

Breaking Down Brick Walls: Design, Construction, and Prototype Fabrication Knowledge in Architecture

ABSTRACT

Architectural designs are not just collections of 3D objects. Architects have both high-level aesthetic design intent, and intent for the functionality of the building; these must eventually translate into real-world construction materials and processes. Physical prototypes are still essential for the architect and their clients to get a feel for whether designs “work”. An exciting recent development in architecture is the use of industrial robots to automatically construct 3D prototype architectural models. But programming the robots requires tedious procedures of low-level commands, far removed from the designer’s intent.

Adeon is a system that integrates high-level architectural design knowledge, including aesthetic and stylistic intent, with knowledge about materials and construction processes, and robot programming code for constructing prototype 3D physical models. It centers around collecting and associating “common sense” knowledge, expressed in English and converted to a knowledge representation about the various levels. It provides a graphic editor that allows architects to draw high-level aesthetic designs, perhaps referencing known styles or historical examples, and retrieving relevant construction, materials, and cost information. It automatically produces a robot program for constructing the prototype. We present examples detailing the design of various styles of brick walls. Adeon is an

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interesting example of how to provide an interface for creative work that spans both high-level and low-level concerns.

Author Keywords

Commonsense Reasoning, architecture and design, digital fabrication, robotics, goal oriented interfaces, architectural design tools and methodology

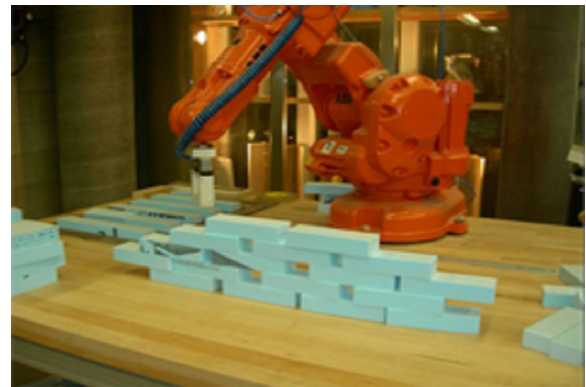


Figure 1. The IRB-140 robot arm stacking blocks.

1. INTRODUCING ADEON

In this paper, we present ADEON, an architectural design application that interfaces with a digital fabrication device: a “pick and place” articulating robot arm for constructing architectural models, the IRB-140 (Figure 1). The global objective of ADEON is to bridge the gap between design, construction, and prototype fabrication knowledge. We use a “common sense” knowledge base that contains knowledge at all three levels, and provides automatic integration of relevant knowledge for a particular design.

The goals of ADEON include:

- a) A simple to use graphical editor for sketching architectural ideas.
- b) Retrieval and display of design, construction, and prototype fabrication knowledge relevant to the design being drawn.
- c) Provide cost estimates and material usage estimates for the design drawn in the editor.
- d) Translate user drawn information in the design editor to machine readable code for the prototype fabrication robot.

The robot explored in this research is a five axis articulating arm, the IRB-140, used primarily for cutting and assembling blocks of foam construction material. In this research, the robotic arm picks and stacks brick-sized blocks.

Conventional software design tools do not exhibit knowledge of the design situation at hand. If a user is confronted with designing a wall system in a two-dimensional CAD drafting environment for example, CAD does not know that the design intention is perhaps a wall of linear dimensionality, placed in the context of a residence or maybe a museum. The proposed system assists the user based on live textual and graphical feedback about the feasibility of construction and machine fabrication technique.

Adeon is a prototype for our methodology of connecting knowledge across the different levels. It is not, at present, a general-purpose architectural design system. Our goal was to show that we can provide an end-to-end system for capturing knowledge at all levels from vague sketches where the concerns are mainly aesthetic, all the way to machine code for programming a robot constructing architectural models (and perhaps in the far future, robots actually performing final construction).

