Biomimetic Robotic Construction Process
An approach for adapting mass irregular-shaped natural materials

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Beaver dams are formed by two main processes. One is that beavers select proper woods for constructing. The other one is that streams aggregate those woods to be assembled. Using this approach to construction structure is suitable for natural environment. In this paper, we attempt to develop a construction process which is suitable for all-terrain construction robot in the future. This construction process is inspired by beavers' construction behavior in nature. Beavers select proper sticks to make the structure stable. We predict that particular properties of sticks contribute gravity-driven assembly of wood structure. Thus, we implement the system with machine learning to find proper properties of sticks to improve selection mechanism of construction process. During this construction process, 3D scanner on robotic arm scans and recognizes sticks on terrain, and then robot will select proper sticks and place them. After placement, the system will scan and record the results for learning mechanism.

Keywords: Biomimetic Design, Machine Learning, Natural Material, Point Cloud Analysis, Robotic Fabrication

INTRODUCTION
Contemporary construction process is good enough, Today's construction projects are characterizing by short design and build period, increased demands of quality and low cost. These problems can be approached by a flexible automation using robots based on computer assisted planning, engineering and construction management (Bock 2008). However, there are some shortcomings. Construction waste is becoming a serious environmental problem around the world; This is due to the growing in volume and complexities of modern economies (Erekpi-tan et al. 2015). Using natural materials for architectural designs was abandoned during and since the industrial revolution, having a negative impact on the environment as a whole [2]. One of the biggest challenges of natural materials to be used in digital crafting process is its unevenness and controllability (Chen and Hou 2016). Therefore, architects usually give up using natural materials in their design.

Local natural materials
Rivers bring and erode trees into mass driftwood especially in Taiwan's typhoon season. But, it is difficult to utilize by conventional industrial process; If we can make good use of these natural materials instead of throwing them away, we can save lots of resources and provide architectural field with new possibilities.
Inspiration from nature
On the Earth we live in, the ecosystem works without waste. Living creatures develop ways to build shelter by following the character of natural material. For example, termite mounds, bird nests and beaver dams (see Figure 1b). Beavers especially make good use of natural materials for large-scale construction. The biggest scale of beavers' construction is a beavers' dam located in Wood-Buffalo-NP, north-east Canada (see Figure 1a). The dam's width reaches 850 meters [3]. This scale is comparable with human being's construction. Beavers' construction can be generalized into three types such as beaver dams, lodges, and food caches. The amazing scale and variety of construction is rare in nature. Hence, beavers are regarded as an architect in the animal world.

Beavers' construction can even adapt its structure to hydro-logical environment and surrounding forest species effects (Janiszewski 2006). The main structure is composed of woods. Mud, weeds, and tiny sticks can be used as infill. In fact, the completion of beavers' construction is attributed merely half to beavers' construction skills. Self-assembly mechanism of materials adapting river force makes half contribution to the construction (Blersch and Kangas 2014). Both beavers' construction skills accumulated with experiences and self-assembly mechanism of materials play essential role in the construction. If those principles of beavers' construction are grasped, it is possible to make construction robots utilizing local resource for full-scale buildings.

Robotics Fascination
In other cases of using natural materials, the Woodchip Bran project of AA's team challenges using branch to construct barn in main structure, they used optimized algorithm in this process of project for finding suitable arrangement then employed robotic arm milling to form the connections solving the design problem of using branch. Additionally, Robotic Softness project of ITECH challenged softness materials to construct woven space improving the possibility of combining 3D scanner and robotic arm for adapting natural softness materials [6]. Rock Print Project is the first architectural installation to be built from low-grade granular material and constructed by robotic machines. Conceived as an intriguing vertical object, the installation presents a new category of random packed, potentially fully reusable, poly-dispersed jammed structures that can be automatically fabricated in non-standard shapes [7].

Those mentioned cases also explore how to use robotic arm for adapting complex properties of natural material. Those research involved material and behavior levels of biomimicry in architecture. However, Robots are still difficult to utilize local resource and construct without materials processing.

