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TOWARDS A MOTION GRAMMAR FOR ROBOTIC STEREOTOMY

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Abstract. This paper presents progress towards the definition of a *motion grammar* for robotic stereotomy. It describes a vocabulary of motions able to generate complex forms by cutting, slicing, and/or carving 3-D blocks of material using a robotic arm and a custom made cutting tool. While shape grammars usually deal with graphical descriptions of designs, a motion grammar seeks to address the 3-D harmonic movements of machine, tool, and material substrate *choreographically*, suggesting motion as a generative vehicle of exploration in both designing and making. Several models and prototypes are presented and discussed.

Keywords. Generative Fabrication; Robots in Architecture; Hot Wire cutting; Shape Grammars; Stereotomy; Computational Making.

1. Introduction

During the last decade, robots found their way into architectural discourse, both in academia and practice (Reichert et al. 2014), (Willmann et al. 2013), (McGee et al. 2014). These machines fascinated designers by their precise actuation, human-like behaviour, and flexibility (Braumann & Brell-Cokcan 2012). While design practitioners and researchers have used robots as aids in design, prototyping, and fabrication processes, most approaches have focused on these machine's fabrication capabilities (Daas 2014). Robotic control requires highly-skilled users, and mainstream CAD packages suffer from the lack of native robotic programming functionality support, which is crucial to plan and manage fabrication processes (Stouffs et al. 2013). Recently, several software projects have sought to incorporate robots into design workflows, providing interfaces that help designers orchestrate robotic procedures, including KUKA RPC (Braumann & Brell-Cokcan 2012) and HAL

(Schwartz 2013). These software packages help designers work in visual programming environments while simulating the robot behaviour in real time.

While these software tools have been key to enable designers to explore the capabilities of robots in architecture and design, we believe that there is much to be gained by further defining and navigating these machines' "design-spaces" at lower levels of abstraction. Integrating the robotic characteristics, restrains, and technical issues with design process will result in an active dialogue between robot-tool assembly (RTA) and design process. We define a robotic "design-space" as the space of possible outcomes that can result from the combination of a particular RTA and a given material substrate. In this paper, we propose a method for defining and exploring such "design-spaces" by a) studying an RTA's motion affordances, b) identifying a vocabulary of RTA motions and their material effects, c) defining a series of basic grammar rules for design exploration, and d) generating series of material derivations based upon these rules.

2. Background

Motion can be described as a change in the state of position and orientation that happens through time (von Laban 1956). Although the starting pose and ending pose of a given body might be the same, movement is the process of the change that happens in between. (Zhao & Badler 2001). Comparatively, in an abstract process of combination, the movement of an RTA in space can transform objects. This movement can be visualized as the displacement of a series of points in space, which in turn define lines (Klee et al. 1953). Synthesizing these views, we sought to formalize a vocabulary of motions able to generate complex forms.

Robotic control is hard to grasp for unexperienced users, but motion in space is a tangible phenomenon. We define a grammar of robotic motions to formalize the ways a particular RTA is able to transform three-dimensional blocks of material through operations of carving and slicing. The idea that design can be described through grammars and vocabularies Grammars borrows from Shape Grammar theory (Stiny & Gips 1971), (Stiny & Mitchell 1978), and later developments including Parametric (Stiny 1980) and Color (Knight 1993) Shape Grammars, and "generative fabrication" grammars for manufacturing (Cardoso & Sass 2008). Recently, researchers have tried to incorporate motion into grammar formalisms, although mostly to define kinematic behaviour (El-Zanfaly 2011) or bodily transformations (Ferreira et al. 2011) as insight into the design of architectural structures.

In our case, we implement a motion grammar as a way to address machine and material-specific aspects of robotic stereotomy—the use of a robotic arm to precisely cut, slice, and carve 3-D blocks of solid material. Thus, the grammar's vocabulary members are not shapes nor objects, but movements. Its derivations are not artefacts as much as *choreographed* assemblages of robot, tool, and material, with a tangible result. In our motion grammar, a rule **A→ t(A)** defines a movement in which **(A)** is the state of the RTA in a specified pose and time, and **t(A)** represents a new state by applying **t transformation** onto the original state. A and t(A) might be the same pose, but generated **motion** is the process between these two states (Figure 1).

