Summary for CIFE Seed Proposals for Academic Year 2018-19

Proposal number:	2018-06
Proposal title:	Robotics Evaluation Framework
Principal investigator(s)[1] and department(s):	Martin Fischer SDC – Civil and Environmental Engineering
Research staff:	Cynthia Brosque, Graduate Student, Civil and Environmental Engineering
Total funds requested:	$ 51,978
Project URL for continuation proposals	**http://**
Project objectives addressed by proposal[2]	**Buildable, Sustainable**
Expected time horizon	**2 to 5 years**
Type of innovation	**Breakthrough**
Abstract (up to 150 words)	**The problem:** As robotic construction methods are being prototyped and adopted on site, it is critical to analyze the potential and actual impact of the deployment of robots. For example, we need to know how many product, organizational, and process boundaries have to be crossed to make a robot cost- and schedule-effective. What are the implications for the workforce, particularly regarding safety? How does decision making by owners, designers, and builders change with the introduction of robots? **The proposed solution:** A Robotics Evaluation Framework that allows AEC practitioners to holistically consider the impact of robotics. **The proposed research approach:** For three types of robots that are being tested on sites, this research will develop cost, schedule, quality and safety analysis to formalize an evaluation framework for robots.

[1] The PI(s) must be academic council member(s) at Stanford.
[2] For this and the next points, delete the answers that don't apply to your proposal.

Engineering or Business Problem

As robotic construction methods are being prototyped and adopted on site, it is critical to analyze the potential and actual impact of the deployment of robots. There is no current robot evaluation framework to guide owners, designers, builders and subcontractors. For example, we need to know how many product, organizational, and process boundaries have to be crossed to make a robot cost- and schedule-effective. What are the implications for the workforce, particularly regarding safety? How does decision making by owners, designers, and builders change with the introduction of robots?

Test case

Cynthia Brosque (the graduate research assistant proposed for this research project) is carrying out ongoing research to determine the impact of drilling robots. The project under study is the House of Archives for iPark Eiendom, a 14,300 sqm building constructed by Kruse Smith and finished in 2017, where automated vertical drilling was incorporated for drilling holes of installation hangers on concrete slabs. The drilling robot is produced by nLink (now affiliated with CIFE member Hilti), a Norwegian start-up, and its aim is to reduce the strain of repetitive work and make vertical drilling more efficient.

The robot drills precise and continuous series of holes based on the coordinates of the holes taken from the Building Information Model (Fig. 1). One operator controls the robot with an iPad to select the group of holes to drill, and a joystick to intuitively move the robot in the floor plan. After the holes of one subcontract are finished, the operator color-codes them following a project convention (Fig. 2).

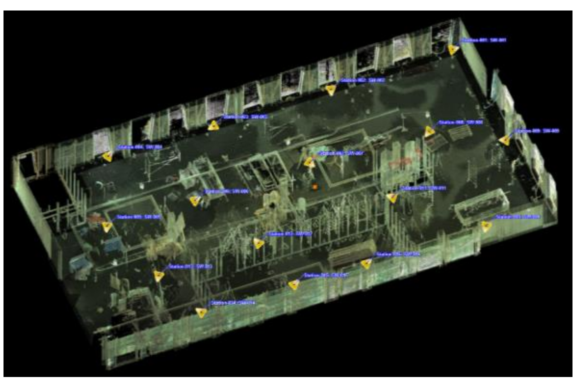


Fig. 1: Point cloud Model, Kruse Smith (2017)

Fig. 2: Color-coded holes on slab, Kruse Smith (2017)

This was the first time the builder implemented a robot on site, and as such, it provided a special opportunity to study the challenges, and lessons learned by the company. Given that half of the project was drilled manually, we can directly compare robotic and manual drilling in the same environment and with the same installation crews for ventilation, piping, sprinklers, and ceiling.