RESEARCH OBJECTIVES
In this research, we investigate how the robotic construction utilizing unprocessed natural materials. The dimensions of beaver's constructions reach hundreds of meters long, as a result, using unprocessed natural materials as construction materials is a potential approach for artificial buildings. However, human beings depend on low technology and conventional design methodology. This research proposes a solution to solve the design problems.

The system of biomimetic robotic construction process is designed to simulate beavers' construc-
tion, including beavers’ construction skills and self-assembly mechanism of materials. Therefore, the system contains two major parts. One part is to arrange materials placements automatically. The other part is finding appropriate materials by machine learning mechanism. This mechanism can judge whether current materials are suitable. Unlike conventional industrial process, which involves processing raw materials, this biomimetic robotic construction process can save mass resource by utilizing unprocessed irregular-shaped natural materials like sticks (see Figure 2).

**SYSTEM DESIGN AND PROTOTYPING**

In this research, we investigate two key techniques of biomimetic robotic construction process. One technique is to make robotic arm know materials characteristics, including curvature, diameter, and length through 3D scanner. The robotic arm can also locate the materials and grip them precisely. The other technique is to sense the structure stability after placing materials and activate machine learning mechanism. This mechanism will give priority to better material characteristics when selecting construction materials (see Figure 3).

**Prototyping**

The prototype is established on common tools that usually appear on academic and industrial fields. Therefore, it is convenient to be modified by other people. For instance, using 6 degrees of freedom robotic arm (KUKA KR6R700) usually appearing in industrial production and common parametric design software (Grasshopper) used in design field as development platform. In the tendency of architects using digital design and fabrication, the workflow combining parametric software and robotic fabrication became more and more popular, we expect that developing biomimetic robotic construction process in it as open source can accelerate this construction process practiced in real environment.

As a result, in later versions, the robot fist scans all materials. Next, every time it places each stick, it scans all materials again. This revision helps the robot take instant reaction to environment changes. Besides, in the beginning, we use computer vision
to recognize the shape of sticks and use gravity sensor on gripper to sense the center of gravity of materials. By doing so, we can use physical simulation program to find appropriate placements. However, those methods are failed, because physical simulation may optimize construction for fewer, large, or regular-shaped materials. Nevertheless, in this research, we focus on mass, small, and irregular-shaped sticks for building structure as beaver lodges. According to our experiment, physical simulation is unsuitable for mass, small, and irregular-shaped sticks. Gravity is ineffective in small-scale sticks structure but curvature and length are keys to construct successfully. Therefore, we use 3D scanner instead of gravity sensor to scan sticks because it is useful to analyze those properties from point cloud data.

The completed version of system generalizes series components from various incidents on Grasshopper (GH) for adaption. For example, when construction robot perceives structure sway, robot will adopt infill program gripping sawdust from terrain as infill to strengthen structure (see Figure 4). In this way, construction robot can adapt various sticks and terrain to improvise a stick structure as beaver lodge.

**Components of system**
The followings are components in the system of biomimetic robotic construction process (see Figure 5).

**Natural materials**
The natural materials in this research are about 20-centimeter long and irregular sticks (without any branches). These sticks are used as scaled-down driftwood, which are common natural materials in Taiwan. Typhoons and rivers erode driftwood into sticks without any branches. If we can make good use of these natural materials as construction materials instead of throwing them away, we can save lots of resources and provide design field with new possibilities.
Workspace
A workspace simulates complex natural environment to test the adaption of construction robot. It is made of sawdust on a wood tray (see Figure 6), the sawdust terrain is easy to be shaped, as a result, the workspace can be reused for different rugged terrains. A soft of sticks will put into the workspace randomly captured by gripper as construction materials during experience.

Robotic arm and gripper assembly
The prototype of biomimetic construction robot consists of KUKA kr6r700, KinectV2, and a material-adaptive gripper (see Figure 7).

