A Methodology for Evaluating the Hygroscopic Behavior of Wood in Adaptive Building Skins using Motion Grammar

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Abstract. The challenge in designing kinetic architecture lies in the lack of applying computational design and human computer interaction to successfully design intelligent and interactive interfaces. The use of 'programmable materials' as specifically fabricated composite materials that afford motion upon stimulation is promising for low-cost low-tech systems for kinetic facades in buildings. Despite efforts to develop working prototypes, there has been no clear methodological framework for understanding and controlling the behavior of programmable materials or for using them for such purposes. This paper introduces a methodology for evaluating the motion acquired from programmed material – resulting from the hygroscopic behavior of wood – through 'motion grammar'. Motion grammar typically allows for the explanation of desired motion control in a computationally tractable method. The paper analyzed and evaluated motion parameters related to the hygroscopic properties and behavior of wood, and introduce a framework for tracking and controlling wood as a programmable material for kinetic architecture.

1. Introduction

Interactive architecture generally lies at the intersection between digital technologies and physical spatial experiences [1]. Gu and Wan define it as the intersection of four disciplines: computer science, interaction and experience design, architecture and behavior and social studies [2]. The technology behind interactive architecture is influenced by many disciplines including physics, biology, mechanics and electrical engineering and human computer interaction (HCI). Smart materials are increasingly becoming a significant constituent in such systems, where actuation and sensing properties are currently embedded in everyday objects and surfaces [3].

As per Mark Weiser's observation, "The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it." This has encouraged researchers in the fields of pervasive and ubiquitous computing and the Internet of Things to introduce new interfaces, such as Tangible User Interfaces (TUIs). Interactivity in tangible interfaces is driven from physical elements or devices in the physical environment with properties of objects such as appearance or sound. The recent shift from tangible user interfaces to natural and organic user interfaces – and more recently smart material interfaces (SMIs) – has dramatically pushed the limits of interactive architecture, where the seamless interaction between the physical and the digital occurs primarily through material properties [4].

Traditionally, the development of interactive and kinetic systems, specifically for building facades, relied heavily on the implementation of sophisticated hard mechanistic systems. Fox and Kemp argue for the "*End of Mechanisms*"; a paradigm shift in kinetic systems from using mechanical devices to passive biological systems [5]. The use of smart materials was proposed as a part of this argument, due to the close relation between smart material behavior and the mimicking of natural behavior [6].

An inherent property in smart materials is their responsive behavior, where they can change their properties and can exhibit control and reversibility to respond to environmental stimuli. Programmable material is a type of smart material in which this composite material is fabricated and programmed to respond to external stimuli with a specific desired behavior. This phenomenon can be directly applied in interactive and responsive architecture.

This paper attempts to identify a theoretical basis for capturing and controlling the movement of programmable materials – specifically as related to the hygroscopic properties of wood – for further implementation in kinetic and responsive structures. This study explores motion grammar as a method for capturing and analyzing motion in programmable material. Literature in motion grammars is primarily discussed from two viewpoints: linguistics and computer science, and image processing in the robotics domain [7]. Little has been done however to replace mechanical actuators in responsive systems with programmable materials. This requires the definition of a clear methodology to investigate, capture and control the behavior of smart materials. This paper addresses the following questions: How does material fabrication and development affect the realm of responsive and kinetic architecture? How can programmable material behavior be analyzed and captured through Motion Grammars?

2. Methodology

The challenge in applying Motion Grammars as a method to capture the motion of programmable material lies in the inherent properties of that material. This material is analyzed in relation to the various components of robotic systems and series of tasks done. Hygroscopic property of wood is used as a main generator for programming wood motion according to moisture content. A series of experiments are conducted to analyze and understand the behavior and response of wood to moisture content. By comparing and analyzing the motion and process of robotic systems to that of the hygroscopic response of wood, a set of Motion Grammar parameters are deduced.

3. Embedded Material Intelligence

Smart materials are generally classified and defined in different ways. Addington & Schodek differentiate between smart and traditional materials via five main characteristics: transition, selectivity, immediacy, self-actuation and directness. The capabilities of materials with these properties can be divided into property changing capability, energy exchange capability, discrete size/location and reversibility. One of the most significant characteristics of smart materials is the ability to change in size. They are also known to have either reversibility or bi-directionality properties. Reversibility is the ability of a material to exchange its input and output form, while bi-directionality is the ability of a material to change either its input or output energy properties as phase changing materials [8]. Ritter also classified smart materials as those that can reversibly and repeatedly change their properties in response to external stimuli as changes in temperature or light. Semi-smart materials can change their properties once or a limited number of times. Smart and semi smart materials are called functional materials [9]. The term "Stimuli-responsive

materials" (SRMs) is also used to denote materials that alter their properties according to external stimuli [10].