As such, it was necessary to limit the scenarios we were working with, so we could collect an adequate amount of design and construction knowledge appropriate to the scenario, and to tailor the system to a particular fabrication device, the IRB-140 robot. We chose to focus on a particular set of design scenarios, constructing different types of brick walls. Though brick walls are conceptually simple, there many examples of aesthetically innovative and historically important brick wall designs (some of which we will explain in detail). We also chose this domain to simplify the prototype fabrication step (though it still leaves plenty of room for problems to happen!). Expansion to other architectural domains and other fabrication techniques is possible with additional efforts in knowledge collection.

More generally, we think systems like Adeon can show the way towards providing systems that integrate both high-level and low-level concerns, in a variety of fields beyond architecture. Designers of consumer electronics devices such as phones or music players, for example, must think both about the industrial design aesthetics, the functionality, manufacturing, and the cost of devices. We believe that one of the essential elements of creativity is to be able to play with high-level and low-level concerns simultaneously, and flexibly go back and forth between them.

2. CONVENTIONAL METHODS FOR PROTOTYPE FABRICATION

While architects are excited about the prospects of using industrial robots for prototype fabrication, conventional methods of doing so involve many disparate steps in order to complete an end-to-end process from conceptual design to prototype fabrication. Many of these steps must be done manually, repeated for each design iteration or change. Low-level knowledge of arcane languages, operations and feature sets is often necessary. They involve several incompatible hardware and software interfaces and data formats. The complexity of these processes often serves as a barrier to non-experts, and is error-prone even in the case of experts.

In a typical conventional process the major elements may include:

- A Computer-Aided Design (CAD) software environment,
- A Computer-Aided Manufacturing (CAM) software environment (e.g. the proprietary EZ-CAM),
- A hardware interface to a Computer Numerical Controlled (CNC) fabrication machine. A CNC machine is used to mill two-dimensional physical artifacts based upon exported CAD geometry.
- Software CNC interface (e.g. Techno CNC).

Take for instance, fabricating an architectural artifact using a Computer Numerical Controlled (CNC) machine. We counted a total of twenty-seven distinct steps in the complete workflow. To give a taste, we present part of a typical sequence with the Techno CNC software:

1. Send machine to pick up tool – Tool Change = 5 (equivalent to 1/8" router drill bit)
2. *Optional (often mandatory) – Physical simulation, set tool head Z-axis above material and trace milling path.*
3. Control axis of CNC machine to user origin using arrow keys.
4. Set drill bit head on stock material using +/- keys.
5. On Techno Interface – set user origin, Zero>ALL
6. Open G-Code file > Preprocess
7. Hit Start 3 times.
8. End milling process (Did product mill correctly? i.e. Did it mill according to desired outcome? If not, proceed from Step 1.)
9. Send machine to put back tool in carriage –Tool Change = 0.
10. Send machine to origin –Home>ALL

The several steps to conclude at a satisfactory end product is sometimes left to chance. The unpredictability in using digital design fabrication tools are attributed to the variability in stock materials, maintenance of machining tools, as well as humidity and temperature of the work environment. The inconsistency in the end product can either prove positive or detrimental depending on the working environment.

We see developing an end-to-end workflow as an important factor in democratizing access to seamless experimentation for designers.

3. ADEON'S SYSTEM ARCHITECTURE

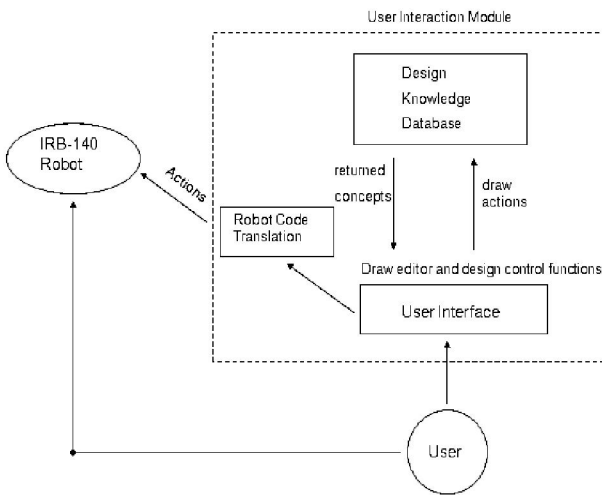


Figure 2. System architecture

The heart of Adeon's architecture (Figure 2) are knowledge bases that encode three types of architectural knowledge.

