler, et al., Mobile robotic fabrication beyond factory conditions: case study mesh mould wall of the dfab house, Construct. Robotics 3 (2019) 53–67, https://doi.org/10.1007/s41693-019-00020-w.
[22] H. Hu, R. Su, M. Zhou, Y. Liu, Polynomially complex synthesis of distributed supervisors for large-scale amss using petri nets, IEEE Trans. Control Syst. Technol. 24 (2016) 1610–1622, https://doi.org/10.1109/TCST.2015.2504046.
[23] H. Hu, Y. Liu, L. Yuan, Supervisor simplification in FMSs: comparative studies and new results using petri nets, IEEE Trans. Control Syst. Technol. 24 (2016) 81–95, https://doi.org/10.1109/TCST.2015.2420619.