Another classification that relies on the relation between materials, technologies and environment, divides smart materials into two types; property changing, and energy exchanging materials. Property changing materials are those whose properties change according to an energy input, such as electro chromic glazing. Energy exchanging materials are those that transform the material input energy into another form of energy, such as photovoltaics, which transform solar radiation into electric energy [8].

Shape-shifting materials are classified according to their trigger stimuli into photostrictive materials that are stimulated by light, thermostrictive that are stimulated by the effect of thermal energy, piezoelectric that are stimulated by the effect of pressure and tension, electroactive that are stimulated by electrical energy, magnetostrictive that are stimulated by the effect of magnetic fields, and chemostrictive that are stimulated by chemical energy. According to Ritter's classification, shape shifting materials encompass thermostatic materials and electroactive smart materials [9].

Thermo-bimetals (TB) are another recently applied example of smart materials. They are laminated composite materials composed of a minimum of two metal layers having different thermal expansion coefficients. The layer with lower thermal expansion coefficient is the passive layer, while the active layer is the one having the higher thermal expansion coefficient. By changing the temperature, the composite material changes from a straight to a curved strip with the active layer facing upward and the passive layer facing downward.

This paper focuses on the use of wood as a programmable material due to its hygroscopic properties. Relevant work includes the efforts at the Institute for Computational Design (ICD) at the University of Stuttgart, and the Self-Assembly Lab (SAL) at MIT. Various experiments have been done to maintain, control and enhance the embedded motion in these materials [11]. Hygroscopic design in wood has been introduced to programmable materials due to the ability to program the response of wood specifically in relation to moisture content [12]. Wood is stimulated by humidity in the air and the moisture content inside wood. Figure shows the response of a beech veneer sample exposed to humidity. The continuous shrinking and swelling depends on relative humidity and the moisture content inside the sample.

Wood is selected for its low carbon footprint and embodied energy [13]. Studies have shown different ways in controlling the motion of wood through grain orientation, thickness and layers of lamination [14]. This research builds on these studies and uses Motion Grammars to investigate the type of motion taking place in wood upon increase in moisture content.

Figure 1. Time lapse for wood response during increase in moisture content.

4. Grammars

Formal languages are outlined by grammars that demonstrate methods to control systems and express full system dynamics [15]. Shape grammars, the earliest visual method of design and analysis for generative purposes introduced in the early 1970's, are a group of transformation rules that are applied on a shape to generate a new one [16]. This computational method relies on defining a specific initial shape, and a rule which identifies two parameters; the shape that will be replaced and the method it will be replaced with [17].

Motion Grammar differs, as it is targets the 3D movement of tools or materials; thus leading to generative ways to investigate output designs [18]. Motion Grammar is generally the linguistic system application that gives the control to a robot. Significant difference is found between the language of the system and language of specification in linguistic control methods. The system represents the physical object itself as

the controller, while the specification indicates the response behavior of the object. Both are located as formal languages, and the specifications are categorized as formal languages [7]. Motion in hybrid systems as humans and robots are described as continuous and distinct elements. Formal languages are formed through groups of strings. Discrete events and actions are illustrated as a series of atomic symbols; that are called strings [15].

The grammar states all the options of change in assets from the morphemes to achieved basic motions. Combining and sorting these motions are the rules that produce composite motions [18]. The grammar exemplifies continuous dynamics through what is known as Context-Free Grammar (CFG); that depends on isolated strings. These strings are used to replace the variables and terminals, thus forming productions. CFG encompasses a set of productions [19]. This paper focuses on motion grammar as a method to analyze the response behavior of programmable material.

5. Motion Parameters

Elements forming a grammar are variables, terminals and productions (rules). Variables are the initial variables, presented in uppercase letters (also called non-terminals). Terminals are represented in alphabets, and productions are strings that form the rules [19].

Introducing grammars as a way to describe design was developed to encompass parametric design, shape grammar and generative fabrication [18]. Lately, studies have been conducted to define motion in relation to formal grammars [17], including any transformation in position or orientation through time. This refers to the process of change, even if the beginning and end points are the same [18]. Other studies attempted to link tangible elements of kinematics like structure and materials with intangible elements like motion, through the pedagogical learning process of "Imitation, Iteration and Improvisation" that focuses on the process of designing kinetic structures rather than the product [20].

