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Embodied prototyping: exploration of a design-fabrication framework for large-scale model manufacturing

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ABSTRACT
For designers of large products such as boats, cars and houses, there have been few cost-effective machines or methods in support of one-to-one, large-scale physical prototyping. A novel physical production system is demonstrated, aiming at rapid prototyping of large-scale models. Research questions address possible ways that the system can support design prototyping as opposed to manufacturing. We present computational methods used to generate model data, principle of decomposition of a large model, and assembly of components to form 3D prototypes. The process of model making in this study revealed an extended use of human body. Our view on embodied cognition in relation to the development of the large-scale rapid prototyping system is discussed. We end with a projection of new possibilities for large-scale prototyping that engages the human body.

KEYWORDS
large-scale prototyping;
embodied cognition;
scalable planar structure

1. Introduction

Physical prototyping as part of an iterative design process is becoming a standard operation for most design communities. Creating physical models with automated machines is a necessary step across many product scales [36]. However, designers such as architects, civil engineers and vehicle designers are constrained by the physical size of models that can be produced with common, affordable prototyping machines. Makers, in need of large prototypes, vary widely from hobbyists to professionals. Some makers fabricate many prototypical interactive models [24] before fabricating the final product. Some others explore full-scale production of buildings directly from the same data used to build prototypical models [3],[27]. It is important to note that makers are not specialized trade workers such as carpenters, masons or plumbers. They are creative people from a variety of disciplines who are interested in using digital and some manual tools to design and build novel products.

Unlike traditional design, where a designer produces ideas and intentions, and a constructor acts on these intentions, this paper describes an integrated, generative design system that includes design reflection, fabrication-oriented model decomposition and embodied construction (prototyping). The system can be used to create large models introduced here as scalable planar structures (SPS) – 3D physical models made of 2D planar parts (Fig. 1). It minimizes repetitive, manual CAD modeling and interfaces with digital manufacturing machines, such as laser cutters, to facilitate the fabrication of model components.

The aim of this research is development of a design-fabrication framework for emerging designers and makers in need of large, low-fidelity prototypes. There exist successful examples of the convergence between design and fabrication as witnessed in the Fab Lab movement started in 2002 [16]. First, as an online community the Fab Lab program explores, trains, and shares information on product design and production with makers of all levels. Second, the maker culture as described in detail by Gross [18] is a creative community that will emerge to become the new economy. Last, the university culture of design and making is also growing to become an enterprise in engineering and particularly in architecture [26]. In spite of these advances in the field, people continue to work with CAD based software developed for visualization and final machining. Makers, Fab Lab and university systems are missing a framework and supportive software for the efficient production of large physical artifacts.

Now that 3D printing (additive manufacturing) has come of age, small artifact prototyping continues to be the norm for software and machine development

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Figure 1. A model of scalable planar structures created from the proposed system.

[4],[7],[12],[35]. Rapid prototyping falls short in generating new systems for large-scale, low-cost, low-fidelity products. Small-scale model making using 3D printers does not consider that the human body can play role in design-fabrication feedback, which is not true in large-scale prototyping [15]. More information is needed on how designers and makers interact with models and with each other. Little is known about the relationship between the body and mind beyond ergonomic concerns related to time, productivity, energy, exertion, posture, and physical loads [2].

Research questions addressed in this paper pertain to the generation of design-fabrication information and less on model representation or realistic interpretation. Part of the investigation is a search for a prototyping method suited for laser cutting or CNC machining of dense thick material. Secondarily, we investigate cognitive factors that could influence model production as a hand-guided assembly of laser cut parts. We believe these questions will lead to a design-fabrication framework and an advanced software system for design makers.

