Summary for CIFE Seed Proposals for Academic Year 2019-20

Proposal number:	2019-05
Proposal title:	Leveraging Human-Robot Collaboration in Construction
Principal investigator(s)[1] **and department(s):**	Martin Fischer (CEE), Oussama Khatib (CS)
Research staff:	Cynthia Brosque (CEE), Margot Vulliez (CS), Elena Galbally (ME)
Total funds requested:	**$ 117,290**
Project URL for continuation proposals	
Project objectives addressed by proposal[2]	**Buildable, Sustainable**
Expected time horizon	**< 2 years**
Type of innovation	**Breakthrough**
Abstract (up to 150 words)	**The problem:** Current construction robots rely on bulky industrial robotic arms and simplistic control leading to unsafe operating conditions and limited capabilities that do not leverage human expertise. **The proposed solution:** Rethink construction tasks using compact, compliant, safe, and multi-purpose robots enabling collaboration between humans and robots. **The proposed research approach:** Develop a haptic simulation environment to explore light-weight, multi-robot collaborative systems with human interaction for five hazardous and strenuous construction tasks. The results will be experimentally validated.

[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

Robotic applications are being developed and tested on construction to handle heavy, repetitive, and hazardous tasks like drywalling, bricklaying, and welding. These robots mostly rely on bulky industrial robotic arms and overly simplistic control algorithms, leading to unsafe operating conditions and limited capabilities that do not leverage human expertise while performing the construction task on site, other than in the role of an operator that oversees robotic performance.

In addition, the techniques and products used in construction (from brick sizes to gypsum board dimensions) come from a long history of development and traditions based on labor-intensive processes. Efficient robotization may require rethinking some of these methods and standards (Bernold, 1987). By replacing the human worker with a single task machine we could be overlooking what is the best possible product and process for the construction task.

Theoretical and Practical Points of Departure

<u>Construction task automation:</u>

Previous research has evaluated which operations are the most suitable to be robotized and automated. According to Bernold (1987), manufacturing achieved mass production with intensive research and restructuring of their traditional methods to make them more amenable to automation. At that time, both the construction industry mindset and the available technology were not ready to efficiently identify and automate the repetitive tasks that take part in construction projects (Bernold, 1987).

Kangari (1985) and Skibniewski & Nof (1989) referred to repetitive construction operations by breaking them down into individual processes, tasks, and sub-tasks. Similarly, Bernold proposed a hierarchical structure of construction activities as a guideline to evaluate their potential for robotization following six hierarchy levels: *organization, project, activity, process, work task, and motion*. The first three levels were evaluated as unique and non-repetitive activities, while the process, work task, and motion were considered semi-repetitive and repetitive, and thus optimal for on-site robotization (Figure 1).

For example, we could characterize earthmoving as the sequence of loading, dumping, and traveling tasks, and each of these tasks could again be decomposed into several motions such as grab, put, turn, and push. To decompose these complex processes on repetitive tasks we should analyze in detail the present construction method, the robotic alternatives and components for each option, and the process to automate the construction task (Warszawski,1989).

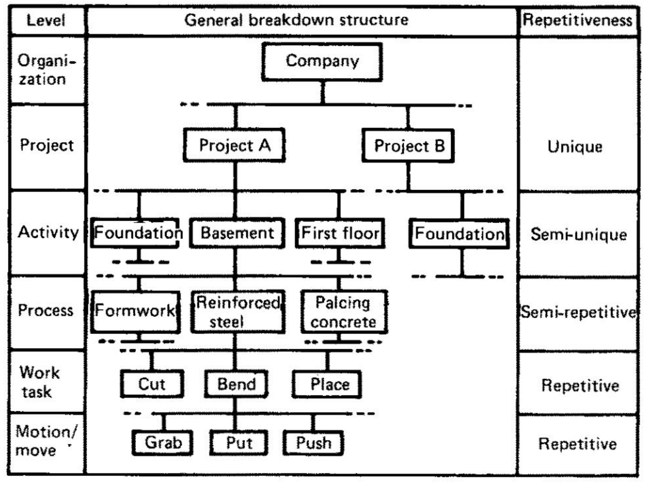

Figure 1: Example of a functional breakdown structure (Bernold, 1987)