Motion Grammar is used to define the setup of robotic systems through Context-Free language. The grammar is the main composer of the motion parser in robotic motion. The parser is a program (part of the processor) that recognizes the input language of Motion Grammar, which is received as a series of instructions and performs the matching semantic rules per each production, as shown in Figure 2 [7].

Motion Grammar elements ($\mathcal{F}$, Z, Ʊ, Ŋ, V, P, K), where;

$\mathcal{F}$ sensor reading

Z tokens showing the robot status (output)

Ʊ robot commands part

Ŋ tokenizing function

V series of non-terminals

P series of productions

K set of semantic rules

The output Z is divided into tokens ζ with the main stream of motion being readable for the parser. Depending on the token sequence, the parser adopts a control action Ʊ to the robot. Token type ζ is responsible for the selection of a suitable production, while the production's semantic rules depend on continuous change in the Z value to achieve Ʊ. This means that the language of the robot's sensor reading is presented by the Motion Grammar. The conversion of the language of sensor reading into the language of controllers and controlling actuators is the Grammar's Motion Parser. Attributes are used to identify semantics of Motion Grammar. They are parameters linked to each token and non-terminal, with continuous change in relation to the continuous-valued variables as sensor values. Continuous and discrete information is transferred between the robot and controller. Discrete events are presented in Ŋ and form part of the string, while the continuous part of the controller is located in the sensor readings or semantic rules caused by attributes of tokens and non-terminals, and is saved by the parser.
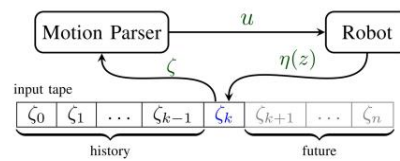
Figure 2. Process of Motion Grammar [7].

A Motion Grammar for any task depends on the nature of the task itself and the robot hardware. By applying this in the field of robotic systems, it is shown that U and Z are respectively the inputs and sensors in the robot. Token Z is designed as a set of discrete events and timeouts through the implementation of task. Tokenizing functions η need to be designed to occur from $\mathcal{F}$ to Z. The tasks are divided hierarchically into a series of easier tasks consisting of nonterminal V and productions P until a closed controlled loop is set. Through the production phase, semantic rules K for each production are obtained. Calculations for the token's attributes and nonterminal in production are done in the semantic rules K phase, till it reaches the end of the control loops, then the computed commands are transferred to the robot. Finally, to close the loop and complete the grammar, the nonterminal start variable is chosen from V as the last part in the hierarchical decomposition.

It is the purpose of this paper to demonstrate how this logic can be applied to the type of motion experienced during the process of hygroscopic behavior of wood as a natural material. Rather than defining motion as a set of controlled and well-structured transformation operations, hygroscopic behavior of wood relies on continuous variation in one important dimension, which is moisture content.

6. Analysing Programmable Material Behavior

Any basic interactive system consists of a three-component loop that consists of input, processing and output. Inputs and outputs are physical components, while processing is where action takes place. Input technology comprises sensors, cameras and tangible computing, while output technology is divided into two classes: display-based and motion-based. Processing typically reads inputs, makes decisions and actuates the output components. Interactive systems are categorized based on processing into: linear, self-regulating, or learning systems, as shown in Figure . Self-regulating and learning systems are capable of modifying their outputs according to external stimuli [1]. Based on these definitions, shape-shifting material responses and motions can fall under the category of self-regulating systems. The focus of this paper is achieving control of the output part of this loop through time to control the behaviour of shape-shifting materials.

In essence, smart materials act as if they comprise a sensing device (sensor function), and a communication network (memory function) that transmits signals from sensors to the decision making device (processing function), then finally to actuators that move the material (actuator function) [21]. The classification by Addington & Schodek demonstrates that smart materials can function as sensors and actuators in architectural buildings. For example, controlling solar radiation through the building envelope can be controlled by sensors and actuators, which can be applied by shape memory alloys, electrorestrictive and magnetorestrictive materials.
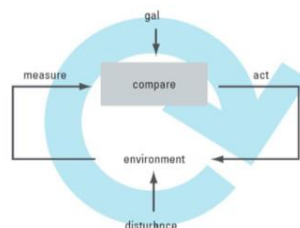

Figure 3. The basic loop of self-regulating interactive systems [1].

Kinetic motion can generally be defined through three spatial transformations: translation, rotation, and scaling, or through movement by material distortion, as in Figure. Translation is the movement of an element on a regular planar path, rotation is the element's movement around an axis, whereas scaling is the change in an object mass by expansion or contraction. Other complex movement types such as twists or rolls are a combination of these three basic movements. The fourth type of material distortion depends on material properties such as elasticity of material [22].
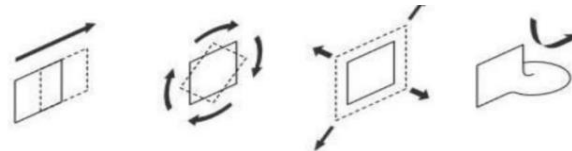

Figure 4. Kinetic motion defined through three spatial transformations (translation, rotation, and scaling) and material distortion [22].

