Towards cloud informed robotics

Sven Stumm[a], Peter Neu[a] and Sigrid Brell-Cokcan[a]

[a]Chair of Individualized Production in Architecture RWTH Aachen University
E-mail: office@ip.rwth-aachen.de

Abstract –

The current construction industry slowly adapts towards the new possibilities created through digitalization. However there still a major gap in the information flow between planning phases and the start of construction. With modern robotics we see a chance to mediate this gap. By using cloud accessible CAD software and linking it directly with a web interface, new means of cloud informed fabrication become possible. Designers can easily obtain feedback regarding recurring issues or design demands. We want to enable users to create their own design based on rules and parameters preselected by the designer. Therefore processes for individual parts require an integrated design. Considering changing user demands and the resulting usage requirements the optimization in the phase of conversion from the user´s perspective can help the design process. A number of fabrication technology services exist, which allow for mass customized product creation. The required web interfaces used for these kind of services however are created on a case by case basis. Additionally the required production parameters have to be transferred to the production process. An easy flow from parametric design model towards a web interface for user feedback and fabrication as a service was developed and is presented within this paper.

Keywords –

Cloud; Robotics; BIM; Production immanent design

1 Introduction

The current degree of automation within the construction industry is still low especially compared to industrial production. In addition to the small lot sizes within construction, high tolerances and variation are very common especially when working with natural materials. Building components are therefore often fitted manually on-site. Efforts are made to mediate this through tighter process control and detailed digital representation within Building Information Modeling (BIM). BIM allows the parametrization and placement of intelligent objects, containing a number of properties, in a common environment for different parties involved in the planning process [1].

However to get this information to the construction workers these models still need to be broken down to physical plans. This leads to a very loose correlation of the current model and the actual construction site. However the multitude of planning phases and experts integrated through BIM give us very intensive a priori knowledge of the environment and the task at hand in the form of a digital model. This knowledge can be employed to fabricate designed parts in lot size one.

High quality data is key to automation. Only if the geometry, position and structure of objects are known, automated processing can be planned and executed. The approach we propose within this paper uses cloud integrated software as the continuous framework for linking design processes directly to production and constitutes a novel strategy. By using cloud accessible CAD & BIM software and linking it directly with robotic fabrication, new means of cloud informed robotics and production are possible. Future developments would allow other robots executing similar task to learn from any other cloud connected robot.

Programmers and designers can also obtain feedback regarding recurring issues during their programs execution. As well as the influences these constitute for the design. A geometric representation and material information of a building element must be translated into an individualized assembly process with adaptive machine control strategies. Within this paper, we present a concept for robotic construction processes informed by data collected within a cloud environment. The geometric data, material structure and user feedback etc. stored in the model will be used for automated process and path planning within the digital built environment. We show the feasibility of the approach and consider information redundancies as well as missing process information.

Within our work we show a first proof of concept for a fully integrated information flow from design to fabrication. Enabling not only consistent flow of information but also new concepts for distributed design and fabrication. This in turn allows for a more efficient utilization of production environments within the field of building part prefabrication. Similar concepts as propagated within industry 4.0 can be used to coordinate designers and integrators of production environment, while allowing for production as needed.

Due to increasing prevalence of 3D printing methods a number of online services where created, which allow the full customization of parts. Similar systems exist for the CNC milling of parts. This specifically became possible through the verifiability of fabrication due to the lower complexity as compared to full production environments. For modern CNC machines the same procedure can be executed over and over again or individual procedures can be executed at the same rate. In order to provide the customer with the possibility of customizing an object, the programming of that machine needs to be flexible, towards automatically creating programs that are safe and lead to aesthetically pleasing results.

Prior to this the easiest way to provide customization was through modular designs. Rather than customizing individual parts, the entire object was customized by replacing entire modules. The big advantage of other technologies are clearly defined requirements for the process, as well as the enforceability of these requirements through automated checks: For 3D Printing this often means, as long as an object fits into a given volume, has a sufficient wall thickness and no geometric defects, it can most likely be printed.