According to Skibniewski and Nof (1989) and Warszawski (1989), the value of robotization of tasks increases when these happen in high altitude, extended periods of overtime work, or under any hazardous condition. Some of these tasks are structured enough to be autonomously performed by a robot, while others must still rely on human workers capabilities (Khatib, 1998). The unstructured and dynamic environment of the construction field poses considerable technical challenges (Kangari, 1985) and, even with today's technologies, construction robotics mostly consist of industrial arms mounted in moving platforms performing a single task (Ragaglia et al., 2017; Usmanov et al., 2017; Yamada et al., 2017; Zedin et al., 2017). This configuration has led to complex set-ups and programming, non-versatile, bulky, stiff, and unsafe robots that do not leverage human collaboration in the field.

Inspiration from robotics:

State of the art robotics has progressed in mobility, autonomous manipulation skills, AI reasoning and planning, and physical interaction with unstructured environments through multimodal sensing and environment modeling. These capabilities are key to the application of robotics in space, underwater, domestic environments, medical settings, and construction (Khatib, 1998). These environments are challenging for robots because they are highly unstructured and dynamic, changing even while the task is performed (Groll et al., 2017; Kangari, 1985).

While the manufacturing industry has traditionally separated workers from robots for safety reasons, integration of humans and robots in the construction industry constitutes a key ergonomic study (Skibniewski & Nof, 1989). Ergonomic studies demonstrate the human intent and address how motions can be optimized on the basis of least energy consumption and safety (Bernold, 1989). To successfully introduce robotics in the human environment we need to develop practical, compliant[3], safe, and easy to use systems that are as reliable as the human worker (Khatib, 1998).

The use of bimanual robotic manipulation, despite its many advantages, is rare in industrial applications (Kempe, 2007; Smith, 2012). Nevertheless, previous research has provided useful implementation models of two-hand object assembly, where the objects held by the robot are increasingly constrained either with respect to the ground or with respect to each other. This gives rise to constraint forces which must be explicitly controlled to prevent damage to the object and control slippage. The virtual linkage model provides a mathematical foundation to control these constraint forces (Khatib, 1996; Williams, 1993). Furthermore, the augmented object model (Chang, 2000) can be used to describe the dynamic behavior of the *two manipulators plus object* system.

Motion coordination for multiple mobile robots and human-robot collaboration leveraging bimanual manipulation has been previously considered for drywall operations (Khatib, 1998). This approach incorporated a combination of autonomous behaviors and guided motion interactions for collaboration between humans and robots (Figure 2). The experiments showed the robots could improve the quality and reduce the strain required to perform the task manually, while the workers contribute their knowledge and experience (Khatib, 1998).

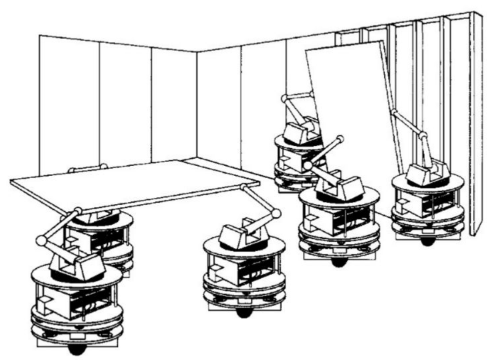

Figure 2: Robotics in construction drywall (Khatib, 1998)

Humans and robots can also collaborate with a haptic-visual interface that combines the dexterity, flexibility, problem-solving, and expertise of humans with the strength, endurance, and precision of robots in the field. A successful example is Ocean One. This underwater humanoid robot successfully exploits collaboration between a robot and a human to execute tasks at depths where divers cannot reach. The human operator is able to feel exactly what the robot feels through a haptic interface used to guide and control the robot (Figure 3).