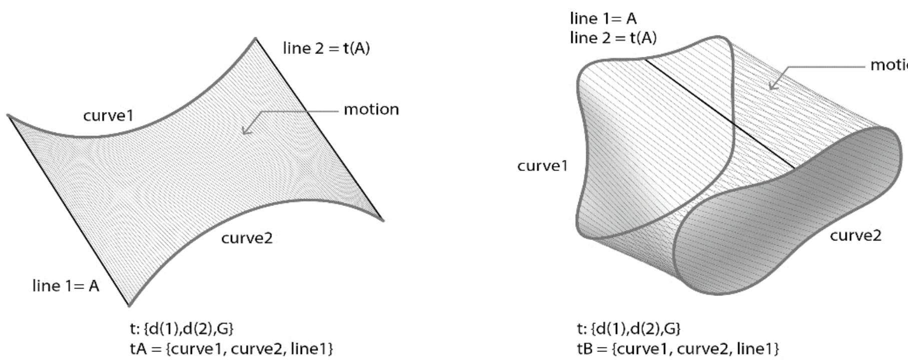

Figure 1. Example of a basic motion rule A→t(A)

3. Method

3.1. ROBOT-TOOL ASSEMBLY (RTA)

We discuss this approach through examples from a particular robot-tool assembly (RTA) comprising an ABB IRB 2400-16 robotic arm and a custom-designed hot-wire cutter (HWC). Our material substrate comprises 3-D blocks of high-density EPS foam. The robot has six degrees of freedom (DOF), three of which enable a working area of 1.55 diameter with 0.1 mm position accuracy, while the three others precisely orient the end effector. Together, position and orientation define the *pose* of the robot's end effector (Corke 2011). The mounted tool is a two feet wide aluminium frame, holding a tensioned Rene' 41 wire which can be heated by electric current into 200-300 c° in order to cut EPS foam steadily and smoothly. (Figure 2)

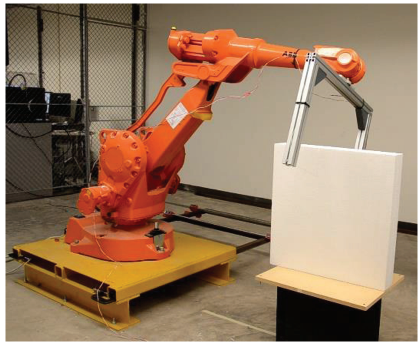

Figure 2. Robot Toll Assembly

3.2. SOFTWARE

The arm's motion was modelled in Grasshopper, a visual programming environment linked to the Rhinoceros modelling software. Parametric modelling helped us to have full control over the elements of design and create a wide range of variations by changing input parameters. In order to simulate robotic motion and generate the RAPID code for the robot's operation, we used HAL, an add-on for controlling industrial robots from KUKA, ABB and UR, developed by Thibault Schwartz. We tested the RAPID scripts in the RobotStudio environment in order to check for execution errors, and finally uploaded them to the robot to be actuated. As other authors have noted, this environment provides the opportunity to visually understand the relationship between changes in generators' parameters, motion of the robot, and produced forms in an interactive environment (Braumann & Brell-Cokcan 2012).

While designers are used to *Cartesian* coordinates to command most 3d modelling packages, laser cutters, and 3 axes CNC machines, robotic control demands six values to codify the tool's position and orientation—accordingly, they can be considered *non-Cartesian*. As researchers have pointed out, it takes great effort to understand the relationship between the Cartesian system of conventional CAD and CNC systems, and the complex behaviour of robots' end effector (Braumann & Brell-Cokcan 2012). Comparing a sample of Cartesian coordination vs. its equivalent in RAPID code depict the difference clearly. (Table 1)

Table 1. Comparing coordination in Cartesian system and RAPID

System	Representation
Cartesian	P10 = {600, -100, 800}
RAPID	p10 := [[600, -100, 800], [1, 0, 0, 0], [0, 0, 0, 0], [9E9, 9E9, 9E9, 9E9, 9E9, 9E9]]; [position],[orientation],[specific robot axes angle],[Positions additional axes]

RAPID data codifies the robot's end effector correct *pose*—including *position*, *orientation*, as well as each specific axis' angles and values. In many design scenarios, designers can think about the pose of the end effector. In such cases, *Kinematics*, which deals with the relation between robot motors/joints and the end-effector motions (Hägele et al. 2008) is not useful, as we should go through an inversed procedure to find the value for every axis to reproduce the desired pose. Thus, these numbers are processed in an inverse kinematic solver to generate the rotating angle for each of the robot's axes.