Through Tylko similar means services for customization of furniture became possible by restricted parameter adaption towards the requested design. This simultaneously allows for the virtual integration of the targeted design through augmented reality.

2 Web-to-Real approach

Within [2] we described our first approach of creating a web based interface allowing users to upload design data to a server for later processing within a stone masonry production environment. An automated easy to use interface for mass customization was created. The implementation of a Web-to-Real platform enabled new possibilities for commissioning. Through this interface designers are not only able create and commission their own stone surface design in a mass customization approach, but are even able to verify feasibility and quality through a preprocess simulation.

The used approach ensures that current simulation is up to date and the results can even be employed for actual robot programming. Any optimization done to the process has a direct effect on the result seen by the customer. The customer gets a direct connection to the product created and has clear influence on how it turns out. Simultaneously the usability of the interface was kept simple through a direct upload of a pattern as an image file, allowing the customer to create a design in whatever software they are used to. The preprocess simulation allowed for a direct verification of the design via the web. This adds direct feedback to the idea of a streamlined process from design to production.

The developed Web-to-Real application however required a custom browser interface. Additionally a scalability of the approach was still not achieved. Using a cloud based infrastructure allows for the complete integration with a wide range of design software. Furthermore means were integrated and developed in order to harmonize the transfer of process parameter through and XML based format, this is further described within section 4.3. Figure 1 shows the resulting Web interface, for the web-to-real approach. Using a cloud integrated work flow brings this approach closer towards cloud robotics and is able to be applicable to a wide range of production environments.

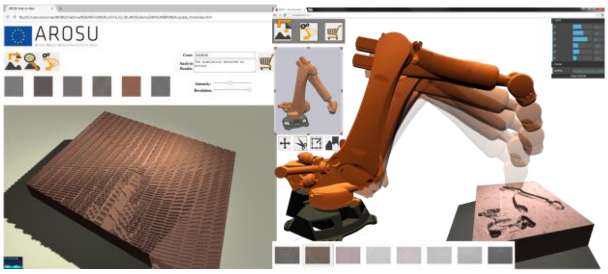

Figure 1. A first prototype of a Web-to-Real interface for stonemasonry. Enabling the individualized fabrication of customized products.

3 Forge Cloud Services

Forge provides a unified way for programs to access the Autodesk Cloud including its storage system and other 3D-model specific services. Data in the Autodesk Cloud can either be user-owned or app-owned. The user-owned object storage system (OSS) is well-known as it is the same backend used in Fusion360, BIM360 and other Team360 programs. Enabling to ask the user for access-permission to the user's projects and process these files in the cloud. Figure 2 gives an overview of the cloud integrated software.

Additionally it is possible to link the user-owned OSS via projects to multiple user accounts and similar. In order to create an open login independent upload of design data, we focused on the app-owned storage for the prototypical implementation. When registering an app through the Autodesk Developer Portal we obtain a unique client-ID and -secret, that are used to identify the programs and authorize them to use cloud services.

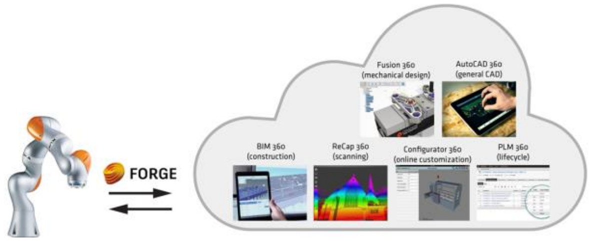

Figure 2. Available client software for the Forge cloud allowing the design, modelling and acquisition of fabrication relevant data.

A general challenge of cloud-interaction is the dependence of the client (program running on local computer) on the server. The transfer of data is done by HTTP-requests that exchange plain text. So information stored in hierarchical structures and objects has to be serialized to text, sent over the internet, and de-serialized to an objects again. This can lead to failure of transfers when formatting on server and client side is inconsistent, therefore the components used for the data exchange need to be well maintained.