This gripper is made of PLA through 3D printer (see Figure 8). The robot makes good use of PLA's high flexibility to adapt natural materials' various sizes. To add friction, abrasive papers are stuck to the joints of the gripper and materials. The servo empowers the engaging lever and transform rotation torque into holding power. Robotic arm's IO controls the gripper, and send digital information to Arduino. Arduino analyzes digital signals and commands the servo on the gripper. The maximum weight for the gripper to lift is 500 g and from 1 mm to 30mm in length.

Environmental sensing
The soft program involves point cloud processing, geometrical poverties, robotic construction behav-ior, and the component of machine learning. Point clouds processing first deals with information from Kinect (see Figure 9).

Firstly, the soft program receives points outside the tray, and these points will be filtered. However, there may be some unreasonable points in the filtrate because Kinect IR points may not be detected, which causes the errors of point clouds location. The component of machine learning can transform received points into mesh by Delaunay Mesh (an algorithm). By calculating each mesh area, we can know the accuracy of point distribution. Besides, errors may exist when the gripper moves back to the observation position. The component of machine learning can also solve this problem through measuring the original position of tray and moving the observed points to that original position. Then, the component exports the data and its job is done. (see Figure 9) left is a real picture, and the right is the scanned data from points cloud.

The component captures geometrical properties. These geometrical properties include materials' position, length, curvature, and radius. They are
obtained from the analysis of point clouds distribution (see Figure 10). Nearby points can be viewed as a group. By analyzing whether the groups present a linear layout, the component can judge if an observed object is a stick. The point clouds data can be further analyzed by Circle Fit (an algorithmic mechanism) to get the object’s curvature. Its length comes from measuring point clouds distribution centerline, whereas the radius is calculated from the distance between centerline and point clouds.

The component also finds a flat area as a proper construction site. By analyzing point clouds, it can test the stability of the structure when placing each material. For example, through comparing new scanned data (material’s actual place) with previous scanned data (material’s expected place), the component can calculate a swept area. The bigger the swept area is, the more unstable the structure is (see Figure 11). All geometrical properties will be recorded and analyzed during construction process.

This process is similar to FDM.
Procedural construction process
The procedural construction process component can dominate the execution order of other components. For example, when we first start up the robotic construction behavior component, the robot arm will move to the observation position and make Kinect scan point clouds. After scanning, it will wait until the data is analyzed. Then, the construction begins. The component controls robot according to point cloud analysis. After determining the construction site through point cloud analysis, the robot will define a circle to measure a construction range. This circle is cut into several segments to show directions and positions for piling the materials. Then, it will control gripper to grips the materials to a proper position based on the data from the previous component. As the terrain changes and materials keep being piled, this circle curve will be submerged by newly scanned point clouds. After each layer is submerged, the new layer will on top of the old curve and become a new placement of materials. In this way, sticks are stacked to form a structure step by step (see Figure 12). The placements will be piled up along the Z-axis. This process is similar to 3D printer's Fused Deposition Modeling (FDM) (see Figure 13).

In this way, the new placement of materials will form as the new circle curve exists until the biomimetic construction robot detects that the structure is swaying. The robot will offset to narrow the circle curve's size to keep the structure from swaying until the circle is too small. Then, construction is finished. It is expected that when the materials are with high quality, the robot will construct a towering and tall cylinder, whereas it will be a short and low arch if the materials are in poor quality. With more experiences, more data can be generalized, and the robot can make better choice of materials. The structure will be more solid and the construction can be taller.

Construction types and processes
In natural environment, there are many incidents happening at any time during construction (For example; structure sway, depression, lack of materials), as a result, we implemented the system with incident response mechanism for adapting complex construction environment. Considering in natural environment, beavers use smaller materials as infill to strengthen structures, the robotic construction behavior component provides two selecting modes such as stick mode and sawdust mode. When the construction structure is stable, the stick mode is on, whereas it switches to sawdust mode and grips sawdust to strengthen the main structure when the construction structure is unstable (see Figure 14).

