Digital Construction Platform: A Compound Arm Approach

Digital Construction Platform: A Compound Arm Approach

A mobile large-scale platform for on-site sensing, design, and digital fabrication

Steven Keating, Nathan A. Spielberg, John Klein, Neri Oxman

Massachusetts Institute of Technology
neri@mit.edu

Abstract. We introduce a novel large-scale Digital Construction Platform (DCP) for on-site sensing, analysis, and fabrication. The DCP is an in-progress research project consisting of a compound robotic arm system comprised of a 5-axis Altec hydraulic mobile boom arm attached to a 6-axis KUKA robotic arm. Akin to the biological model of human shoulder and hand this compound system utilizes the large boom arm for gross positioning and the small robotic arm for fine positioning and oscillation correction respectively. The platform is based on a fully mobile truck vehicle with a working reach diameter of over 80 feet. It can handle a 1,500 lb lift capacity and a 20 lb manipulation capacity. We report on the progress of the DCP and speculate on potential applications including fabrication of non-standard architectural forms, integration of real-time on-site sensing data, improvements in construction efficiency, enhanced resolution, lower error rates, and increased safety. We report on a case study for platform demonstration through large-scale 3D printing of insulative formwork for castable structures. We discuss benefits and potential future applications.

Keywords: Digital fabrication; robotics; large-scale fabrication; 3D printing; insulated formwork; digital construction platform (DCP)

1 Introduction

Robotic systems and digital fabrication technologies are increasingly implemented for architectural design and construction through a variety of material processing techniques and delivery systems (Bonwetsch, Kobel et al., 2006; Gramazio and Kohler, 2008; Lim, et al., 2012). From brick-laying robotic arms (Bonwetsch, Gramazio et al., 2007) to filament winding of structural composite parts for architectural construction (Castro, Seereeram et al., 1993; Shirinzadeh, Alici et al., 2004), robotic construction for large scale systems is enabling architects and engineers alike to further push the envelope of digital design generation and automation. Furthermore, such construction technologies can serve to fundamentally challenge and transform well practiced design traditions.

Despite this promise, on-site design, sensing, and fabrication for large structures are still lacking. In their absence architects are forced to segregate between processes of design generation and processes of design construction. Furthermore, the deployment of robotic fabrication tools and technologies is typically limited to the production of prototypes or off-site small-scale structures.

In this paper we present research-in-progress for a novel digital platform capable of on-site design, sensing, and fabrication of large-scale structures. The system combines a large hydraulic boom arm and a smaller electric robotic arm. Through the control of both arms, the system enables digital fabrication processes at architectural scales. As a result, the Digital Construction Platform (DCP) (Fig. 1) opens up new opportunities for on-site sensing, design and fabrication capabilities.

Fig. 1. The Digital Construction Platform (DCP) is comprised of a 6-axis KUKA robotic arm mounted to a 5-axis Altec hydraulic boom arm.

By attaching a sensor as an end effector to the system, it is able to generate volumetric scanning of physical geometry and environmental conditions, such as radiation, soil stability, temperature, and chemical mapping (Keating and Oxman, 2012). Such scanning technologies have been previously explored as stand-alone applications (Callieri, Fasano et al., 2004). However, by combining sensor data with material deposition logic the designer is able to respond to site-specific environmental data and terrain mapping in real time. In addition, various fabrication methods using a range of end effectors such as a mill, an assembly gripper, or a welding tool, can be implemented as part of the fabrication process. Through these capabilities the DCP system is designed to complete the large-scale tool chain, providing real-time digital sensing, on-the-fly performance-based design, and on-site construction. Potential benefits include the construction of complex architectural forms, improvements in efficiency, enhanced resolution, lower error rates, recorded measurement data and significant increases in safety.

We demonstrate the use of large-scale 3D printing of formwork utilizing the Digital Construction Platform as a first case study implementation. Using quick cure polyurethane foam, insulative formwork can be rapidly 3D printed in doubly curved geometry without the need for support material. Early analyses of foam strength, print speeds, resolution, and preliminary economic figures confirm the feasibility of the project (Keating, 2012).

2 Platform Design

The Digital Construction Platform utilizes a mobile system capable of an extended physical reach, complex functional movement and high load capacity thereby enabling new modes of in-situ construction. The design of the platform was motivated by the need for a flexible system capable of implementing various kinds of large-scale digital fabrication approaches including additive, subtractive, and assembly techniques. Utilizing an extended stationary reach, the DCP system can handle large load capacities as well as high degrees of access and accuracy (Fig. 2).