The data management API is used to access files and allows for the up- and download of any file type. That means other than 3D-objects, that are the primary use-case, we can also exchange metadata like XML-files containing process parameters in our case.

We implemented a mediator between client software and cloud API connection. The Integration of software components is therefore kept independent from the backend for data transfer, which in turn can mostly be updated and maintained independently of the used software client. The mediator manages the authentication and data buckets on its own.

As the uploading and downloading side run on different machines, the server side keeps track of changes. Updates are checked for in regular intervals and can therefore be scheduled for multiple users and user dependent cloud data. The server updates the simulation feedback if there have been changes and calculation time was allocated.

In addition to the basic storage services the Forge cloud offers some features specifically aimed at 3D-modelling. Therefore Model Derivative API can be used to convert between Computer Aided Design (CAD) data from different file types. The sometimes resource-intense conversion is done in the cloud. Almost any file type used in 3D-modelling can be converted to .svf and then be viewed in a conventional web browser. With the viewer provided users can navigate around objects without the requirement of installing additional software. Additionally through the integration of process simulation. Design preview after the actual fabrication can be visualized, using this software and platform independent web interface.

4 Towards Cloud Robotics

Connecting process simulation through a cloud based interface creates further scalability of a Web-to-Real approach. It allows the seamless creation and transfer of CAD as well as process parameters within the following sections the impact for fabrication will be described. There are a number of formats for CAD data available, this information can be linked to fabrication parameters through CAEX or other XML formats [3]. Diagnostics of process execution can in turn be documented either through XML or csv data. With our approach we allow for a simulative feedback from the cloud, enabling a loop that allows for a verifiability of fabrication for complex systems. However for security reasons it is not advisable to directly connect the fabrication to the Internet. Therefore a multi-tiered approach is taken. While the user input is only linked to the simulation of the fabrication path through a public cloud, the operator of the robot has final say in process execution. However through a private cloud the fabrication information provided by the user can directly be employed. Figure 3 illustrates this approach.

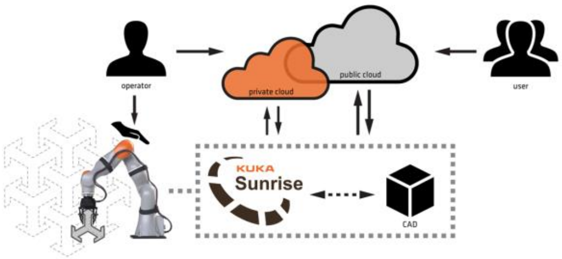

Figure 3. Enabling cloud robotics through a multi-tiered approach.

4.1 Production Immanent Design

Most commercial software for robot programming and simulation are modeled after a position teach-in process of robotic arms. Digital models are placed in 3D space and the robot’s positions are recorded. These movement component can then be coupled with logic components to handle subprograms, loops, conditionals and etcetera. This is oriented on most computer programming languages and creates a widespread interface and a good reproducibility. However this creates challenges with smaller lot sizes, where the programming makes up an increasingly large part of the costs of the final product. This is exacerbated in the construction industry, where complex, free-formed buildings can consist of countless individual parts. However these individual parts are often based on a single, global topology that is then adjusted to fit the local conditions. Rather than manually drawing hundreds of individual panels, parametric design software today allows architects and designers to create a single, parametric model that can be dynamically fitted to the local conditions. In previous research we have developed software tools that allow us to directly integrate the fabrication logic into the same parametric model that controls the geometric shape of the model [4]. Thus, whenever a parametric object is adapted to new local conditions, not only its geometry but also its construction logic updated. This enables immediate robotic fabrication. Parametric robot control [5] employs this approach. Using visual programming languages as a basis for the simulation of fabrication with analytical feedback for reachability and producibility in the process. This process can be implemented through visual programming environment for parametric design built upon CAD software. The main advantage of visual programming for parametric design lie in its accessibility, modularity and visual representation [6], specifically for users without a technical background. Rather than typing code, the user simply picks components from a large library that comes with the software and immediately gets a feedback in the form of a 3D representation. Components perform mathematical or geometrical operations, taking inputs data on its left side, and outputting the results on the right side. Parametric relationships are defined by linking components with each other, thus creating an increasingly complex directed, acyclic graph. Parametric robot control expands upon this visual programming environment beyond parametric design by integrating a series of components that allow the programming and simulation of robotic arms through a plug and play environment. The robotic process planning can therefore be directly linked to the parametric design components that define the local form of a global construction component. The collected parameter therefore directly influence the fabrication process through what we refer to as production immanent design [7] creating a constant fabrication feedback.