3.3. UNDERSTANDING RTA MOTION

3.3.1. Geometry

The Hot Wire tool's design range is defined by *Ruled Surface* (RS) geometry. RSs are formed by the movement of a straight line over a curve in space. They have been used by architects to create complex forms in their projects, including Antoni Gaudi's Sagrada Familia Cathedral (Stavric & Kaftan 2012). By definition, a RS needs a generator line and two directrices to define the pose of the generator and limits of the surface. (Figure 3)

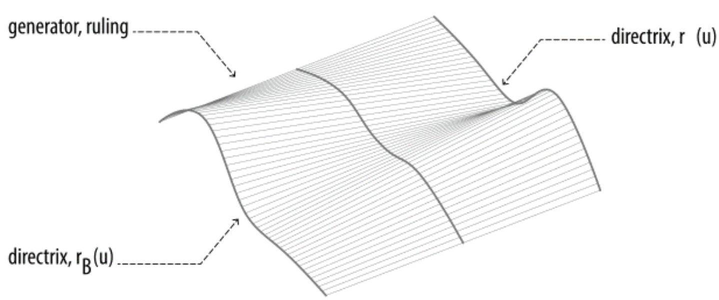

Figure 3. Elements of Ruled Surfaces

In hot wire cutting, the wire plays the role of the *generator*, which moves through *directrices* to cut EPS material. Any changes in the properties of the directrices will affect the motions and consequently the final form. Accordingly, we developed a design space, based upon these possible variations in order to navigate through the possible vocabulary of robot's motion in space.

In Rhinoceros modelling environment, curve may refer to any curve which can be represented by NURBS definition which is a mathematical representation of 3D geometries that can accurately describe any shape from 2D lines to complex 3D forms. (Anon n.d.) In this paper, *Line* or *Polyline* refers to a NURBS curve of degree 1, while *Curve* will refer to NURBS of higher degrees. By definition, generator is always a line, while directrices can be line, polyline or curve.

4. A Motion Grammar for Robotic Hot-Wire Cutting

A motion grammar seeks to address the 3-D harmonic movements of machine, tool, and material substrate *choreographically*, suggesting motion as a generative vehicle of exploration in both designing and making. The grammar defines the possible range of changes in the properties of directrices (*morphemes*) to generate basic motions (*lexicon*) and categorize the methods to combine these motions (*rules*) to generate more complex motions.

4.1. MORPHEMES

Two basic parameters can affect the form of directrices, first degree of NURBS and second their relation in space. By changing the degree, they can shift from a line (or polyline) to a smooth curve. They can be in a same plane, parallel, intersecting or skew ones. Be changing the degree of curve and position of their controlling points, we can generate these basic elements of grammar. (Figures 4)

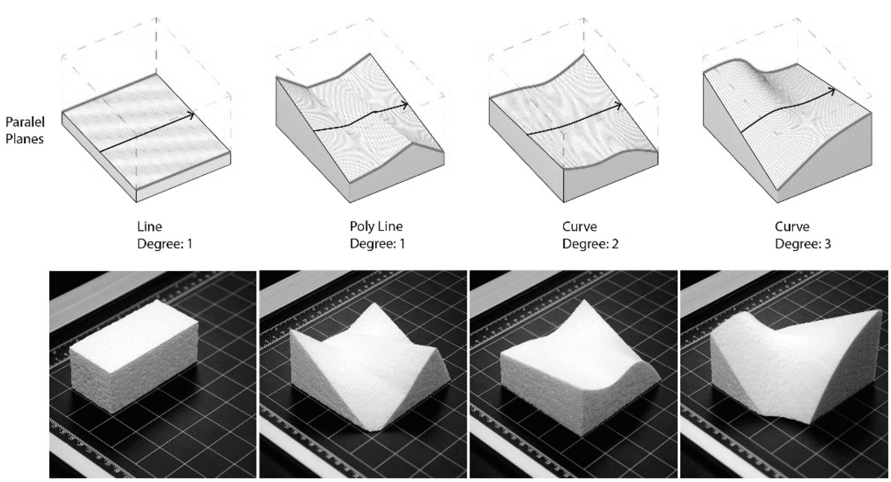

Figure 4. Effects of directrices' degree on the motion

4.2. LEXICON

Based upon these characteristics, a range of motions can be defined, comprising the grammar's vocabulary (Figure 5)

