

Cocoon | Collaborative Construction

***A multi-robot system for complex tasks on construction sites:
Reference case of a brick wall construction***

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1 Introduction

Throughout the last decades, the yearning for originality has only been increasing. Many artists believed that the way to have a breakthrough and achieve originality in art was only possible through a new way of making art. A new architecture can be made possible by a new way of building, a new way of making architecture. The introduction of robotics into the domain of construction holds the promise of this possibility.

The benefits of the introduction of robotic systems into the architectural domain is nevertheless not limited to this promise. Robotic systems on construction sites open up new possibilities for both artistic and technical advancements. This revolution would not only increase efficiency in a sector that is in dire need of it, but also improve working conditions for workers, and even allow for construction projects in extreme environments that would previously be impossible (Melenbrink et al., 2020).

Still, the implementation of on-site robotic automation in the construction industry so far remains very limited. Nevertheless, there is yet another reason for construction sector being a perfect fit for robotic automation systems, which is the 4D principle. This principle suggests that robotic systems are especially fit for implementation for jobs or environments that are dirty, dull, dangerous or difficult. Many of the tasks on a construction site correspond to at least one of these metrics, which is why economists and investors soon expect a robotic revolution in the Architecture, Engineering and Construction (AEC) industry (Kim et al., 2019).

While these immediate practical advantages can be observed already in the industry, the implementation of robotic systems in construction holds promise on a much larger scale. With the recent advancements in technology, automation is getting more and more widespread in all of the industries. The most efficient way of producing anything is standardization and mass production. Still, for certain practices that are ancient and painfully human, such as cooking and architecture, complete standardization and mass production is not an option that is acceptable.

These practices are very tightly woven together with culture, tradition, and community so that they have a bi-directional affect on each other. This reality, together with the idea that the changes in the way of making construction will have a direct affect on the results of the process, which is the architecture that is made, makes it abundantly clear that how we handle the introduction of robots into the architectural domain will determine how our architecture will be in the upcoming decades.