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[3] Compliance refers to the flexibility of the robot to adapt to external forces or torques. The opposite, a non-compliant or stiff robot, is a device designed to have predetermined positions or trajectories that cannot be easily altered (Bélanger-Barrette, 2014).

Figure 3: A human operator guiding the robot in an underwater bimanual task through the haptic-visual interface (Khatib et al., 2016)

Methodology

The goal of this research is to rethink five repetitive and hazardous construction tasks (drywall placing, bolting, welding, painting, and shotcrete) using compact, compliant, safe, and multi-purpose robots that enable collaboration between humans and machine.

To accomplish this we propose to:

- Extract context and production data from construction tasks on site.
- Develop a haptic simulation environment to explore light-weight, multi-robot collaborative systems with human interaction for the five hazardous and strenuous tasks.
- Measure adaptability to workplace situations and production efficiency (e.g., height limit, component sizes, payload, speed, and space).
- Iteratively improve the task design based on industry partners' feedback.
- Validate the robotic process with physical experiments.

Simulation methods

The simulation environment, SAI (Simulation and Active Interfaces), developed by the Stanford Robotics lab in collaboration with Google, integrates the simulation of control and physical interaction. SAI allows its users to control and test robot's behavior through haptic/UI interfaces and provides efficient and realistic simulations of complex environments (Khatib et al., 2004). This simulation environment was previously deployed in the OceanOne project to simulate underwater exploration with pre-loaded scenes. In the same way, we can load the project BIM as a scene to explore the robot interaction with the environment and construction products (Figure 4). 4D models and parametric design and schedules used in construction will help us (the research team) iterate on the robotized task design in order to improve the available processes and products.

We will base these virtual explorations of human-robot collaborations on thorough observations of task context, production data, and motion captures (with Xsens devices) on construction sites for the five tasks: painting, shotcrete, welding, bolting, and drywall. Next, we aim to design bimanual haptic and autonomous controllers to simulate this data with a rich construction environment in SAI. Industry feedback on the simulations will help us iterate and develop compact multi-purpose robot configurations with human-robot collaboration and new construction products or processes better suited for robotic automation.

