ABSTRACT
While robotic tools have greatly expanded the scope of computational control and design freedom in architectural assembly, the vast majority of projects involving robotic customization depend on standardized, mass produced components. By relinquishing some design agency to automated systems which respond to on-site material variations, it is possible to produce methods of construction which rely on locally-sourced components with low embodied energy. Such adaptive automation can provide resource efficiency and the aesthetic advantages of natural or reclaimed materials, but can also beget technical challenges of increasing complexity. By expanding design goals to incorporate intuitive collaborative interfaces, technical gaps can be understood even by non-experts, and leveraged towards new forms of creative expression.

This paper presents the results of an interactive installation in which visitors can provide any variety of objects to a collaborative robotic manipulator (UR5) which recognizes part geometry and attempts to construct a dry-stacked wall from the material offerings. A visual and auditory interface provides suggestions and error messages to participants to facilitate an understanding of the acceptable material morphologies which can be used within the constraints of the system.
INTRODUCTION
The coupling of parametric computer-aided-design tools (CAD) with robotic fabrication equipment has enabled the materialization of designs with previously unfathomable levels of complexity and variation. However, these tools have conventionally been used in linear processes which transition digital designs unidirectionally from geometric models into tangible form. The high precision of robotic actuators and digital surveying tools have created a widespread adoption of “zero tolerance” design strategies, where little affordance is allowed for variation between the digital designs and material outcomes (Sheil 2014). This increasingly obstinate expectation of exactitude on the part of architects has come at the cost of embodied energy, resource efficiency, on-site improvisation, and the aesthetic advantages of naturally- and regionally-variable materiality.

By leveraging the adaptability of robotic systems, it is possible to develop an alternative to practices which create variation from standardized components, and that instead employ the variations found in naturally-produced raw materials, waste products and reclaimed building materials (rubble, salvage, etc.). By using CAD interfaces to provide only general design guidelines, designers relinquish some level of a priori architectural authority but gain immensely from the shift of some design intelligence onto the construction site. Building with nonstandard materials which are locally abundant provides the architectural benefit of reduced transportation and manufacturing energy (unprocessed rock and recycled aggregate exhibit very low embodied energy when compared to conventional building materials)(Alcorn 2001) while also reducing the heavy-handed appearance of computationally-varied geometry. The use of site-specific or regional materials such as manufacturing waste, architectural salvage, or refuse can also increase local cultural sustainability by exhibiting a cross section of regional trades, local industry, architectural history, and consumer trends.

This paper presents an ongoing research endeavor into robotic construction using irregular materials, which was implemented as an interactive installation as part of the 2017 Seoul Biennale of Architecture and Urbanism. The project allows gallery visitors to offer irregular objects (broken tiles, bottle caps, pocket detritus, etc.) to a collaborative robot, which locates these items using computer vision, and uses them to build a dry-stacked wall along a predetermined path (Figure 1). Sensors integrated into a custom end effector detect object properties, and a projection-mapped environment provides visual, textual, and verbal announcements to human participants—affecting insights for why specific objects might be unsuitable for this specific construction method (e.g., if an object is too heavy, small, or porous for the vacuum gripper to pick up, or too large to fit generally within the constraints of the designed wall). By creating an interface which is focused specifically on revealing technical and material deficiencies that would otherwise be concealed in an algorithmic black box, we provide a means by which non-experts can approach and understand robotic fabrication.

BACKGROUND
A number of notable architectural practices have reinvigorated the discussion surrounding regionalism through the adoption of reinterpreted vernacular building methods coupled with the use of low-cost, locally available materials. Relevant projects employ the tiling of architectural salvage (Amateur Architecture 2008), the repurposing of inexpensive and abundant refuse, including automobile parts and carpet remnants (Dean and Hursley 2002), and a general emphasis on local-fabrication (“lo-fab”) with regionally sourced raw materials (MASS 2015). While such projects successfully exhibit the potential of highly-localized material adaptability in design, they are also generally located in regions with relatively inexpensive, semi-skilled labor (China, the rural American South, Sub-Saharan Africa). By exhibiting methods for pairing technologically advanced sensing and fabrication tools with locally-oriented building materials, this project suggests the potential of expanding such design approaches into economies where the additional labor required to implement such projects would render them unfeasible (in comparison to large-scale construction models which reduce cost through repeated details and offsite, centralized manufacturing).