- *Design knowledge.* This is very high level knowledge about the aesthetics and design of buildings. Examples appear in Table 1. The knowledge may reference particular historical or personal examples, or recurring techniques or design elements that serve as inspiration for designs. While this kind of knowledge may at first seem vague and difficult to represent, and far removed from the concrete details of construction, it is very important to collect such knowledge. While not all of it may prove relevant in a given design, we are always looking for opportunities to connect it to the more concrete knowledge. One reason to do so is that there are many concrete ways to realize a given design intent; if a particular design element proves to be infeasible or unaesthetic, the same intent may be able to be accomplished in some other way. Part of the value is to be obtained simply from juxtaposing the concrete design with relevant design knowledge so that the designer is reminded of it.

- *Construction knowledge.* It is not sufficient to display a finished design; the design must eventually be able to be constructed in the real world. Knowledge of construction techniques, such as materials and cost, keeps designs realistic, and eventually will aid in planning construction. Often, what appear to be simple changes in design will have complex impact upon construction. It is important for the designer to be aware of these impacts. As with the design knowledge, establishing the connection between a concrete design and relevant construction knowledge in itself helps the designer.

- *Prototype fabrication knowledge.* In order to produce the prototype architectural model, knowledge of the robot's operation is necessary. We try as much as possible to abstract away from details irrelevant to the designer's intent.

Our approach to collecting knowledge of all three types is rooted in our work on Commonsense knowledge. By Commonsense knowledge, we mean simple knowledge that is "common" either to everyone, or to a more specialized group (in this case architects). It is that knowledge that usually does not have to be explicitly communicated, because it can be assumed that everyone in the community is likely to have that knowledge already.

Unlike work in Expert Systems, or the Semantic Web, or other knowledge collection efforts, we collect knowledge in the form of natural language statements. There is no requirement to encode the knowledge in a mathematical form, a programming language, or in terms of a precise ontology, making it easy for nontechnical architectural practitioners to provide the knowledge.

In the following, we start by explaining our general approach to Commonsense knowledge, Open Mind Commonsense, and then talk more explicitly about the three kinds of architectural knowledge.

3.1 Common Sense Knowledge and ConceptNet

Adeon relies on the Open Mind Common Sense knowledge base (<http://commons.media.mit.edu>) and the use of ConceptNet (<http://conceptnet.media.mit.edu>), the semantic network used to create intelligent applications developed by the Software Agents Group of the MIT Media Lab.

The Open Mind Common Sense (OMCS) Project is a web-based interface that allows contributors over the web to input common sense, or shared knowledge amongst individuals, into a database to teach machines what people would normally accept as common knowledge. To date, there have been over 13,000 people contributing over 800,000 sentences, since September 2000 [1].

ConceptNet is a semantic network, created from Open Mind [2] that "encompasses the spatial, physical, social, temporal, and psychological aspects of everyday life through a semantic network that contains 1.6 million assertions" [2]. ConceptNet is produced by parsing the

original Open Mind sentences, and pattern matching for a set of distinguished relations (explained further below) that embody the majority of the knowledge expressed.

3.2 Collecting Specialized Common Sense

OMCS currently does not contain specialized common sense knowledge such as information that architects and experienced digital fabrication machine users may know. The integration of architectural knowledge begins by gathering a corpus of architectural “common sense” that a computer would need to know about designing, constructing, and assembling objects with the IRB-140.