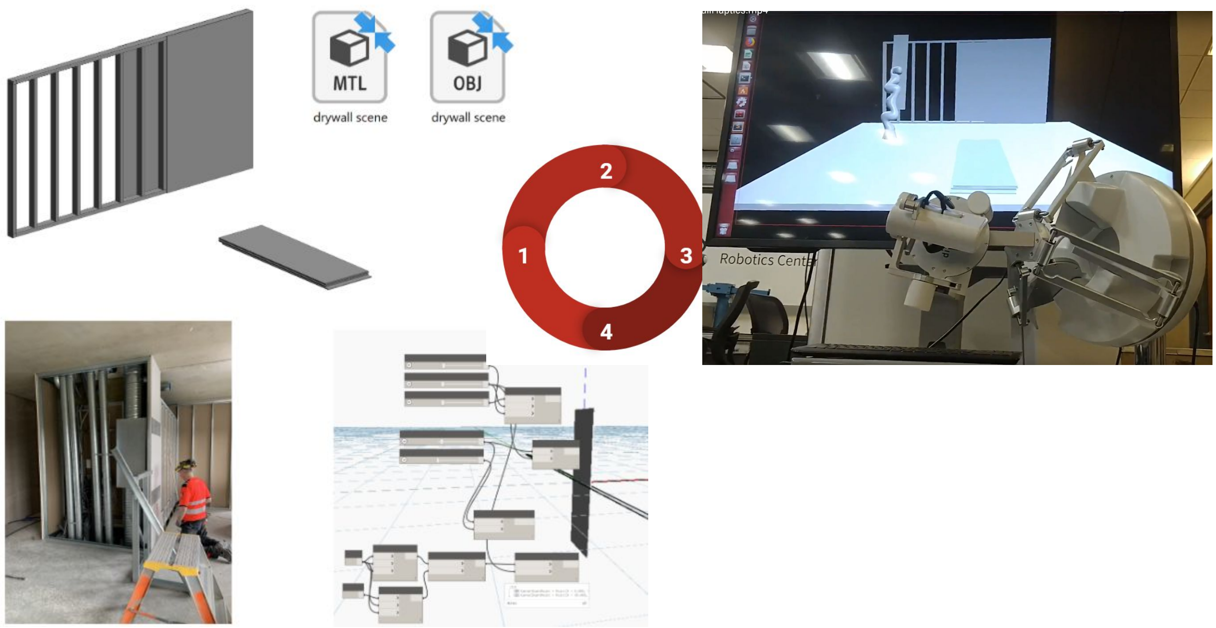


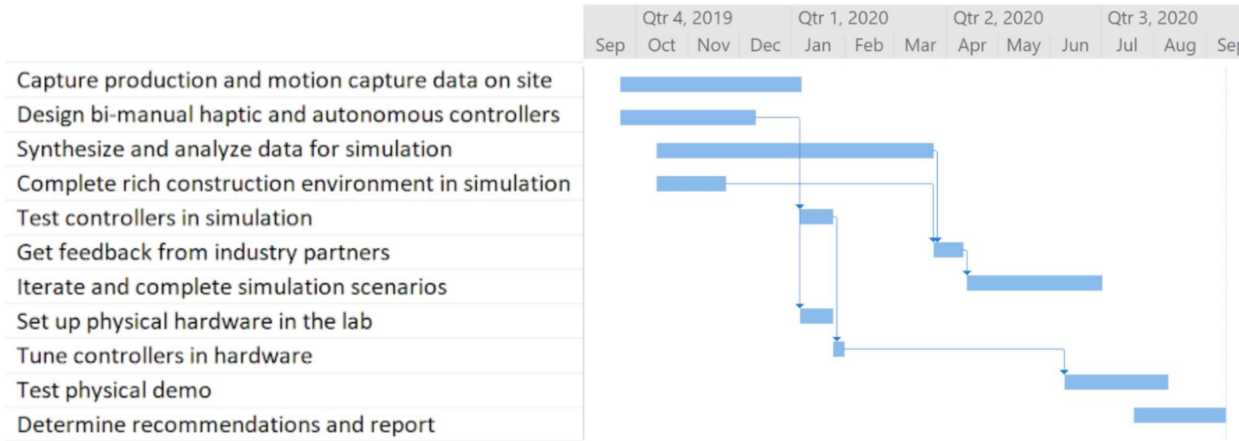
Figure 4: Task context and production data simulation in haptic/UI interface

Expected Contributions and Impact on Practice

Our contributions to the robotics field are exploring robot-human collaboration in an unstructured environment that provides a rich variety of tasks and expanding the understanding of grasp, use of tools, and manipulation skills.

For the construction industry, our expected contributions are rethinking hazardous construction tasks using compact, safe, multi-purpose robots and human-robot collaboration, and collecting production data and motion capture of construction workers to learn from construction experience.

Research Milestones and Timeline



Industry Involvement

We seek involvement from CIFE members to conduct site visits to better understand the construction challenges, acquire motion capture of construction workers in various tasks (with Xsens), share BIM of construction situation for the development of the simulation environment, and obtain feedback on the envisioned human-robot collaboration.

References

Bélanger-Barrette, M. (2014). *How do industrial robots achieve compliance.* Retrieved from https://blog.robotiq.com/bid/69962/How-Do-Industrial-Robots-Achieve-Compliance

Bernold, L. E. (1987). Automation and robotics in construction: a challenge and a chance for an industry in transition. *International Journal of Project Management*, *5*(3), 155-160.

Chang, K. S., Holmberg, R., & Khatib, O. (2000). The augmented object model: Cooperative manipulation and parallel mechanism dynamics. In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No. 00CH37065)* (Vol. 1, pp. 470-475). IEEE.