Fig. 2. The range of motion for the DCP is shown through long-exposure photography (left). The DCP uses a combination system of a 5-axis Altec hydraulic boom arm and a small 6-axis KUKA robotic arm (right).

Furthermore, the DCP functions as a mobile system allowing for fast setup times and ease of repositioning. Compared with existing construction platforms, hydraulic boom arms prevail for flexible manipulation from a stationary position (Saulters and Scarr, 1985). However, these systems typically lack the precision or automation required for digital fabrication techniques. The DCP is designed around a hydraulic boom arm with an added robotic arm effector for compensation of oscillations, increased precision and ease of access.

The current platform utilizes a GMC truck, an Altec L42M boom arm, and a KUKA robotic arm, providing a lift capacity of 1,500 lbs (boom arm mount) with a manipulation capacity of 20 lbs (KUKA arm). The 6-axis KUKA robotic arm is mounted on the end of a two-axis hydraulic jib on the 3-axis boom arm. The system uses a KUKA KR5 sixx R850 arm and is currently being upgraded to a KUKA KR10 R1100 arm for improved mechanical specifications. The robotic arm is controlled via a custom python script package enabling real-time control via the KUKA Robot Sensor Interface (RSI). The controls system is designed as feedback loop based on real-time data from magnetostrictive sensors, rotary encoders, and inertial measurement units.

3 Control System

The control system is designed to accomplish three goals: accurate positioning, high speed and minimization of oscillations at the end effector. Due to its cantilevering structure, slow persisting oscillations in the boom arm are encountered at the end during open loop control as seen in (Fig. 3) and are common in construction equipment (Yong and Rydberg et al., 2005). The oscillation amplitude and duration can be reduced through a controls scheme. However, we must still compensate for the dynamic response to gain the desired positional accuracy and speed for digital fabrication applications. We aim to operate at end effector speeds of up to 0.2 m/s and a targeted accuracy of $\pm$ 0.5 cm. In order to achieve this desired speed and accuracy we plan to incorporate a linear quadratic controller designed to minimize the magnitude of oscillations at the end effector of the large boom arm. Besides this controller, we plan on also implementing a position control scheme to control the localization of the end effector relative to the boom arm.

In order to sense such oscillations, we use the ADXL345 accelerometer and the ITG-3200 MEMS gyroscope on the end of each cantilevered linkage. The velocity of each hydraulic piston on the boom is controlled by mechanically actuating the hydraulic valves with servos. Each hydraulic piston is treated as an ideal velocity source in the control system model. Joint angles are sensed with Balluff BTL6 Micropulse transducer sensors for measuring hydraulic extension. At the base of the arm, the rotational angle is sensed by using a YUMO E6B2 encoder mounted on the rotational hydraulic motor. Each of the sensors is designed to provide feedback for the end effector position through the kinematics. Furthermore, global positioning feedback will be established through the use of a ground reference sensor. The use of LIDAR and other environmental sensors such as magnetometers and ground penetrating RADAR could also provide three-dimensional environmental data for use in optimal construction of structures.