Analysis method

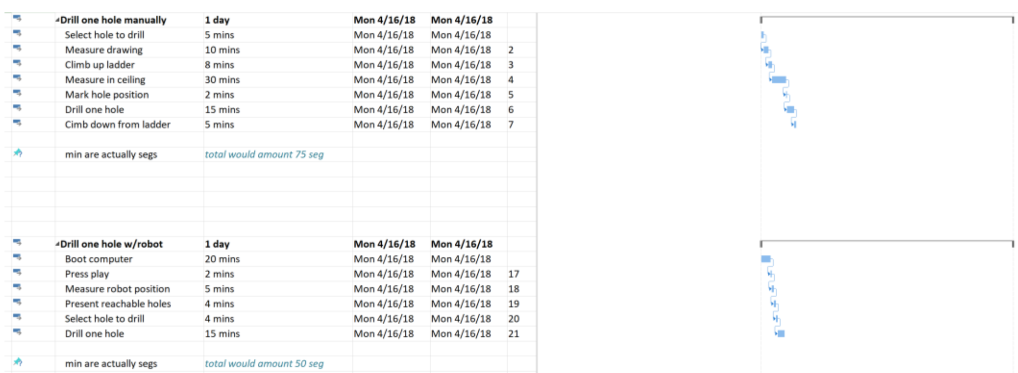
The analysis method consists of a comparative schedule and cost analysis between manually and robotic drilled holes at multiple building and process scales: drill one hole, drill one zone (750 sqm), and drill the entire building (four zones of 750 sqm each). We detailed the workflow for both manual and robot drilling, and analyzed the quality and safety impacts that derived from subcontractors' surveys, interviews with Kruse Smith and nLink, and the robot's reports that track holes drilled/holes planned per zone, and holes drilled/hr. Finally, we have started the creation of 4D models to illustrate the robot and manual drilling progression at the three levels mentioned.

Research findings

The findings obtained so far are summarized in four categories: 1) resource and location-based schedule, 2) cost analysis, 3) workflow analysis, and 4) quality and safety impacts.

1) <u>*Resource and location-based schedule*</u>

The activities to drill one hole (Fig. 3), drill all the holes in one zone (Fig. 4 and 5), and drill all holes in the four zones (Fig. 6 and 7) were scheduled to compare manual and robot completion time.



Drill one hole manually	**1 day**	**Mon 4/16/18**	**Mon 4/16/18**	
Select hole to drill	5 mins	Mon 4/16/18	Mon 4/16/18	
Measure drawing	10 mins	Mon 4/16/18	Mon 4/16/18	2
Climb up ladder	8 mins	Mon 4/16/18	Mon 4/16/18	3
Measure in ceiling	30 mins	Mon 4/16/18	Mon 4/16/18	4
Mark hole position	2 mins	Mon 4/16/18	Mon 4/16/18	5
Drill one hole	15 mins	Mon 4/16/18	Mon 4/16/18	6
Cimb down from ladder	5 mins	Mon 4/16/18	Mon 4/16/18	7
min are actually segs	*total would amount 75 seg*			
Drill one hole w/robot	**1 day**	**Mon 4/16/18**	**Mon 4/16/18**	
Boot computer	20 mins	Mon 4/16/18	Mon 4/16/18	
Press play	2 mins	Mon 4/16/18	Mon 4/16/18	17
Measure robot position	5 mins	Mon 4/16/18	Mon 4/16/18	18
Present reachable holes	4 mins	Mon 4/16/18	Mon 4/16/18	19
Select hole to drill	4 mins	Mon 4/16/18	Mon 4/16/18	20
Drill one hole	15 mins	Mon 4/16/18	Mon 4/16/18	21
min are actually segs	*total would amount 50 seg*			

Fig. 3: Schedule drill one hole manually and with robot

When we compare the time to drill 1 hole there is a 29% time-reduction for robot drilling. Manual work takes about 75 sec., while the robot takes 50 sec. to complete one hole.