Groll, T., Hemer, S., Ropertz, T., & Berns, K. (2017). A behavior-based architecture for excavation tasks. *ISARC 2017 - Proceedings of the 34th International Symposium on Automation and Robotics in Construction*, (Isarc).

Kangari, R. (1985). *Robotics Feasibility in the Construction Industry*. Retrieved from http://www.iaarc.org/publications/fulltext/Robotics_feasibility_in_the_construction_industry.PDF

Kemp, C. C., Edsinger, A., & Torres-Jara, E. (2007). Challenges for robot manipulation in human environments [grand challenges of robotics]. *IEEE Robotics & Automation Magazine*, *14*(1), 20-29.

Khatib, O., Yokoi, K., Brock, O., Chang, K., & Casai, A. (1999). Robots in human environments. *Proceedings of the 1st Workshop on Robot Motion and Control, RoMoCo 1999*, 213–221. https://doi.org/10.1109/ROMOCO.1999.791078

Khatib, O., Yeh, X., Brantner, G., Soe, B., Kim, B., Ganguly, S., … Creuze, V. (2016). Ocean one: A robotic avatar for oceanic discovery. *IEEE Robotics and Automation Magazine*, *23*(4), 20–29. https://doi.org/10.1109/MRA.2016.2613281

Khatib, O., Yokoi, K. Chang, K., Ruspini, D., Holmberg, R., & Casal, A., (1996). Vehicle/arm coordination and multiple mobile manipulator decentralized cooperation, *2*, 546–553 vol.2. https://doi.org/10.1109/IROS.1996.570849

Khatib, O. (1998). Mobile manipulation: The robotic assistant. *Robotics and Autonomous Systems*, (26), 175–183.

Skibniewski, M. J., & Nof, S. Y. (1989). A framework for programmable and flexible construction systems. *Robotics and Autonomous Systems*, *5*(2), 135–150. https://doi.org/10.1016/0921-8890(89)90006-7

Smith, C., Karayiannidis, Y., Nalpantidis, L., Gratal, X., Qi, P., Dimarogonas, D. V., & Kragic, D. (2012). Dual arm manipulation—A survey. *Robotics and Autonomous systems*, *60*(10), 1340-1353.

Ragaglia, M., Argiolas, A., & Niccolini, M. (2017). Cartesian-Space Motion Planning for Autonomous Construction Machines. In 34th International Symposium on Automation and Robotics in Construction (pp. 983–990). Taipei: International Association for Automation and Robotics in Construction. https://doi.org/https://doi.org/10.22260/ISARC2017/0136

Usmanov, V., Bruzl, M., Svoboda, P., & Šulc, R. (2017). Modelling of industrial robotic brick system. In *34th International Symposium on Automation and Robotics in Construction* (pp. 1013–1020). Taipei: International Association for Automation and Robotics in Construction. https://doi.org/https://doi.org/10.22260/ISARC2017/0140

Warszawski, A. (1987). Application of Robotics to Building Construction by. *International Council for Building Research Studies and Documentation*.

Williams, D., & Khatib, O. (1993, May). The virtual linkage: A model for internal forces in multi-grasp manipulation. In *[1993] Proceedings IEEE International Conference on Robotics and Automation* (pp. 1025-1030). IEEE.

Yamada, M., Fujino, K., Kajita, H., Hashimoto, T., & Technology, A. (2017). Survey of the line of sight characteristics of construction machine operators to improve the efficiency of unmanned construction. In *34th International Symposium on Automation and Robotics in Construction* (pp. 588–593). Taipei: International Association for Automation and Robotics in Construction. https://doi.org/https://doi.org/10.22260/ISARC2017/0082

Zedin, T., Vitalis, L., Guéna, F., & Marchand, O. (2017). A method based on C-K Theory for fast STCR development: The case of a drilling robot design. In *34th International Symposium on Automation and Robotics in Construction* (Vol. 34, pp. 464–471). Taipei: International Association for Automation and Robotics in Construction. https://doi.org/https://doi.org/10.22260/ISARC2017/0064