Several robotic processes have emerged within the past several years which protract the design process to enable materially-aware fabrication strategies by using digitized material properties to alter and clarify fuzzy design objectives: “Bandsawn Bands” allows the fabrication of doubly curved surfaces from live-edged wood slabs by bounding the initial design concept within the material morphospace of 3D-scanned naturally occurring geometries (Johns and Foley 2014). Similarly, the “Wood Chip Barn” exploits the potential of natural materials by employing robotic joinery and computational iteration to create a large-scale structural truss from digitized tree-fork sections (Self and Vercruysse 2017).

A number of other projects leverage robotic sensing to work with industrially produced timber components which have non-standard dimensions on one or more sides. “Stratifications” demonstrated an early example of robotic stacking using blocks of variable thickness, while...
“Interlacing” presents the interactive robotic piling of sticks with irregular lengths (Gramazio Kohler Research 2011; Dorfler, Rist and Rust, 2013). Adaptive fabrication of shingled, nonuniform wood panels is explored in the “MAS Robotic Pavilion”, and the digital surface packing of irregular, scanned wood scraps is presented in “Mine the Scrap” (Eversmann 2018; Certain Measures 2016).

Robotically produced vertical stacks of pre-scanned irregular stones have been achieved through autonomous detection and pose planning (Furrer et al. 2017). Beyond the domain of architecture, the robotic recognition and grasping of irregular objects is a widely researched problem with numerous industrial applications (Correll et al. 2016).

While many precedent projects have begun to approach the problem of materially adaptive architectural fabrication, fully automated building with found materials seems to be an infinitely expanding problem: any given solution breaks down at some point when provided with a previously unforeseen material attribute or environmental condition.

The present intention of this work is thus not to solve all the technical issues of irregular material stacking, but rather, to create an intuitive interface which enables non-specialists to explore a wide range of material types and to more clearly grasp the potential and limitations of industrial robots in building with nonstandard components. By taking the stance that full automation with every possible contingency is not the objective, we can recalibrate robotic fabrication processes to include human interventions, and our understanding of system limitations can be leveraged to creative ends.

This project makes use of the Adaptive Assembly library (Johns 2018) for Processing (n.d.), which was developed as part of an ongoing research initiative at Columbia GSAPP that focuses on experimental robotic assembly using rejected and repurposed materials. The library provides methods for computer vision, computational geometry and robotic control, and has been used for student projects in the course “Assembling All Sorts” to enable automated workflows for creating constructs from materials ranging from light bulbs to rubble, dried food, and broken glass (Figure 3).

METHODS

The setup (Figure 2) includes a Universal Robots manipulator (UR5) equipped with a custom vacuum gripper. The robot is mounted to a moveable cart which can be manually rolled to various areas along the worktable on which a wall is to be built. The cart contains a compressed air source, the robot controller, DC power supply, and a wide, slow-moving conveyor belt (controlled by the robot’s I/O). A projector provides graphic overlays to the scene which indicate what the robot is currently doing, what it sees, and...
how it is planning the wall as it builds. Projected guides also indicate the border curves of the wall-to-be and provide suggestions for the maximum- and minimum- sizes of material offerings. A touchscreen laptop with a control software (written in Processing) is connected to the robot’s controller, cameras, projector, and speakers (Figure 4).

Users can place one or more material offerings on the conveyor belt (Figure 5), and these are detected by the robot-mounted camera. The robot attempts to pick up these objects and place them correctly on the wall, making visual and audible announcements when it is incapable of completing the action. When an object cannot be picked up, or there are no objects visible for a specified duration of time, the robot advances the conveyor to make more objects visible and within reach, while also eventually dropping failed objects onto the floor at the base of the cart.

End Effector
The end effector is designed to appear as a simple extension of the robot’s wrist, but contains a dense packing of a number of functional components into a small package. (Figure 6 & 7). A spring-loaded suction cup assembly allows for intolerances in known heights when picking and placing objects. This assembly is also linked to a spring-loaded potentiometer, which registers an analog voltage to the robot’s I/O which is linearly proportional to the amount of suction-cup-carriage depression. At each picking and placing action, the robot moves downwards in small increments towards the target position until the analog voltage is changed, and the measured voltage and robot position are sent to the controlling software which uses this information to determine the object’s height.