An attempt to do so begins by analyzing the three case studies of traditional and non-traditional uses of brick in architecture. The buildings that serve as case studies are 1) Louis Kahn’s Philips Exeter Library, 2) Atlantida by Eladio Dieste, and 3) Gramazio and Kohler’s Gantenbein Winery. Table 1 illustrates the process of analysis for Philips Exeter Library. The table illustrates a phase where the case study observation undergoes a reformulation to befit the Open Mind Commons form.

LIBRARY AT PHILIPS EXETER ACADEMY
ARCHITECT: LOUIS KAHN
TRADITIONAL BRICK ARCHITECTURE

Design Knowledge IRB-140 Knowledge	Construction Knowledge
Louis Kahn can design brick walls. (CapableOf)	An exterior brick wall wants to be designed for stopping water ingress from melted snow, rain, and ice. (Desires)
Brick is a type of load-bearing material. (ISA)	Something you need to do before you lay bricks is to mix mortar. (HasPrerequisite)
Philips Exeter Library is designed in brick to keep with the traditional New England campus. (HasProperty)	Hand mixing mortar requires masonry cement, sand, clean water, mortar box, mortar hoe, square point shovel, and a bucket. (HasPrerequisite)
Philips Exeter Library is a brick building designed to keep with the traditional New England campus. (ISA)	Mortar is created by mixing masonry cement, sand, and clean water. (CreatedBy)
The Philips Exeter Library is the building designed by architect, Louis Kahn. (DefinedAs)	The first thing you do when you prepare mortar is place the bag of mortar inside a mortar box. (HasFirstSubevent)
Philips Exeter Library’s brick piers are wider nearer to the ground where their loads are greater. (HasProperty)	One of the things you do when you have mortar in a mortar box is to divide the mix in half. (HasSubevent)
The brick wall is interspersed with apertures for windows. (HasProperty)	One of the things you do when you divide mortar mix in half is spread sand on top of the mortar cement. (HasSubevent)
You would put openings in a brick walls because you want a door or window. (MotivatedByGoal)	

Table 1. Case study observations of Philips Exeter Academy Library

The table demonstrates the use of the eighteen OMCS relations, highlighted in bold, necessary to form sentence structures for the OMCS database. For example, “Brick *Is A* type of material” which falls under the relation “Is A”; the eighteen relations function as a textual form for web users to formulate concepts to teach the computer. In essence, the extraction of design, construction, and prototype fabrication

knowledge are broken down into initial base descriptions. Figure 3 illustrates the filtering process of architectural knowledge for the Gantenbein Winery by Gramazio and Kohler.

An example break down of Case Study 3: Gantenbein Winery

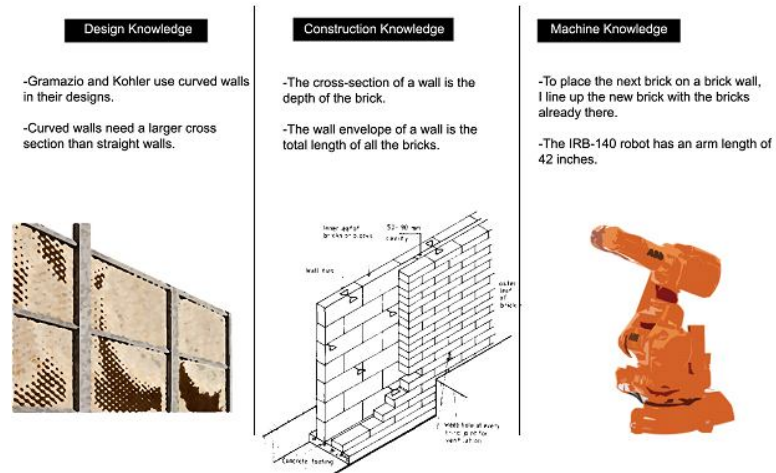


Figure 3. Design, Construction, and Prototype Fabrication Knowledge

The three types of knowledge, once inserted into the Open Mind Commons database, form a semantic network from which ConceptNet, can extract the assertions. The semantic network (Figure 4) for Case Study Three, illustrates how concepts such as “curved walls” or “IRB-140” form nodes and connect to other nodes via OMCS relations (i.e. CapableOf, HasProperty, and so forth).