The paper is sectioned into cases and results based on the development of SPS. The next section provides a review of related work, expressing the need to expand existing design-fabrication frameworks, with ideas related to human action and cognition [34]. Section 3 is a sequenced presentation showing exploration and development of the SPS system with modeled examples. An experiment of the system production follows in Section 4, which also presents physical and cognitive factors based on quantitative and qualitative evaluation of results. Last, Section 5 attempts to address concerns of several fabricators by mapping views within embodied cognition to unexplained results. We conclude with recommendations for a design-fabrication framework that might lead to an interactive system for designers, makers and fabricators. A major contribution of this paper is the principles of decomposition of large structures, and a discussion of the human factors that would potentially provide feedback for the system development.

2. Related work

Digital manufacturing technology, such as 3D printing, has standardized our expectation on prototyping; however, standard approaches have limitations, which have motivated alternative digital methods for prototyping. Most of these methods provides a reasonable level of automation but requires human intervention at certain stages.

2.1. Digital prototyping methods

The most common digital prototyping method is layered, additive manufacturing [Fig. 2(a)]. A 3D model is digitally segmented into slices and is built slice by slice. The model materials range from powder based plastic to metals bonded by liquid; they are deposited at designated position one slice at a time [12],[13]. Large-scale layered manufacturing attempts to build artifacts to the maximum capacity of the build envelope many meters in height or width. A number of researchers have investigated ideas related to large-scale 3D printing [5],[6],[32]. There also exist a few commercial layered manufacturing machines - one in particular can build very large models within a build volume up to four meters square [33].

Cellar structure manufacturing [8–10] is a relatively new system of additive manufacturing that builds models with layering machines, while software controls the location of material binding during the manufacturing process [Fig. 2(b)]. Cellular products are 3D printed models that convert sliced data into smaller structures or meso-structures. The cellular models are built with a solid exterior surface and a hollow lattice-like interior. Distributed geometry on the inside of the model maximizes material use and minimizes machine time.

Planar structures are models composed of interlocking planar sections generated through a 3D model [Fig. 2(c)]. This system of production was first noted in the literature in 2002 [14] and then demonstrated as a way to produce furniture and toys [25]. Most recently, planar structures were investigated in depth; for example,

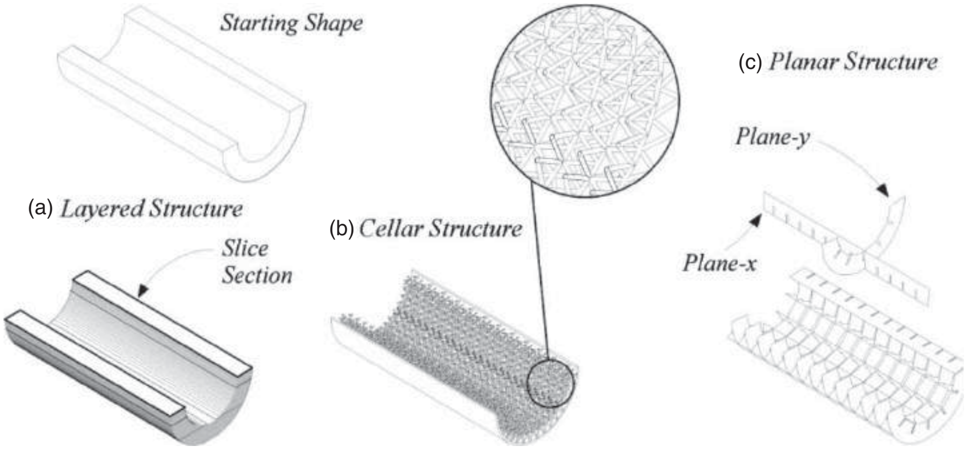

Figure 2. Three descriptions of modeling: (a) layered structure, (b) cellar structure, and (c) planar structure.

Saul et al. [28] created a chair-design system, in which the orientation of planes could vary according to the geometry of a design as a way to improve chair strength and comfort. Hildebrand et al. [21] proposed an algorithm to vary the angle and location of planes based on visual goals while maintaining structural goals. Le-Nguyen et al. [23] allowed for unequally spaced planes leading to rationalized models with strong visual representation. Schwartzburg and Pauly [30] described an algorithm to generate interlocking slots to connect non-perpendicular planes. Cignoni et al. [11] showed that by loosening the rigidity constraint of a planar component, complicated structures could be assembled from ribbon-like, bendable planar components. Finally, a commercial example of this method was developed by Autodesk. Their system is named as 123D Make that allows the user to generate a planar structure from a 3D mesh model in several ways.