This paper investigates the application of continuous change, using Motion Grammars, on wood as a programmable material by means of its embedded transformation properties in relation to moisture content (MC). An experiment was conducted to explore the types of exhibited motion acquired through the increase in moisture content on a rectangular sample of wood veneer. Increasing moisture content on a single side of the sample caused the wet layer to expand more than the dry layer. These unequal expansion values caused the strip to curl in relation to time. This phenomenon caused continuous and sequential differences in the deflection value (h), length (L) and radius (r) of curvature of the sample through time, as shown in Figure . A reverse motion occurs when the sample dries.
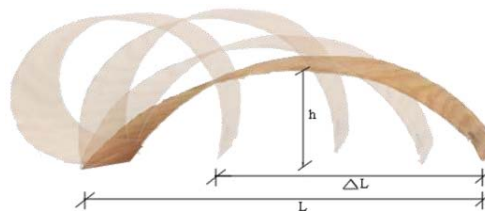

Figure 5. Sequential response motion of wood upon increase in MC.

Based on Motion Grammar logic and the motion parameters defined earlier, the following motion grammar elements can be understood accordingly as follows:

$\mathcal{F}$ refers to the values of the readings measured in this experiment through manual recordings or through sensing devices, for example the moisture content within the material sample, in addition to the current time, deflection, and length of sample measured upon applying moisture.

Z refers to the output motion, which is linked to the properties of the material, such as thickness, type, lamination, and grain orientation. This output is reflected in the values of ΔL, reflecting change in sample length; Δh, reflecting change in deflection; r, reflecting change in radius of curvature; in addition to duration of response time.

Ʞ refers to the main tokenizing function related to increase or decrease of moisture content, where moisture content defines the main driver for motion in wood.

V denotes the series of non-terminals that affect the motion outcome such as: thickness, grain orientation, type of material and lamination layers.

P refers to a series of productions that are divided into two phases. Each phase consists of discrete events located in the Ʇ tokenizing function that can be represented by a series of events. The first phase begins

due to an increase in moisture content, which results in an increase in deflection and radius of curvature, and a decrease in material length, as shown in Table. The reversible motion of the sample takes place in the second phase, which exhibits a decrease in moisture content as the sample dries, leading to a decrease in deflection and radius of curvature, and an increase in material length to return to its initial state.

K refers to the semantic rules that are directly linked in this case to the ability of the material to absorb, handle and release water, in addition to the mechanical properties of materials regarding its expansion and shrinking percentages.

U robot commands refer in this context to the overall expansion and shrinkage of wood, as a low-level action, e.g. bending the material, and flattening the material.

By defining these motion grammar elements, the framework of material motion behavior due to hygroscopic properties and change in moisture content can be identified. By programming these elements and tracking wood behavior under different conditions and using different types, thicknesses, grain orientations, and lamination mechanisms, different mechanisms can be devised to achieve desired controlled behavior.

Table 1. Defining productions, semantic rules and robot commands of wood motion in relation to motion grammar

Productions (P)	Semantic rules (K)	Robot Commands (U)
Production 1	Increase in MC	Bending the material
	Increase in Δh	
	Increase in r	
	Decrease in ΔL	
Production 2	Decrease in MC	Flattening the material
	Decrease in Δh	
	Decrease in r	
	Increase in ΔL	

7. Conclusion

This paper introduced a method to track and analyze the motion derived from programmable materials through Motion Grammar (G_M). The implication of G_M on programmable materials relies on the way the material is fabricated in which the same material acts as a sensor, processor and output element. This embedded property is enhanced through the way material is programmed. Using G_M permits an analysis method for each property and variable in this material. Tracking and analyzing this motion-embedded material allows for passive control of smart material behavior for kinetic structures in buildings.

Based on the framework in this paper, as the tokens, attributes, tokenizing functions, non-terminals, productions, semantic rules, and commands are identified, specific and customized kinematic operations can be defined to allow for material programming and to achieve a desired behavior; for example, in response to specific climatic conditions. Future development will include further investigation of motion grammar parameters for different programmable materials as a method to analyze and track their response behavior. Experimenting with wood under different conditions and climates is a direct application of the proposed framework.

8. Acknowledgment

9. References

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