2 Literature Review

2.1 State of the Art

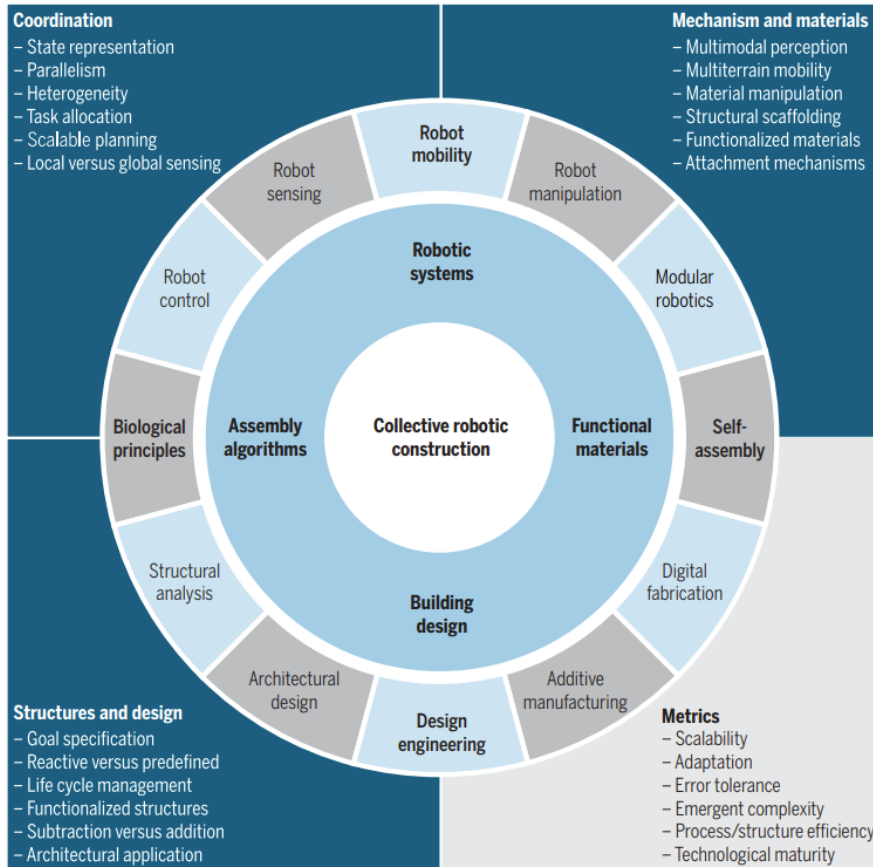


Figure 1: Diagram showing how collective robotic construction depends on and interacts with many other fields. (Petersen et al., 2019)

The implementation of robotic systems in construction sector has already proven itself fruitful in several case studies. Three of these case studies are handled here as good examples of robotic systems on construction sites, all exhibiting different levels of autonomy.

The first example of these cases is one that is largely embraced by the industry, the SAM100 robotic bricklaying aid, which assists workers by helping to carry the load of assembly blocks. While this robotic implementation is on the lower end in terms of level of autonomy, its practical safety mechanisms make for a good example solution for situations where workers have to carry heavy loads. (Madsen, 2019)

Another example that makes the construction workers life easier is HILTI Jaibot (Xu et al., 2022). This drilling robot takes location information from IFC models which include specially designed IFC objects, and executes the drilling operation according to the retrieved location information using its sensors. This implementation case is not only admirable for pro-

viding an automated solution to a very common construction task, but also for relieving the construction workers from this highly strenuous activity.

To go one step further, the example of Mueller and King (2008) demonstrates the construction possibilities with autonomous robots in environments unsuitable for human workers. In exoplanetary construction, lunar in this case, the robotic systems are not an option but usually a necessity. Still, in construction and site preparation tasks as demonstrated in Mueller and King (2008), there are multiple factors that determine the suitability of a multi robot systems that has to be considered on top of traditional metrics, such as the light-weightness or multi-functionality of robots.

2.2 Research Gap

Introduction of robotic systems into construction sites has been taking up speed and receiving more and more attention throughout the last decade. Still, there are many gaps to be filled for a complete autonomous workflow to be possible on the construction site. One of the major gaps, as stated by Melenbrink et al. (2020) is the lack of solutions to coordinate multiple robots with different capabilities that operate on the vast amounts of different construction tasks. Filling this gap is crucial for a multi-robot system to be functional on any construction site. The shift in the understanding of construction site planning and scheduling from temporal planning to spatio-temporal planning, such as LEAN scheduling, provide a good starting ground for robotic systems scheduling solutions on construction sites.

Another point for major improvement lies in the myriad amounts of data that is being produced for any and every construction project. Data coming from IFC/ BIM models are not utilized anywhere close to their full potential. Even though there are some use cases with limited implementation, such as Hilti Jaibot which utilizes IFC data for locations Xu et al. (2022), there is still a major potential for IFC data utilization for fabrication data and robot motion generation.

One other gap that needs to be taken into consideration before a fully automated MRS (Multi-Robot System) on the construction site is possible, is lack of reference processes for certain common construction tasks. Tasks such as drilling, brick laying, painting, tiling and many more, are fundamental to many construction projects all over the world. Producing reference processes for these tasks would open up vast possibilities for immediate implementation of MRS on construction sites. Since subcontracting is already a common practice within the industry, pinpointed solutions automating or assisting workers for very specific processes, such as Hilti Jaibot and SAM100 respectively, are embraced in the industry and adopted relatively faster. These task specific solutions would also be a crucial chain for a complete fully autonomous MRS on construction sites.

3 Prototype

3.1 Complete Workflow of IFC to Fabrication

This prototype aims to demonstrate the possibilities of information retrieval from a standard IFC model, and the extents to which this information can be utilized for planning, optimization and fabrication data generation.