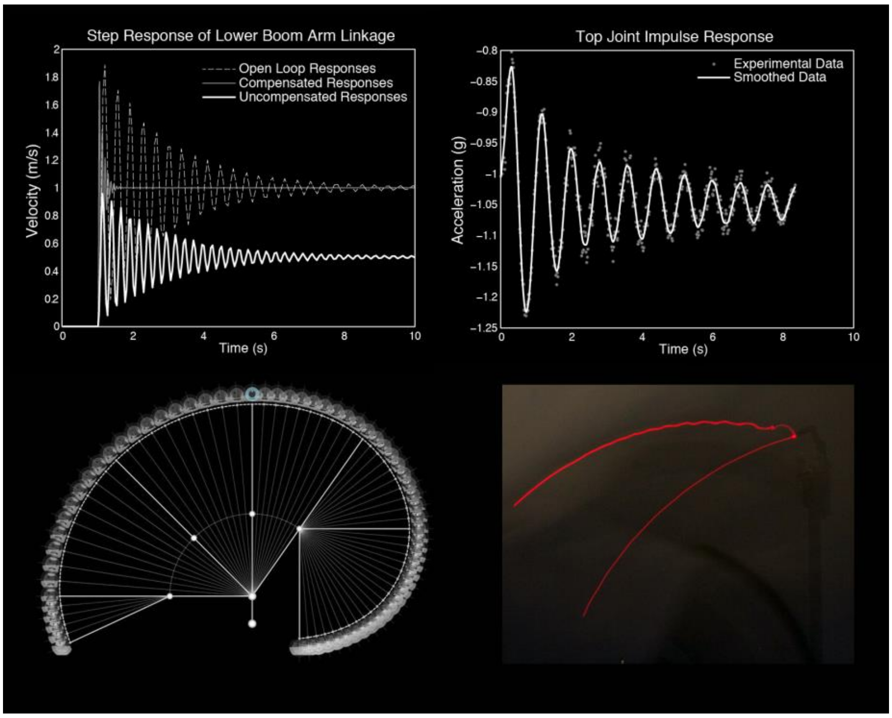

Fig. 3. The control model for the DCP allows a range of motion (bottom left) and compensates for robotic arm oscillations (image bottom right, acceleration data top right). The figure demonstrates a simulation of open loop, compensated and uncompensated response from the controls model (top left).

In the current controls model, by linearizing the boom linkage joints about a small angle and deriving a system model, we demonstrate that a PID controller is able to reduce the time and amplitude of open loop system oscillations (Nise, 2010). The system is linearized about a nominal optimal operating position. In small deviations from this nominal position the linearized model is valid within acceptable error. We are currently investigating a nonlinear system model for improved response.

By using a STMicroelectronics LIS331DLH MEMS 3-axis digital accelerometer with a sensitivity of 1 mg/digit, we have characterized open loop system properties. This was achieved by performing an impulse response test in each joint of the boom arm (Fig. 3). From this impulse test we derive the mass, spring, and damping system characteristics by quantifying the period and decay of the measured acceleration output. These mass, spring, and damping characteristics dictate the open loop system dynamics and are used in simulation to construct an estimated system model. The simulation results conducted in MATLAB Simulink for the boom arm are given in (Fig. 3). In order to compensate for these minimized oscillations, the KUKA robotic arm operates via a custom python script using the RSI package for real-time control. The python script enables the operation of the KUKA controller via packet communication from a main computer that integrates the programmed tool path, sensor data, and a graphic user interface. The KUKA motions are dictated through feedback from an accelerometer at the base of its arm that enables compensatory real time trajectories. The resulting compensation action is made possible by the fast response time of the small robot arm in comparison to the frequency of the boom oscillations. The home location of the robot arm end effector is designed to be located in the center of its spherical working area. This home position will allow for maximum oscillation amplitude adjustment. The two systems work in tandem through a unified controls scheme, with the addition of feedback from each of the joints.

We intend to incorporate additional sensors to provide a ground reference point for redundancy. In addition, this secondary ground reference sensing will reduce hysteresis and small error accumulation in the position measurement of the end effector. Other errors such as the change in external working temperature will be compensated for through closed-loop feedback of real time positioning, which increases the robustness of the controls system. Interference can be minimalized by the use of a real time kinematic GPS sensing system for ground referencing. The combination of this ground reference sensor along with the other accelerometers, and position sensors on each joint will close multiple loops allowing for accurate end effector positioning.

4 Material Case Study

Robotic fabrication systems provide increased efficiencies of existing processes, enable transfer of unsafe human techniques to machines, support novel manufacturing techniques, and - most importantly - open new design possibilities for a more integrated architecture. The DCP is not intended to replace people; rather, it is designed to augment capacities in which robotics excel, namely precise, repetitive, and dangerous tasks. In addition, the DCP is designed to allow for novel on-site integration of sensor data, design and fabrication techniques. Instead of a static design, the DCP supports data capturing and integration of site data such as topography, material analysis, and environmental conditions. This concept of real-time sensing and integration into fabrication processes offers improvements in form, reliability, and customization of design form to fit functional and site-specific environmental requirements. Under this framework we introduce a novel additive fabrication technique enabled by robotics as a case study implementation for our DCP system.

Since the early days of assembly lines, multiple proposals for automated housing construction have been attempted. Thomas Edison's single-pour concrete housing, patented in 1917 (Edison, 1917), was one of the first to explore this concept. Edison's dream of a re-useable mold for castable concrete houses, complete with fine details, resulted in a well-documented failure due to mold issues and the inability to customize individual designs. In modern day practice, housing construction techniques are primarily based on manually assembled structures while automation holds significant potential to improve safety, form, and efficiency. The current field of architectural-scale additive manufacturing has explored direct extrusion of cementitious materials or the use of binder material, as seen in Contour Crafting or D-Shape (Khoshnevis 2004; Khoshnevis, Hwang et al. 2006). However, limitations relating to materials, complex forms, and on-site scalability still remain (Lim et al., 2012).