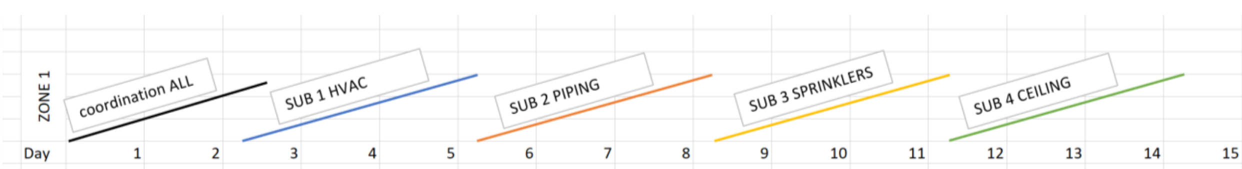


Fig. 4: Resource and location- based schedule drill all holes in one zone manually (14 days)

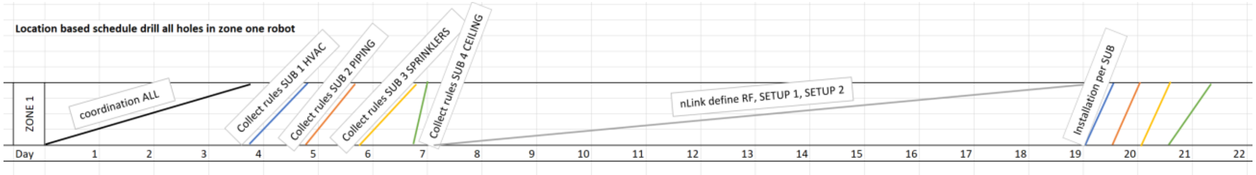


Fig. 5: Resource and location- based schedule drill all holes in one zone with robot (21 days)

However, as we consider one entire zone there is a 46% time-increase for robot drilling compared to manual drilling. This 7-day difference accounts for the added coordination time required for the deployment of the robot. Installation time is reduced by approximately 33% thanks to the pre-drilled holes. The robot drills 129m2/day with an average of 2.22 holes/m2.

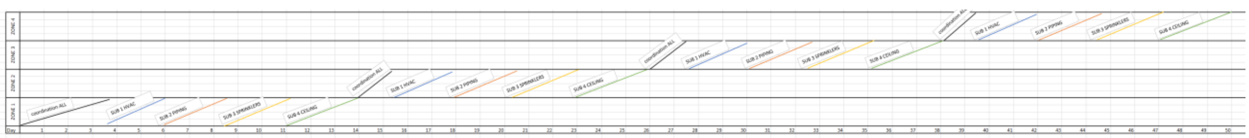


Fig. 6: Location and resource-based schedule: drill four zones manually (51 days)

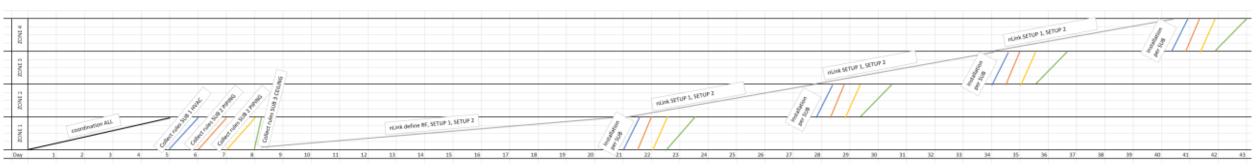


Fig. 7: Location and resource-based schedule: drill four zones with robot (42 days)

When the whole project (4 zones) are taken into consideration for the comparison, again the robotic drilling proves to be faster with a 17% time-reduction compared to manual drilling. This 9-day reduction is consistent with the data obtained from the project (each subcontractor reduced their time by approximately two days, which adds to an 8-day reduction). We can observe from this that robotic drilling is more time-efficient when deployed in the whole building because the most time-impactful pre-construction tasks of collecting design information and automating hanger-placement take about the same time for one zone than for the whole building.