Data recording
Data recording component will record the data after it scans the materials (see Figure 15). Machine learning component will analyze the correlation between each material’s geometrical features and its
construction process. Different materials may have different advantages and limitations. As more experiences and data are collected, machine learning component will help robot select the best material feature from the database as a model. Whenever new materials are found in the natural environment, the component will choose the material which best fits the criteria of that model as the material for main structure.

**Machine Learning**

System will be executed with machine learning mechanism and keeping improving stability of assembly by choosing appropriate sticks. We predicted that particular properties of sticks (for instance, curvature, length and radius) will influence the stability of assembly. Thus the system is designed to find the best value for assembly by machine learning. The method of measuring assembly stability is generating a swept area from predicted place to actual place. The smaller the swept area is, the higher of the assembly stability is. Thus, we can analyze correlation between assembly stability and individual material properties. Considering that the correlation between material properties and assembly stability may be nonlinear. As a result, we develop the learning mechanism based on Spearman Rank Correlation in this system (see Figure 16).

At the beginning, the system records several data of material properties and assembly stability. Next, the system will define the value of assembly ability as different scores. Then, it will calculate temporary appropriate properties for assembly. If the current property is closer to temporary appropriate property, the assembly is likely to be more stable. In the algorithm, the temporary appropriate property is dynamic may due to data accumulation. Therefore, machine learning mechanism can find influences of those material properties (curvature, length and radius) on assembly stability. The system can select proper sticks through evaluation of machine learning mechanism (see Figure 17).

**CONCLUSION**

The results in this study indicate that the system gives priority to materials with 65-centimeter curvature radius when selecting materials. The curvature plays the most important role in the selecting section, while length is ranked as second crucial factor and diameter seems not an essential factor. Proper curvature can grab other materials tightly and avoid them rolling away when swaying (see Figure 18). Besides, material gaps and infill can be organized well with proper curvature. Machine learning mechanism can preclude unsuitable materials and strengthen the structure of the dome. As construction experiences increase, machine learning mechanism has made the construction height higher than the first time (see Figure 19).

In this research, we focus on how to develop the process for adapting complex environment instead of constructing a predefined structure; each final form in an experiment are unpredicted. Final form is influenced by context of materials and terrain. In the context, if materials are too short or bent
and terrain is too rugged, it will cause the structure to be failed, the final form might be low or small, as a result, the performance of Biomimetic Robotic Construction Process resemble “form follows natural materials”. Any variety can cause result to be different (see Figure 20).

On the whole, this research attempts to seek a solution to two issues in architecture. First one is environmental impact from architecture and second is architectural impact from automatic, we combine these two to develop a Biomimetic Robotic Construction Process as a solution; We review architecture industry bring material and energy waste from large scale production and then propose a Construction Process combining natural material to reduce resource waste. Adapting natural materials is widespread in natural environment, especially beaver construction is a paradigm. Through studying beaver construction behavior, the Construction Process combining natural materials.
new technologies is possible to be achieved. This research (Biomimetic Robotic Construction Process) is different from most of digital fabrications because this Construction Process need not predefined form for input, the final form is due to materials and terrain in environment.

We expect biomimetic robotic construction process can be used for real construction environment the after improving reliability, it can be use for full-scale material (larger stick or driftwood) (see Figure 21). And therefore, workers are not necessary to be exposed to danger. Instead, Construction Robot can be employed on rugged disaster area for makeshift bridges, embankments and shelters. On the other hand, in non-disaster area Construction Robot can be employed for river and landscape improvements. After progressing biomimetic construction robot through newer technology, the updated robot may be widely used on permanent buildings. By doing so, this natural material-based biomimetic construction robot will be able to reduce waste of resource from construction in the future, this approach will allow designer to use unprocessed natural materials more easily and stimulate the design concept of "Form Follows Natural Materials"

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