To enable the variation of material properties with any castable material while providing enhanced speed, a new technique based on formwork was created. Similar to insulated concrete forms, leave-in-place insulating formwork can be 3D printed for castable structures. The process, termed Print-in-Place construction, is designed for on-site fabrication of formwork for castable structures, such as concrete exterior walls and civil infrastructure (Keating and Oxman 2013). Print-in-Place Construction provides a method by which to overcome the complexities associated with direct concrete extrusion. In addition, mold printing allows for a stronger product as the material is instantly cast instead of it being constructed through successively layering (Keating and Oxman 2013).

The polyurethane spray foam utilized in the prototype system (Dow Chemical FROTH- PAK foam) is a two-component chemical foam with a cure time of 30 seconds. It is an expanding foam that is strong, lightweight, and designed for a high insulative value. Due to the rapid cure time, a large structure can be printed very quickly. For example, the curved twelve foot long wall structure demonstrated in (Fig. 4) was printed in less than five minutes using the KUKA robotic arm to control the nozzle position. Time estimates for small exterior house structures are under a day (Keating, 2012).

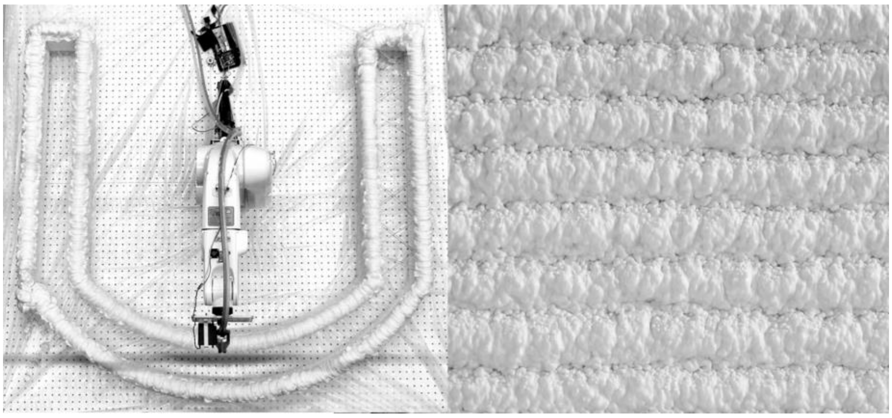

Fig. 4. Additive fabrication tests using polyurethane spray foam with a KUKA 6-axis arm (left) produced test insulative formwork samples with consistent and tunable layer heights (right).

In addition to additive printing, the Print-in-Place technology utilizes subtractive techniques to improve surface finish and reduce manufacturing time. The formwork is printed in thick layers of around two inches enabling fast build times followed by a surface mill to achieve a higher resolution. The resulting resolution from a cast structure inside a printed and milled mold is shown in (Fig. 5).

Fig. 5. Combining additive and subtractive processes in a compound end effector (right) facilitates fast build times and high resolutions, as seen in the cast structure produced from a printed and milled mold.

Furthermore, subtractive processes, combined with embedding objects (such as rebar or tie structures) in the printing process, enable achieving complex details such as windows, wiring areas, and embedded sensor integration.

Compared with traditional construction practices, the benefits of the designed system are substantial. Whereas the former method requires human labor and large construction machines, the latter allows for buildings to be printed with cost-effective mobile printing units. From a material standpoint, the DCP system wastes few resources and uses only the amount of bulk material that is required for construction. This reduces the price of construction down to the bare minimum based on the price of the bulk material components (insulating foam and castable materials for structure). From a speed standpoint, reducing the construction site time and integrating processes improves efficiencies. Finally, custom formal manipulations are easily achieved, as the geometry is not constrained by rectilinear paths.

Overall, printing formwork is an effective method that offers benefits over the difficulties involved in printing concrete directly or using a powder/binder process. By printing dual-purpose foam that acts as a mold for the concrete as well as insulation for the building, Print-in-Place Construction is significantly more versatile and can incorporate different materials or variations of concrete. The process can also be rapidly integrated into current building strategies and regulations as the Print-in-Place Construction method aligns directly with traditional insulated concrete form (ICF) technology. Once the mold is printed, conventional methods and regulations that apply to ICF construction are applicable to the Print-in-Place process (Keating and Oxman, 2013).