As seen in Fig. 5 and 7, an advantage of the robot is the drilling for all subcontractors simultaneously, providing flexibility to the installation tasks. In traditional construction only one subcontractor can be in one zone at the same time.

An additional optimized schedule was developed to compare the best-case scenario for both manual and robot drilling (Fig. 8 and 9). To remain competitive, manual work should coordinate all the subcontractors to have continuous flow between the four project zones.

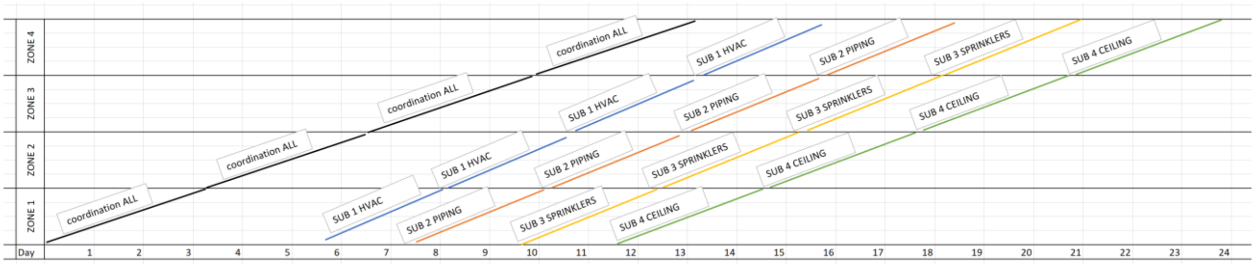


Fig. 8: Optimized schedule for manual work: continuous work between subcontractors (24 days)

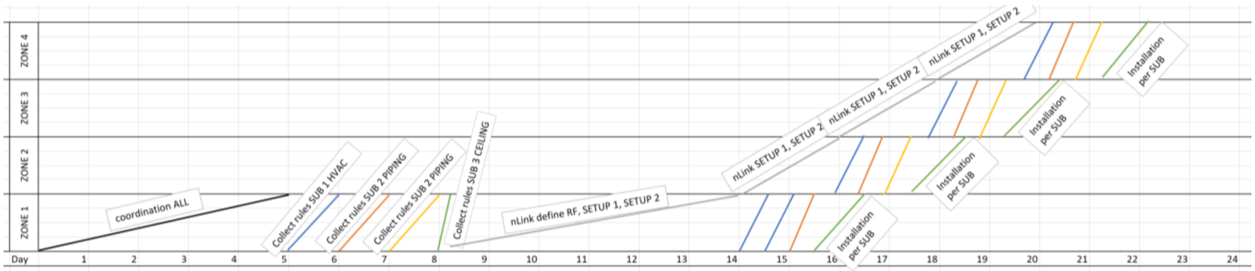


Fig. 9: Optimized schedule for robot: night shifts (22 days)

2) *Cost analysis*

The cost to automate the drilling was considered by weighing the robot cost and extra BIM design hours against the man-hour reductions for early delivery. The values provided by the builder were the following:

- $10.5/sqm robot cost
- $6.75/sqm extra design cost
- $43.75/hr. of onsite traditional work

Kruse Smith engaged four subcontractors and the owner, who shared the costs of the robot in equal parts. The overall cost was about $28,000 (not including owner incentives for early delivery).