Simultaneously these parameters directly inform the fabrication strategy which in turn allows for mass customization, automatically writing new robot control files each fabrication part. Through new interfaces developed for Industry 4.0 the adapted tool path can directly be transferred to the robot via an Ethernet based interface, which was originally developed in order to allow process control via a Programmable Logic Controller (PLC). This is especially useful for applications that are inherently repetitive, such as simple manipulation of objects with e. g. subtractive or additive methods. The mxAutomation interface for KRC4 KUKA Robot controllers as well as our implementation of a similar interface for the new KUKA sunrise controller therefore allow the direct execution of new fabrication logics. Simultaneously the visual programming environment enables testing methods for the fabrication-steps and the individual evaluation of each produced part.

Most Computer Aided Manufacturing (CAM) software allows for the path generation of gantry kinematics based on CAD. However in this case fabrication parameters are often connected to specific motion commands and not to a parametric design model. Fabrication with articulated robot arms increases the complexity while simultaneously allowing the fabrication of new geometries as well as surface aligned fabrication.

CAD is by now a standard practice within Architecture Engineering and Construction (AEC) industries. CAD models encompass different degrees of detail ranging from simple geometric models, over Meta data pertaining to materials and part spacing, towards intelligent objects containing parametric digital models that allow immediate dimensioning of objects according to the required specifications. Through this parametric robot programming we are able to employ this information directly to fabrication processes, linking geometry and fabrication process. In parallel these parameters can in turn be used in order to visualize fabrication constraints as a user feedback. Additionally fabrication results are send back to the user via a web interface allowing an immediate visualization of the process result for verification as illustrated in figure 4

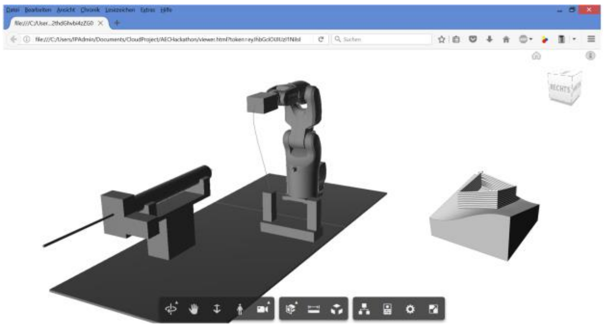

Figure 4. Process results as well as the production environment visualized through a web viewer.

4.2 Software Integration

The first implementation of upload, download as well as visualization of the simulation prediction through the web browser were implemented using components within the parametric design tool Grasshopper which runs as an extension to the CAD Software Rhino 3D. Additional data can be added using the json format.

The approach was then transferred and implemented within the parametric design software Dynamo, which can be used as the standalone version Dynamo Studio or as an extension to the BIM software Revit. Similar interface components were created to connect the components with the same data mediator program.

The viewer html file used to display geometry in the web browser is stored locally whilst the object it displays is stored in the cloud. So, when opening the html file in the web browser we need to provide it with the objects storage urn in the cloud and a token, which authorizes the client to view the design preview. As the location of the viewer does not change most modern web browsers tend to cache the information. This can in turn lead to difficulties within displaying the updated cloud model.

Figure 5 illustrates the setup for the cloud integrated robotic simulation as well as the associated fabrication process.