5 Conclusions

The Digital Construction Platform (DCP) is designed as an enabling design and construction platform to sense, design, and construct highly integrated architectural constructs. The increased capability to automate synchronized fabrication sequences creates the opportunity to design an interwoven set of relationships between structural, architectural and environmental systems - in turn enabling true building integration. This is achieved through the DCP's versatility and capacity to create feedback loops between real-time site-specific sensing and fabrication processes. Compound arm techniques on a mobile platform bridge the digital and physical domains by enabling the transition of digital fabrication into large-scale on-site building construction. Our investigations into additively fabricated insulative formwork highlights the type of novel possibilities enabled by the DCP platform. Future work entails fitting out the mechanical and sensing systems, completing material testing and investigating multi-platform collaboration with swarm construction techniques. Finally, we aim to design and construct a full-scale architectural pavilion using the DCP system in the near future.

6 Acknowledgements

We would like to acknowledge Altec Industries for their support of this project and technical assistance. In addition, this research was supported in part by an NSF EAGER grant award #1152550 “Bio-Beams: Functionally Graded Rapid Design & Fabrication”. We would like to thank the Mediated Matter group and the MIT Media Lab for their kind help and support. Specifically, we would like to acknowledge Ali AlShehab, Benjamin Jennet, Dr. David Wallace, Dr. Franz Hover, Hannah Barrett, Sergio Falcon, Will Bosworth and Xiaoyue Xie for their assistance with this project.

7 References

Bonwetsch, T., F. Gramazio, et al. 2007, 'Digitally fabricating non-standardised brick walls.' *ManuBuild, 1st International Conference*, Rotterdam.

Bonwetsch, T., D. Kobel, et al. 2006, 'The Informed Wall: Applying additive digital fabrication techniques on architecture.' *Proceedings of ACADIA*, Louisville, Kentucky.

Callieri, M., A. Fasano, et al. 2004, 'RoboScan: an automatic system for accurate and unattended 3D scanning.' *3D Data Processing, Visualization and Transmission.* 2nd International Symposium, IEEE.

Castro, E., S. Seereeram, et al. 1993, 'A real-time computer controller for a Robotic Filament Winding system.' *Journal of Intelligent and Robotic Systems* 7(1): 73-93.

Edison, T. 1917, 'Apparatus for the production of concrete structures'. Patent No. 1326854

Gramazio, F. and M. Kohler 2008, 'Digital materiality in architecture', Lars Muller Publishers, Baden.

Keating, S. 2012, 'Renaissance robotics: novel applications of multipurpose robotic arms spanning design fabrication, utility, and art'. M.Sc. Thesis, Mechanical Engineering, Massachusetts Institute of Technology.

Keating, S. and Oxman, N. 2012, 'Immaterial Robotic Fabrication'. *Proceedings of RobArch: Robotic Fabrication in Architecture, Art and Design.*

Keating, S. and Oxman, N. 2013, 'Compound fabrication: A multi-functional robotic platform for digital design and fabrication.' *Robotics and Computer-Integrated Manufacturing* 29(6): 439-448.

Khoshnevis, B. 2004, 'Automated construction by contour crafting - related robotics and information technologies.' *Automation in construction* 13(1): 5-19.

Khoshnevis, B., D. Hwang, et al. 2006, 'Mega-scale fabrication by contour crafting.' *International Journal of Industrial and Systems Engineering* 1(3): 301-320.

Lim, S. et al. 2012, 'Development in construction-scale additive manufacturing processes'. *Automation in Construction*, 21 (1), 262-268

Nise, N. 2011, 'Control systems engineering.' Hoboken, NJ: Wiley.

Saulters, J. D. and R. H. Scarr 1985, 'Method and apparatus for controlling the position of a hydraulic boom.' Patent No. 4514796A

Shirinzadeh, B., G. Alici, et al. 2004, 'Fabrication process of open surfaces by robotic fibre placement.' *Robotics and Computer-Integrated Manufacturing* 20(1): 17-28.

Willmann, J., F. Augugliaro, et al. 2012, 'Aerial Robotic Construction Towards a New Field of Architectural Research.' *International Journal of Architectural Computing* 10(3): 439-460.

Yang, Y. et al. 2011, 'Recycling of composite materials.' *Chem. Eng. Process.*

Yong, Y., Rydberg, K. and An, L. 2005, 'An improved pi control for active damp-ing of a

hydraulic crane boom system.' *Proceedings from the International Society for Optical Engineering*