3) *Workflow analysis*

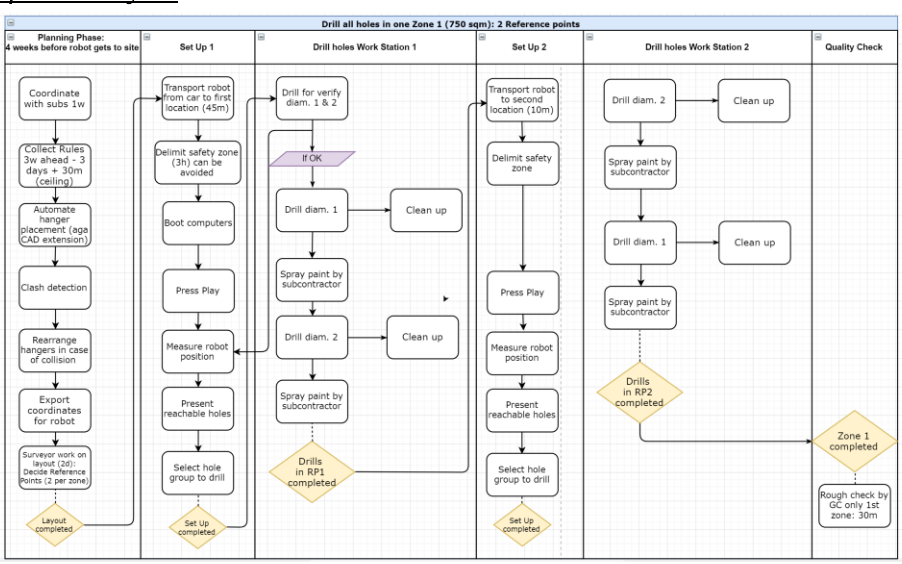


Fig. 10: Workflow for robotic drilling of all holes in one zone.

The manual and robot workflow to drill one hole and to drill all the holes in one zone (Fig. 10) were analyzed to evaluate the robot's necessary input such as hole coordinates, information format, and coordination tasks between subcontractors.

4) *Quality and safety impacts:*

The quality implications studied for the robot use were rework percentage (2%), number of clashes avoided during preconstruction (50), visual management and quality control of installation work, measurements taken from the 3D model instead of manually, and BIM LOD 400 leveraged to prefabricate hangers. The safety impacts observed were reduced muscle strain of overhead work, reduced noise (-10db), and cleaner working conditions since the robot includes a vacuum system that absorbs drilling dust.

Observed challenges

The increased design time and coordination among subcontractors for robot drilling was one of the main challenges of the project. Since the robot was not planned to be used from the start, subcontractors' work was already underway while the robot's planning phase begun. The project faced resistance from the subcontractors, who saw the robot as an imposed reduction of their scope, instead of an opportunity to take other jobs because they would finish the project faster. We could speculate that both aspects contributed to a slower upfront coordination time.

Another challenge found in this first case study was the scarcity of information due to the novelty of robotics application on construction sites. The project team did not possess benchmark results to compare the relative speed and quality of robotic drilling. There were also difficulties in assessing the economic impact of the drilling and the influence it had in effort and work for each subcontractor. Additionally, contrary to when robots are used, traditional construction does not customarily track installation rework on site, overtime work, number of clashes detected and avoided, and percent plan completed at different stages of the project, which can create difficulties in the comparison of robotic and manual work.

These challenges led us to question whether it is possible to formalize an evaluation framework for robots on site. We propose to answer this question by completing the drilling robot analysis and two more robot types analysis.

Case studies of robot types

1) *Single-task robot*

This type consists of a multi-jointed robot arm on top of a platform that can be either fixed or mobile (with wheels, tracks, guidewires) (Paulson, 1985). Single-task robots, as their name indicates, can be programmed to attain extreme precision in one task. The work conducted so far focuses on this type of robot.

2) *Exoskeletons*

Exoskeletons have been around since 1960, first developed by General Electric. According to Arai (2011), the advances in computer technology have brought to life practical applications of power assist mechanisms that can support workers with heavy lifts. Some of the key elements that make it possible are portable energy sources, compact actuation mechanism design, and appropiate human/robot interface. This second case study will be conducted by direct observation of labor productivity on site. As in the first case, we will consider different project levels to test the effect of the tool.