The prototype requires only a standard IFC Model as input. An IFC model prepared for a hypothetical single storey residential building in the scope of Prototyping Project Course WS 2023-24 is used in this prototype as an example. Fabrication data generation including generation of the robot motions, does not require any additional input.

The prototype can be divided into two individually functional parts: IFC Information Retrieval with Python, and Fabrication Data Generation with Cocoon Discrete Assembly Plug-in for Rhino Grasshopper.

3.2 IFC Information Retrieval with Python

The information stored within IFC model is retrieved in this step using Python and IFC OpenShell API. This information is then translated into fabrication data and robot motions inside the Rhino Grasshopper environment.

```

1
2 # Import necessary libraries and functions.
3
4 import ifcopenshell
5 import ifcopenshell.api
6 from ifcopenshell.api import run
7 import ifcopenshell.util.sequence
8 import ifcopenshell.util.placement
9 from collections import Counter
10
11 ### DEFINITIONS ###
12
13 # Retrieve all IFC Tasks and their hierarchical information.
14
15 def print_all_tasks(ifc_model):
16     printed_tasks = set()
17     leaf_tasks = {}
18
19     def print_task_with_gap(task, level):
20         print("___" * level + "Task_ID:", task.id())
21         print("___" * level + "Task_Name:", task.Name if hasattr(task
22             , "Name") else "N/A")
23         print("___" * level + "-" * 40)
24         printed_tasks.add(task.id())
25
26         if level in leaf_tasks:
27             leaf_tasks[level].append(task)
28         else:
29             leaf_tasks[level] = [task]
30
31     def print_nested_tasks(tasks, current_level=0):

```

```

32     for task in tasks:
33         if task.id() not in printed_tasks:
34             print_task_with_gap(task, current_level)
35             nested_tasks = ifcopenshell.util.sequence.
                 get_nested_tasks(task)
36             if nested_tasks:
37                 print_nested_tasks(nested_tasks, current_level +
                                     1)
38
39     print_nested_tasks(tasks)
40     return leaf_tasks
41
42 # Find the highest level in hirearchy, since the tasks on this level
43 # will be the first tasks to be completed in the schedule.
44
45 def print_task_levels(leaf_tasks):
46     for task in leaf_tasks[max_level]:
47         print(f"Task_ID:_{task.id()},_Task_Name:_{task.Name_if_
                 hasattr(task,'_Name')_else_'N/A'},_Level:_{max_level}")
48
49 # Find all relevant tasks for the desired IFC product, using keywords
50 # such as "wall, slab, beam" etc.
51
52 def filter_tasks_by_keyword(tasks, keyword):
53     filtered_tasks = []
54     for task_list in tasks.values():
55         for task in task_list:
56             if keyword.lower() in task.Name.lower():
57                 filtered_tasks.append(task)
58     print('_', f'{keyword}_tasks')
59     for task in filtered_tasks:
60         print(f"Task_ID:_{task.id()},_Task_Name:_{task.Name_if_
                 hasattr(task,'_Name')_else_'N/A'},_Level:_{max_level}")
61     return filtered_tasks
62
63 # Get tasks predecessor information.
64
65 def get_predecessor(task):
66     # Use the BlenderBIM API utility functions
67     predec = ifcopenshell.util.sequence.get_sequence_assignment(task,
68         sequence='predecessor')
69     return predec
70
71 # Find tasks without predecessors, since these tasks have to be
72 # carried out first. This definition helps avoid scheduling
73 # problems, such as scheduling a wall finishing job before the wall
74 # assembly job.
75
76 def find_initial_tasks(tasks):
77     tasks_wo_predec = []
78     for task in tasks:
79         predec = get_predecessor(task)
80         if not predec:
81             tasks_wo_predec.append(task)
82     return tasks_wo_predec
83
84 # Find tasks' products, and write them into a new IFC file
85
86 def find_task_products(tasks):
87     outputs = []
88     for task in tasks:
89         products = ifcopenshell.util.sequence.get_direct_task_outputs
90             (task)
91         for product in products:
92             walls_model.add(product)
93             outputs.append(product)
94     return outputs
95
96 # Find center points of products. This location will be the starting
97 # point for each robot for their respective tasks.