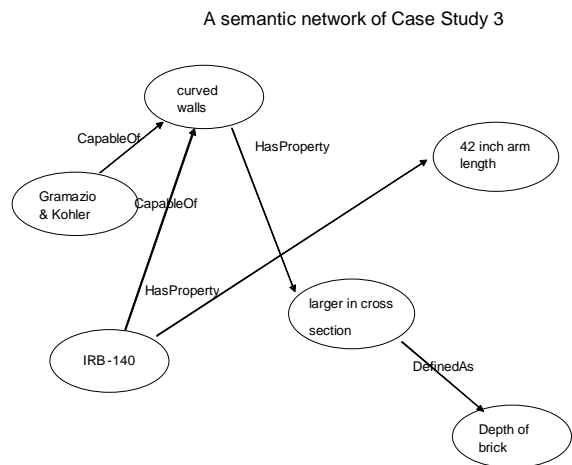


Figure 4. A semantic network of the Gramazio & Kohler wall.

4. DESIGN SCENARIOS WITH ADEON

A user instantiates Adeon through a graphical user interface containing a draw editor for creating brick walls with the option of three different geometrical configurations: vertical, inclined, and curved walls. The three geometric wall selections serve as initial test options for the user to engage with, leaving an opportunity for further types of wall creations containing complex geometry into future versions of Adeon. While the user is drawing/designing a brick wall, the system Adeon, recognizes the type of wall configuration and displays relevant design, construction, machine, and cost information pertinent to the type of wall drawn onto the editor and in turn, transforms that design into readable machine code for digital fabrication. Currently, Adeon interprets user drawing sketches upon the draw window and returns design, construction, and machine data in natural language text.

4.1 Design Scenario I: Vertical Brick Wall

Suppose an architect would like to design a vertical brick wall using the pick and place robot, IRB-140. The user instantiates Adeon and selects the vertical wall design tool available on the Graphical User Interface (Figure 5). As the user is drawing a vertical wall, the system updates itself to reflect the current costs of total units per brick used in the design, total brick count, and lastly design, construction, and prototype fabrication knowledge (Figure 5c). Upon completion of the vertical brick wall within the editor, Adeon displays the estimated total cost of units per brick as well as total bricks used in the design. The cost suggests the use of a modular brick unit at the rate of \$0.39 per block. Three text windows also display three types of knowledge relevant to the current design.

The “Design Knowledge” window informs the user in the vertical wall design example: *You would want to use brick as a building material because you want the aesthetic of having the forces of gravity and weight to be evident in the construction.* The Design Knowledge window outputs a sentence that articulates design at a level of aesthetic reasoning, where “forces of gravity and weight” are meant to imply brick as a visually heavily weighted object. Design knowledge at this level of abstraction describes a relationship between a visual representational figure and a rhetorical one. In T. Knight and G. Stiny’s *Classical and Non-Classical Computation*, verbal representation “is the kind...we use all the time to communicate to each other...and to conduct most of the affairs of the day” [3] Despite the division between the verbal and visual representation, both representations form an interconnected relationship [3] dependent upon one another.

Adjacent to the “Design Knowledge” window on the graphical user interface is the “Construction Knowledge” window. In the vertical wall design example, the output under construction knowledge reads: *Loadbearing walls should be aligned consistently from floor to floor and should be continuous from the roof to the building foundation.* This particular knowledge reflects a design intention for the creation of a load bearing wall system, and directly indicates valuable information for designing in the situation that the designer may otherwise overlook. If the walls were *not* aligned from floor to floor and from roof to building foundation, then the resulting configuration becomes a partition wall without shear dependency. The functional requirements of a brick wall is given by Adeon’s “knowledge” repository and access to the basic information for understanding building construction, this allows the user to make informed design choices based upon Adeon’s output consultation.