3) *Automated machines*

Existing research on earth-working equipment has incorporated advanced control techniques into construction machinery such as excavators, graders, compactors and bulldozers. These robots incorporate path-planning systems, anti-sway systems and pick-and-place operations (Paulson, 1985). The study will follow the same format as the previous two cases.

Research methods and work plan

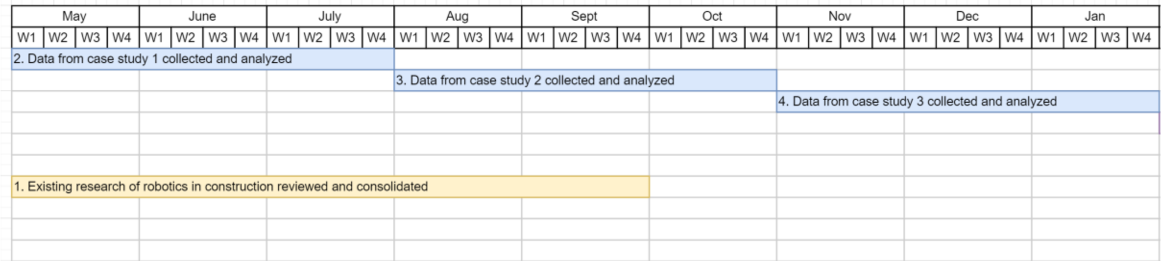
The proposed research will develop in three phases:

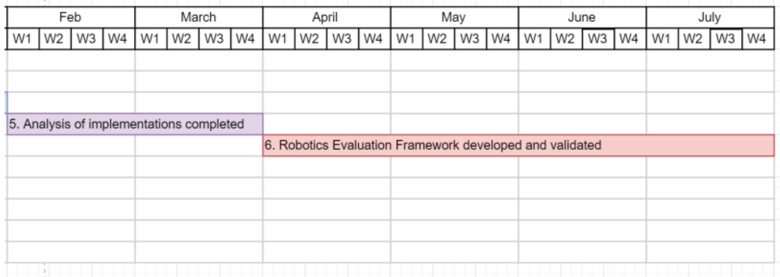
1) *Literature review*
   - Interpret and consolidate existing information.
   - Define, examine and classify the various technologies being used on site.

2) *Analysis of three types of robots being used on construction sites*
   - Gather project data through direct observation, design, 3D/4D models, schedules, and budget. Contrast data to the conventional method without robot assistance. Comparison metrics will be revised with industry partners.
   - Conduct interviews with relevant stakeholders: robot manufacturer, owner, designer, builder, and key subcontractors.
   - Study planning activities and workflow required to deploy the robot onsite.
   - Analyze safety and quality impact.
   - Analyze feasibility of robotics application in terms of schedule and cost from product, organization and process levels. Determine how many boundaries must be crossed in order to validate the use of the proposed technology.

3) *Framework development*
   - Compare the results obtained from the three cases.
   - Assess whether the information can be used to formulate an evaluation framework for robots.
   - Develop and validate the robot evaluation framework.
   - Provide recommendations for the adoption of robots.

Research milestones





1. Existing research of robotics in construction reviewed and consolidated.
2. Data from case study 1 collected and analyzed.
3. Data from case study 2 collected and analyzed.
4. Data from case study 3 collected and analyzed.
5. Analysis of the implementation of robotics completed.
6. Robotics Evaluation Framework developed and validated.

References

Arai, T. (2011). Advanced Robotics & Mechatronics and their Applications in Construction Automation. *28th Internatonal Symposium of Automation and Robotics in Construction* (pp. 7-12). Seoul: ISARC.

Paulson, B. J. (1985). Automation and robotics for construction. *Journal of Construction Engineering and Management, 111*, 190-207.

Warszawski, A. (1984). Robotics in Building Construction. Technical Report R-84-147. Pittsburgh: Department of Civil Engineering, Carnegie-Mellon University.