The suction cup is controlled by a mini 24 V DC solenoid valve, and the tool contains an internal Venturi device, silenced exhaust port, and analog vacuum sensor. During “picking” motions, the robot continuously monitors the vacuum strength. If a certain vacuum threshold has not been reached while the object is still flat on the conveyor belt, an error message is sent via socket to the controlling laptop, which triggers an audible text-to-speech announcement (Gradwohl 2009) and projected notification that this object is likely too porous to pick up. If a vacuum threshold is reached while initially picking up the object, but is lost during the transfer motion, it indicates that the robot has dropped the object. In this instance, a different error message is sent from the robot to the controlling laptop, and another announcement is made: “Oops. I dropped something. I think this is too heavy.”

The tool also contains stereo cameras (deconstructed webcams connected to an internal USB split), for which the intrinsic and extrinsic parameters have been calibrated using OpenCV (2013). The tool also contains a 5 V red line-laser which is controlled by the robot’s I/O (via...
a 5 V DC buck converter), for facilitating contour recognition. However, due to the efficacy of the potentiometer in determining relevant aspects of the scene using touch alone, these vision features are largely redundant and the salient material attributes are generally obtained using only a single camera.

**Projection Mapping**

A single short-throw DLP projector is mounted overhead such that it can project directly onto most visible parts of the robot, cart, table surface, and rear exhibition walls (Figure 8). The 2D projector coordinate system is calibrated with the global 3D coordinate system (the base of the robot when the cart is as pictured in Figure 5) by creating a number of point pairs which are used to calculate the projector coefficients such that for any given 3D point, the correct projector pixel can be selected which produces a 3D ray which collides with that point (Snyder et al. 2015). We use a measured model of the environment, and a forward kinematic model of the arm to determine the 3D location of each limb in real time, and the corner points of a number of masked planar quads connected to these limbs. Axis positions for the kinematic model—and other attributes such as joint speed, force, and temperature—are streamed to the central software using UR’s Real Time Data Exchange (RTDE) for UR 3.4 (Universal Robots 2016). This information is used to color each robotic limb separately based on the speed of motion or joint temperature, and the end effector based on whether or not the vacuum is currently running. As the position of the cart with respect to the projector can change as the cart is rolled along the table surface, preset alignment markers indicate a fixed number of positions, and the software GUI allows the operator to specify the current cart position to ensure the projection mapping remains aligned. The intention of these projections is to use the robot to physically embody its programmed behaviors and system states (beyond motion), and to provide methods for intuitive error detection and debugging for human observers.

The front of the cart is projected with instructions for arriving visitors, and 1:1 dimension-references which suggest maximum and minimum recommended sizes of objects to offer to the robot. The conveyor belt is projected with colored zones which indicate the general region for placing objects, and the entire surface flashes red caution.
stripes when the belt is in motion (Figure 10). The plan view of the goal wall is projected onto the table, while text-based status messages, the camera image, and the detected shapes and their outlines are projected onto the back wall of the gallery.

**Algorithm**
The placement routine (Figures 10-13) is managed using a custom library for robotic control and geometry management, written in Java for Processing. The library consists primarily of functions for communicating with the UR controller, and a class for detecting, storing and modifying the properties of found objects. The robot is sent a number of routines as formatted URScript via socket, and these routines have built-in responses at key points in order to re-inform the control software about the robot’s status within the designated program.

After driving to the scanning position, the robot informs the control software that it has arrived, and an image of the conveyor belt is captured. Two-dimensional blobs (Gachadoat 2012) are recognized in this image as simple polylines, and the library manages the deletion of nested geometries (removing accidental shapes-within-shapes from textured objects), and the removal of shapes above and below the given size threshold. It then sorts the found objects for pick ordering (generally by size, but any other parameter could be used), and determines the 2D convex hull, centroid, and minimum arbitrarily-oriented bounding-box (AOBB) for each shape. From this information, an edge is selected for alignment with the goal curve. This edge corresponds to the one of two longest edges of the AOBB which has the most vertices of the outlined shape within a given threshold distance. The shape is then aligned with the goal curve which defines the desired wall boundary (Figure 9).

Once placed, an offset copy of this shape (to provide buffers around edges of placed geometries) is checked for collisions with all previously placed shapes on that layer using Java’s built-in shape class (Oracle 1998). If a collision exists, the shape is moved further along the curve until no collision exists. If the shape reaches the end of the path without finding an acceptable location, a new layer is started. While relatively simple in its implementation, this quasi-brute-force strategy of finding acceptable locations generally results in tightly packed geometry and does not require any foreknowledge of all available components (as it is often only given one piece at a time).