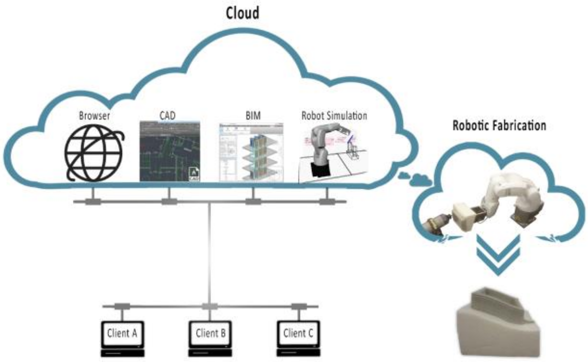

Figure 5. Framework structure for the cloud integrated Robotics approach.

4.3 Parameter selection

The current cloud integration allows us the exchange of parametric design files containing the parametric constraints. However this is currently not fully integrated and requires the informed design from the integrator or operator of the fabrication system. Therefore Design relevant parameter are selected by the Integrator of the robotic process. An exemplary interface for this design process is illustrated in Figure 6.

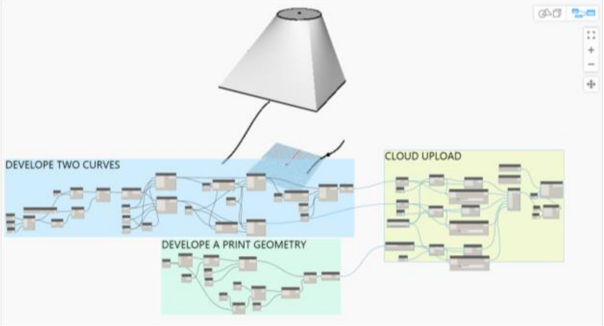

Figure 6. Parametric design input for fabrication through subtractive (Surface curve description) and additive processes (CAD).

Additionally Figure 7 shows the resulting data for the parametric robot process planning for a combined subtractive and additive fabrication process.

Within future work the selection of the design relevant parameters will be generalized allowing the automated generation of a web to real interface, while simultaneously allowing CAD design through multiple common design tools. Additionally a further integration of BIM parameters is planned for in order to achieve a full utilization of BIM data for fabrication.

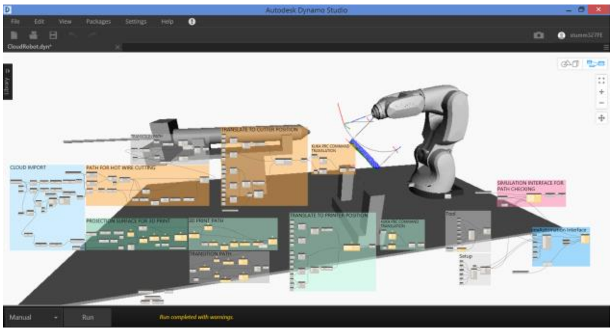

Figure 7. Parametric robot process planning through cloud imported data on an exemplary combination of a subtractive and additive fabrication process.

5 Distributed Design

While current architectural work is still often seen as a hierarchical and sequenced approach, employing cloud provided data for fabrication allows to increase the possibilities for a collaborative work environment.

As part of the AEC Hackathon in Munich we were able to test this approach for the first time. Enabling students to design parts as well as enabling them to program the robotic process directly through a parametric robot programming interface. While the design of elements through predetermined parameters seemed easy to grasp. Planning fabrication processes, while keeping in mind the constraints of the fabrication environment required significantly more time. Figure 8 shows the setup at the AEC hackathon in Munich.