The remaining window, “Robot (Prototype Fabrication) Knowledge” also displays pertinent textual information regarding the design of a vertical brick wall relative to the digital fabrication machine itself. The “Robot Knowledge” window box displays, *IRB-140 can accommodate the design within 50 to -230*

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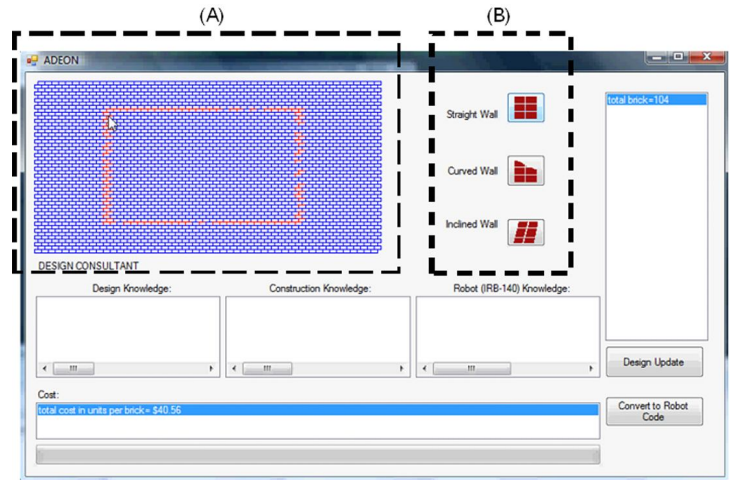


Figure 5. (a) Drawing a straight wall in the draw editor, by (b) selecting the “Straight Wall” tool.

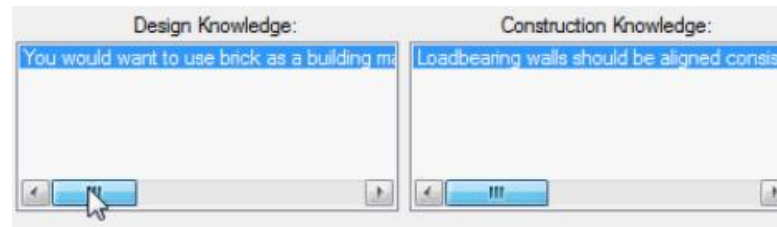


Figure 5c. Resulting knowledge feedback from drawing the straight wall into the draw editor.

The resulting design from the draw editor translates into machine readable code where the IRB-140 executes the straight wall design as seen in Figure 6.



Figure 6. Vertical wall configuration as performed by the digital fabrication device.

4.2 Design Scenario II: Curved Brick Wall

Should the designer decide to switch from designing a vertical to a curved wall instead (Figure 7a), the system recognizes the switch in tasks and is capable of relating pertinent information to the new design scenario.

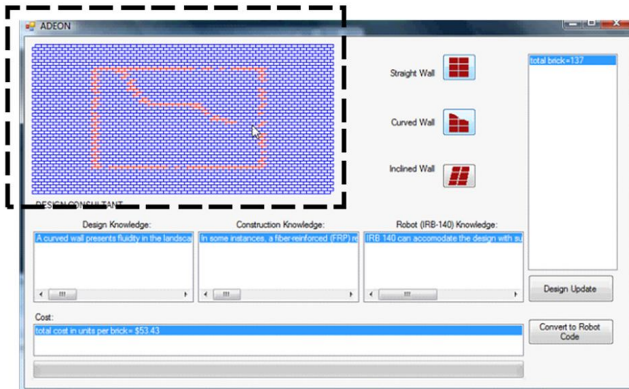


Figure 7a. Drawing a curved wall in the draw editor.