**RESULTS**
Through the development of software and hardware interfaces which incorporate machine vision, geometric intelligence and interactive visualizations, we demonstrate the potential for collaborative construction workflows which balance the aesthetics and efficiency of natural
materials with algorithmic intelligence, robotic dexterity, and human creativity. By working within the constraints of design objectives, and understanding the limitations of given “machinic-” and “material-” morphologies (Menges, 2012; Johns and Foley 2014), it is possible to construct designs which balance design intention and material behavior while more clearly illustrating the adaptability and variation enabled by digital design tools.

The setup developed for the exhibition provided for the continuous and automatic robotic assembly of stacked walls, without the need for frequent expert intervention. Gallery visitors could quickly comprehend their role in providing materials to the robot by reading limited instructions (projected diagrams and text in Korean and English) or by watching others. The simplicity of the interaction allowed for a number of children to engage with the robot, placing materials on the conveyor and observing the behavior of the system. Through simple trial and error, participants could easily assess the capabilities of the robot in locating and successfully placing that material.

More than with expressions of amazement at the robotic ability to find irregular parts and stack them into a wall, the authors appreciated observing user reactions to system inadequacies or failures, and that user’s ability to quickly resolve workarounds for those issues (i.e. by providing another object that was lighter, or one with different geometric or material properties). Whereas many robotic demonstrations stoke the illusion of robotic infallibility by minimizing variables or concealing errors, this project intentionally engages unknown variables and interactivity—establishing clear error reporting routines such that issues can be worked around by users or resolved by experts.
Based on observations, future improvements to the process will include the implementation of additional strategies for managing sectional variation by scanning the wall as built (for detecting changes from settlement, partial collapse, or direct user intervention), and using this information to prioritize objects with heights that can better equalize courses.

**REFLECTION**

This project presents an interface for collaborating with a materially-adaptive robotic assembly process and creates a framework for non-experts to understand the potential of robotic construction with irregular objects (Figure 14). By recognizing the “sign stimuli” (Gould and Gould 2007) that trigger certain robotic behaviors, users can adapt their actions to better take advantage of the robot’s unique capabilities. Just as Hubert Duprat leverages the caddisfly’s tendency to build by offering it selective materials (Duprat and Besson 1998), so can we study and alter the inputs of simple robotic assembly processes to creatively orient their outcomes. By working within the constraints of design objectives, material availability, and robotic capabilities, it is possible to use adaptive robotic assembly to produce regionally specific forms which empower both the designer and the material.

Despite the motivation of digital architecture to convey the adaptability and freedom of virtual design spaces, the eventual locking of these designs into tightly tolerated and materially-expensive toolpaths can render these processes as extremely immalleable and contrived. On the other hand, the careful arrangement of found materials tends to convey an air of natural belonging, despite requiring a higher level of technical complexity in its implementation. In contrast with traditional parametric fabrication strategies, this extra effort can come across visually as a lack of effort; as such, we consider the potential success of adaptive assembly strategies as a kind of architectural incarnation of Baldassare Castiglione’s concept of *sprezzatura*, or ‘artful artlessness’ (Castiglione 1976). While the prevalent top-down strategies used by parametric designers often seems at odds with the working methods of vernacular and regionally oriented architectures (Hawthorne 2016), it is important to recognize that this does not have to be the case; robotic fabrication processes coupled with machine intelligence have the potential to unite the previously incongruous concepts of regionally-oriented adaptive assembly with digitally assisted design and manufacturing.

**CONCLUSION**

This paper presents an interactive model for allowing non-experts to collaborate with robotic tools to produce architectural assemblies from non-standard, found components (Figure 15). Through the use of projection mapping techniques and audible messages, we allow the fabrication tools to provide “social cues to people,” ensuring that the fabrication process can both be informed by the human operator, and can also inform him or her (Breazeal and Brooks 2005; Johns, Kilian, and Foley 2014). By recognizing
Gallery visitors place objects from available bins—or their pockets—on a conveyor belt in front of the UR5 robot. "Adaptive Assembly" 2017

the limitations of both machinic- and material- morpho-spaces, computational methods can begin to prescribe methods for organizing, modifying, and aggregating irregular, found objects.

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REFERENCES


IMAGE CREDITS

Figures 1, 8, 7, 10–15: Ayesha Gosh.

Figure 3: Student work images as attributed.

All other drawings and images by the authors.

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