```



```

90
91 def find_center_point(product):
92     matrix = ifcopenshell.util.placement.get_local_placement(product.
93         ObjectPlacement)
94     # get location
95     location = matrix[:3, 3]
96     # Calculate center point
97     center_point = tuple(location)
98     return center_point
99
100 # Create a dictionary with tasks and center points of their
101     respective products.
102
103 def match_tasks_w_points(tasks):
104     center_points = {}
105     products = find_task_products(tasks)
106     for product in products:
107         center_point = find_center_point(product)
108         center_points[product] = center_point
109     return center_points
110
111 ### MAIN FUNCTION ###
112
113 # Define a main function to create the robot world and a dictionary
114     which stores the locations of tasks.
115
116 if __name__=="__main__":
117     directory = "/home/doga/src/mrta/"
118     ifc_file_path = os.path.join(directory, "basemodel.ifc")
119
120     # Open the IFC model, and retrieve necessary information using
121         respective definitions.
122
123     model = ifcopenshell.open("basemodel.ifc")
124     tasks = model.by_type("IfcTask")
125     leaf_tasks = print_all_tasks(model)
126     max_level = max(leaf_tasks.keys())
127     wall_tasks = filter_tasks_by_keyword(leaf_tasks, "wall")
128     initial_wall_tasks = find_initial_tasks(wall_tasks)
129
130     ### create robot world ###
131
132     # Create a new IFC model containing only the relevant IFC
133         products and their 3D geometric representation.
134
135     walls_model = ifcopenshell.file(schema=model.schema)
136     walls_project = run("root.create_entity", walls_model, ifc_class=
137         "IfcProject", name="Walls")
138
139     # TIP: 3D geometries will not be represented in the file if you
140         don't assign units.
141
142     length_unit = "MILLIMETER"
143     run("unit.assign_unit", walls_model, length_unit)
144
145     context = run("context.add_context", walls_model, context_type="
146         Model")
147     body = run("context.add_context", walls_model, context_type="
148         Model",
149         context_identifier="Body", target_view="MODEL_VIEW", parent=
150         context)
151
152     # Add relevant products into the model using find_task_products
153         definition.
154
155     walls = find_task_products(initial_wall_tasks)
156
157     # Write the new IFC model.
158
159     walls_model.write('walls_model.ifc')

```

```

149
150     ### create task-location dictionary ###
151
152     match_tasks_w_points(initial_wall_tasks)
  
```

3.3 Fabrication Data Generation with Cocoon Discrete Assembly Plug-in for Rhino Grasshopper

After the information retrieval phase is complete, the newly created IFC model is fed into the Rhino environment for this second phase. This is the intended use for a complete workflow starting with a raw IFC model, yet it is also possible to feed a manually manipulated .obj file in this step.

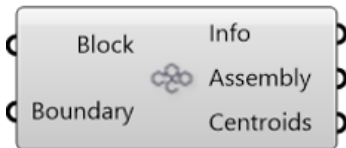


Figure 2: Example of a component from Cocoon: Discrete Assemblies plug-in.

Design of the plug-in is rather simple. All components have two inputs, labeled as Block and Boundary. All components have an Info output, and depending on the component several other outputs, which can be Block, Assembly, and Centroids.

- Block(Input): Mesh representing a unit block for the discrete assembly.
- Boundary(Input): Mesh representing a boundary for the discrete assembly.
- Info(Output): Text output streaming errors and execution information.
- Block(Output): Transformed mesh, representing the oriented assembly block according to the given initial block and assembly boundary.
- Assembly(Output): Discrete assembly generated according to the given Block and Boundary.
- Centroids(Output): Center points of each assembly block, to be used for generating robot pick-and-place motions.

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