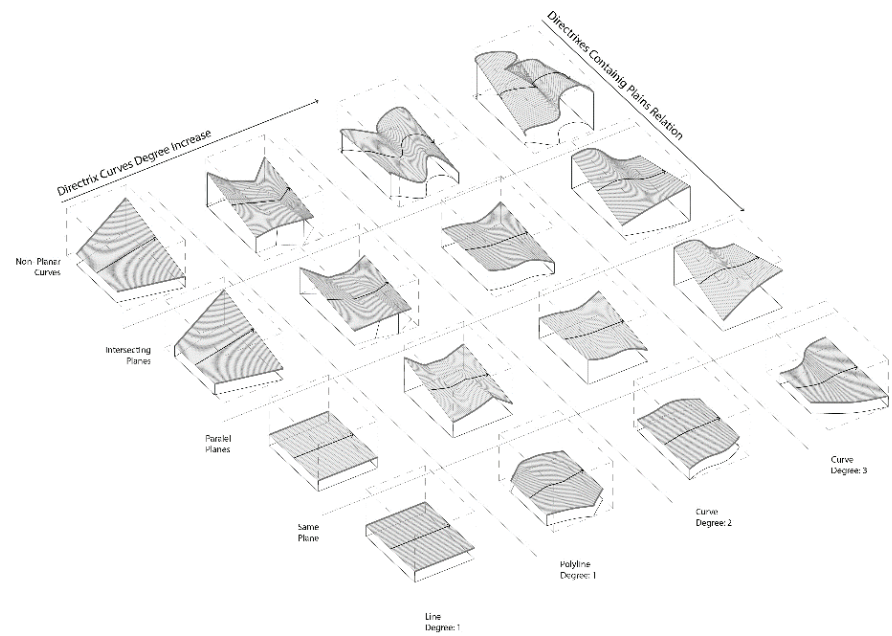

Figure 5. Vocabulary of motions (Lexicon)

4.3. RULES

Motions can operate on each other in order to generate more complex motions (and more complex material effects). We categorize these rules in two basic groups:

4.3.1. Sequential

Sequential rules join two vocabulary members into a new motion. Members can be joined either by the generator, or by the directrix. Sharing the generator will result in a continuous motion, meanwhile, sharing a directrix requires the robot to finish the first motion, find its initial pose for the second motion and then perform it to complete the procedure. (Figure 6)

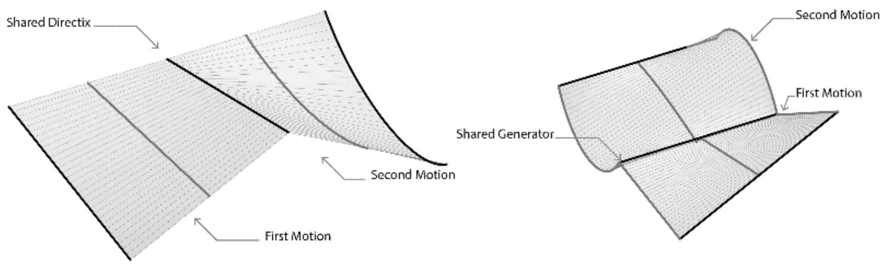

Figure 6. Sequential Combination, $M = m_1 + m_2$

Therefore, we can annotate this procedure as:

$m_1 = A \rightarrow t_1(A)$ and $m_2 = t_1(A) \rightarrow t_2(t_1(A))$ (1)

$M = m_1 + m_2$ (2)

4.3.2. Composite

Composite procedures are two or more motions cut each other to generate a new virtual directrices and trim previous generators. This composition can generate extremely complex motions. While in sequential procedures the length of the generator is constant, in composites it is variable (Figure 7).