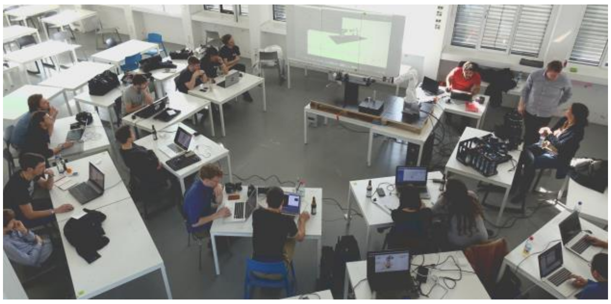

Figure 8. Setup at AEC Hackathon in Munich

However making a Fabrication environment accessible to others can possibly reduce downtime for customized production without the requirement for mass production. Figure 9 illustrates the cloud integrated fabrication process.

Figure 9. Robotic system Demonstrating additive and subtractive fabrication.

6 Synopsis

Through our interface we created a first proof of concept for cloud based robotic fabrication. However this approach was only test based on a short process chain, which contained a subtractive as well as an additive fabrication process.

Our future work will focus towards a full parameter integration within the web interface, which reduces necessity for parametric design experience from the user's point of view. While this approach is feasible for fabrication processes, robotic systems enable a very high number of processes. Therefore another focus of our future work will be on the integration of assembly skills, as well as our developed strategy for adaptation and information collection through haptic robot programming [8]. Figure 10 illustrates the planned integration for the Interactively & Dynamically Assisted Assembly (IDAA) Project.

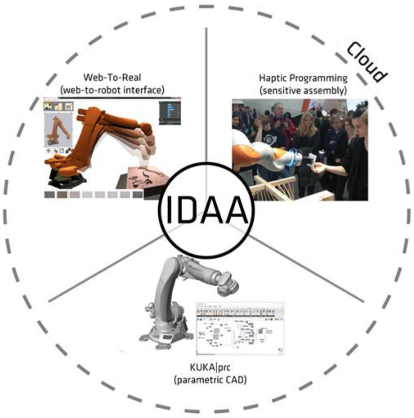

Figure 10. IDAA integrating parametric design, cloud robotics with human robot collaboration.

In conclusion the approach of making individualized robotic fabrication accessible through a cloud based interface has the potential to enable new distributed design opportunities as well as new forms of product commissioning.

Acknowledgements

The developments presented within this paper were made possible by Autodesk and the Forge Research Grant Program.

References

[1] Eastman, C. and Teicholz, P., Sacks, R., Liston, K.: *BIM Handbook – A Guide to Building Information Modeling for Owners*, Managers, Designers, Engineers and Contractors. Wiley; 2011.

[2] Stumm, S.; Neuhaus, M.; Braumann, J.; Brüninghaus, J.; Brell-Cokcan, S.: *Web-to-Real Application for Artistic Robotic Surface Processing of Natural Stone;* 33rd International Symposium on Automation and Robotics in Construction (ISARC 2016)

[3] R.Drath Datenaustausch in der Anlagenplanung mit AutomationML: Integration von CAEX, PLCopen XML und COLLADA. VDI-Buch. Springer, 2010.

[4] Braumann Johannes; Brell-Cokcan, S.. *Visual Robot Programming – Linking Design, Simulation, and Fabrication*. 2014.

[5] Braumann, J. and Brell-Cokcan, S. *Adaptive Robot Control - New Parametric Workflows Directly from Design to KUKA Robots*, In: Real Time - Proceedings of the 33rd eCAADe Conference, pages 243–250, volume 2, 2015.

[6] Davis, D.J.B., Burry, M. *Understanding visual scripts: Improving collaboration through modular programming*. International Journal of Architectural Computing 2011; Vol.9: pp.361–375.

[7] Braumann Johannes; Brell-Cokcan, S.. *Robotic production immanent design: Creative toolpath design in micro and macro scale.* CADIA 2014: Design Agency, Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture 2014; pp.579–588.

[8] Stumm, S. and Braumann, J. and von Hilchen, M. and Brell-Cokcan, S., *On-site robotic construction for assembly using a-priori knowledge and human robot collaboration*, IFToMM/IEEE/euRobotics 25th International Conference on Robotics in Alpe-Adria-Danube Region RAAD (2016)