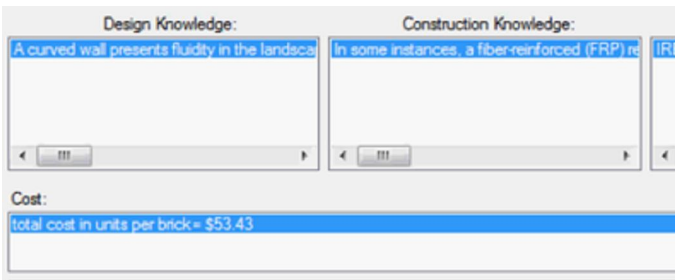


Figure 7b. Updated knowledge feedback window on curvilinear design

Upon the new curved wall design, the Design Knowledge label box now reads, *A curved wall presents fluidity in the landscape. An example of this is Atlantida by Eladio Dieste where walls are generated by straight line segments whose ends were translated along a sinusoidal path.* The

Construction Knowledge labelbox, also updated, now advises: *In some instances, a fiber-reinforced (FRP) rebar is used for highly specialized brick work because of its high tensile strength and light weight, corrosion resistance and dielectric (nonconductive) properties.* Lastly, the Prototype Fabrication Knowledge box reads, *The IRB-140 can accommodate the design with a supplementary load at 32 inches reach of the 5th axis* (Figure 7b). Along with this, total costs of bricks per unit and bricks used for the design also display updated information. The result as performed by the IRB-140 lends to the following illustration in Figure 8.

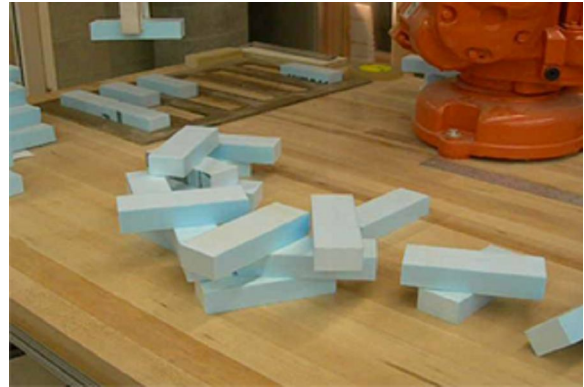


Figure 8. A curved wall assembly as performed by the IRB-140.

5. EVALUATION

To date, we have not conducted a systematic usability study with the Adeon prototype. We realize that, for not-so-well defined problems like architectural design, there are few standardized tasks or objective performance measures. Individual variance in working styles is high. We would like to be able to treat a greater range of design choices and collect a more extensive knowledge base before attempting head-to-head comparisons between Adeon and more traditional sets of architectural design and fabrication tools.

However, there are several ways in which we have verified that Adeon is grounded in real architectural practice. First, the case studies were carefully chosen to be representative of design problems treated in the architectural literature and architectural education. Most importantly, rather than being constructed by hand, the architectural knowledge base is collected from architectural practitioners. Almost all the design and construction knowledge is deemed plausible by independent observers, and retrieved knowledge shows good relevance to proposed designs. Finally, we verified that, for these domains and the range of examples studied, we can take representative designs down to correct robot programming code and produce faithful models.

6. RELATED WORK

The use of robotic technologies for building construction has gained prominent use in Japan. The use of robots in construction presents a not so distant future of automation and the potential advancement of robotic “common sense reasoning” approaches to the design and building construction process. The SMART System by Shimzu Co. located in Japan, uses advanced computer automation at a grand scale in the construction processes, unifying underground work, steel erection, finishing, and equipment work to erect multi-story buildings. The SMART system utilizes prefabrication, computer, and robotic technologies:

The *SMART* system uses an automated erection system, which provides shelter for the work environment, to construct individual floors. The erection system uses overhead gantry cranes to install steel columns and beams on a floor, and then uses hydraulic jacks to move up to the next floor. The erection system grips previously installed columns in order to lift itself to the next floor. Shimizu expects the *SMART* system will decrease labor dependence and shorten construction duration [5].

The description of robots completing the construction of a building at a massive scale not only demonstrates an alternative construction automation process, but exemplifies how traditional on-site construction methods can be potentially outperformed by the advances in robotic automated technologies [6]. The development of ‘common sense reasoning’ for robots serve as an essential component for the creation and improvement of intelligent robots in context based reasoning.