$m_1 = A \rightarrow t_1 (A)$ and $m_2 = B \rightarrow t_2(B)$, $M = A \rightarrow t_i (m_1, m_2)$ (3)

$t_i (m_1,m_2) = [curve_1,(m_1,m_2)_{int}, A_{[0,t]}]+[(m_1,m_2)_{int}, curve_4, B_{[t,1]}]$ (4)

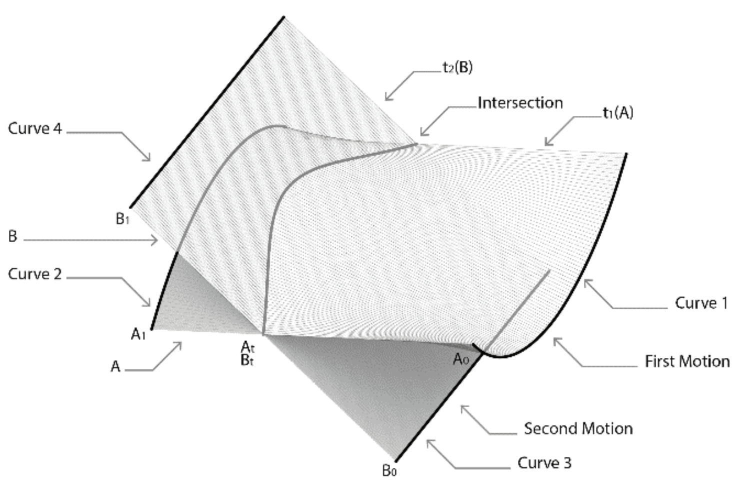

Figure 7. Composite combination

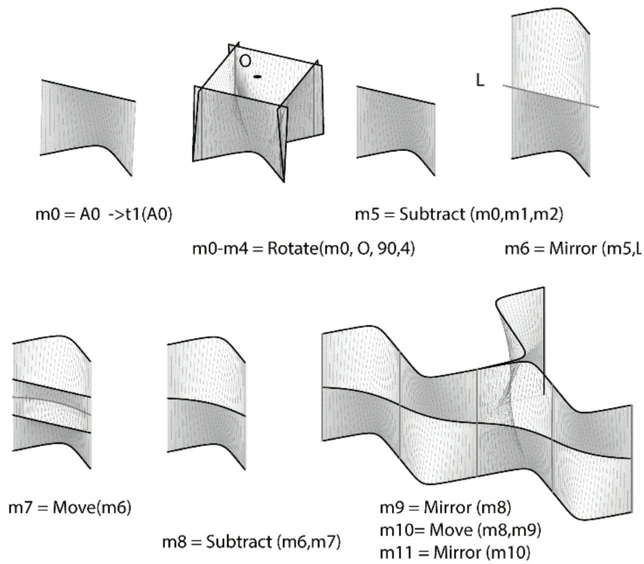

Figure 8. Sequence of applying the grammar

5. Contributions and Next Steps

The foundation of a machine-specific motion grammar for robotic stereotomy was proposed. The grammar and prototypes in this paper are mainly a proof of concept, and the foundation for more complex studies. Next steps in this route will focus on defining a detailed ruleset of both sequential and composite rules. The sequential or composite character of the rule set will enable both top-down and bottom-up design processes. This framework will amplify the potential of our RTA as a vehicle of design exploration, constituting a truly generative framework for stereotomic processes.

A major motivation behind this paper was to develop a new approach toward robotic fabrication by proposing a new way to describe and interpret robotic characteristics in relation with form finding procedures in a machine and material-specific framework. Although our motion grammar is specific to hot wire cutting and architectural-grade EPS foam, our method of studying robotic fabrication as a series of choreographed (sequential or composite) motions, and formulating a vocabulary and a set of grammar rules, can be applied to other combinations of RTA and material systems. To illustrate an example of such approach, a similar grammar can be adopted to match the *Robotic Filament Winding methods* (Reichert et al. 2014), addressing the dialogue between robotic motion, geometry of framework and thread weaving patterns to generate variations in the framed design range.

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