6.1 Fabricating a Speculative Facade

In a digital design fabrication experiment [7] used to create a speculative façade at MIT, the undertaken linear manufacturing process had resulted in inconsistent physical results. Several machine and software factors lead to variable and often unstable product results. The unpredictability in using digital design fabrication tools are attributed to the variability in stock materials, maintenance of machining tools, as well as humidity and temperature of the work environment. The inconsistency in the end product can either prove positive or detrimental depending on the working environment.

Empirical testing reveals that press-fit assemblies rely on specific material properties and precise fabrication tolerances in order to sustain a rigid connection between elements [7]. However, different materials displayed varying behavior at different scales, making it difficult if not impossible to predict possible changes in material behavior at different model scales and what that would mean in terms of model assembly and the efficacy of the friction joints. Ideal scenarios were

achieved with cellulose-based materials (plywood and masonite) that allowed for slight material deformation during assembly. Attempts at similar assemblies with aluminum proved less successful due to the inelasticity of the material. The most successful press-fit joints that were achieved in aluminum were “slot” connections which provided an equal amount of supporting material on each of the mating pieces [8].

With the variability in material, recursive steps contribute a long and arduous process to conclude with a satisfactory product. The steps required to reduce this process is not mentioned, but a need for closing the distances between the designer and machines are of necessity.

DISCUSSION

The use of the IRB-140 together with Adeon, currently demonstrates a one-way relationship where the IRB-140 interacts with Adeon *after* a design has been drawn onto the editor for machine readable interpretation. A future implementation is to let Adeon and the IRB-140 to demonstrate a two-way relationship instead, where the IRB-140 interacts with three dimensional spatial design and can reflect/output its understanding of assembly and the particular idiosyncrasies that can occur during production (Figure 9).

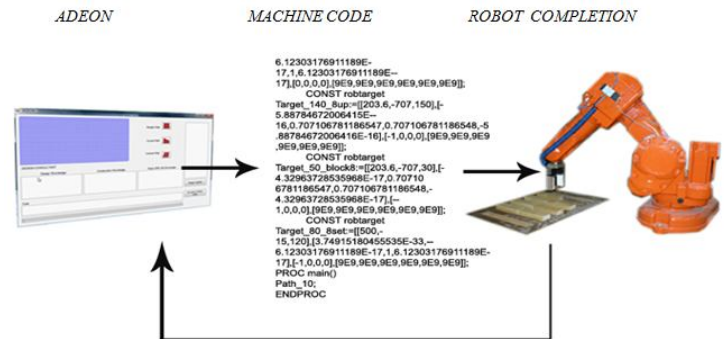


Figure 9. With vision-cam, the robot can deliver live information feedback to Adeon.

A two-way relationship between Adeon and the IRB-140 can be brought possible by implementing robot vision-based processing, where the IRB-140 can scan its environment during production assembly and recognize anomalous qualities about the artifact.

Further development includes placing Adeon onto a central server for architects and designers to use as an online consultant. Designers can update knowledge via user input that directly interfaces with the Open Mind Common Sense database where resourceful information associated with the current design context for production can be easily accessible.

CONCLUSION

The challenges designers face when using machines occur when tasks are not properly understood by the machine, or when a machine misinterprets a designer's intentions. Currently, the means for remedying this type of encounter demands the user to do any of the following: summon technical support, resort to technical manuals and/or online support forums, or in some cases, hire a consultant. Whether or not this proves as a barrier to the progression and development of a project, machines require the capability to integrate and adapt itself into understanding common design practices; to collaborate as an active agent in various field processes. This research looks to make that possible, offering a contribution on how architects can relate differently with machines and extend to the initial formations for a collaborative approach. Our machines, as Rodney Brooks puts it, present themselves as an external reflection of the biological [4]. If this is true, then our machines as design tools are an extension and expression of that biological nature in ultimate creativity.

ACKNOWLEDGMENTS

We thank Terry Knight of the...and Martin Bechthold of the ...at....

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