With planar structures, models can be manufactured from common laser and CNC cutting machines; it is possible to have greater user control over the description of the overall structure. What is missing in the literature is a framework that takes into account the scalability of planar structures. Questions related to decomposition of a large planar structure have not been addressed.

2.2. Cognition and making

Building any large artifact from many smaller parts, of any material, is a complex set of operations. Limitations in model effectiveness as part of a creative design process could arise from unpredictable physical and cognitive struggles during assembly. Best ways to proceed can come from an investigation into the actions between the body and mind and how the body will contribute to our thinking [1]. For example, one can examine if physical fatigue can be measured against design reflection as previously illustrated by Schon [29]. Researchers in this area declare that making is more than pragmatic activity and perhaps not suitable for automation [22]. Perhaps, greater intelligence could be encoded in each component for greater feedback and learning during physical assembly [17].

Again, the greater purpose of prototyping is contribution to design. This concept starts with the premise that bodily activities also contribute to design knowledge and modification of the state space. The goal is neither to consider assembly as a complex operation in need of new tools [20], nor to consider it a problem of ergonomic efficiency [31].

A way to look at the two fields is that digital prototyping is focused mostly on pragmatic principles of model production that work well with fully automated systems. In contrast, embodied cognition is built on complimentary principles dealing with unpredictable human interaction. We hypothesize that if explored as an integrated theory, digital prototyping and embodied cognition will create new insight and integrated domains of learning that could support a novel design-fabrication framework.

3. Scalable planar structures

SPS is a generative modeling system that starts with a 3D mesh model and ends with a set of numbered drawings. The technical challenge addressed in this section is physical production of 2D simple surfaces without holes, represented in the Cartesian and polar systems (Eqs. 3.1 and 3.3). As with previous research [11],[14],[21],[23],[25],[28],[30], planar structures are built by hand as an assembly of friction fit parts; each part has a specific role and is not interchangeable with other parts. Hand assembly was guided by slotted connections laser cut into each planar component. The system was designed in three phases with a goal in systematic

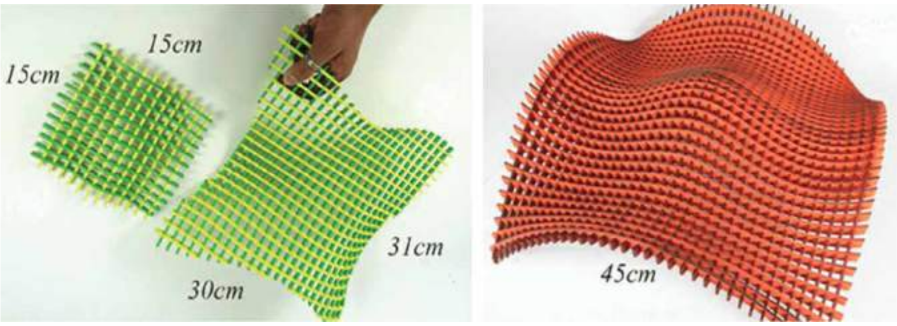

Figure 3. Models as thin wall "wafer" structures of a finite size.

construction of large volumes. Three model types are presented as cases, each capturing a phase in the development of SPS. Functions developed for the first model type can generate limited sized planar structures, whereas those developed for the other types are incorporated with the principles of decomposition so that the production of SPS of arbitrary sizes is feasible.

3.1. Case 1: one surface

In this case, a surface is prototyped as interlocking planes with inclusive slotted geometry. The surface function should be representable by

$$z = f(x, y) \tag{3.1}$$

This requires that a point (x,y) corresponds to a unique z value. Models of this type are limited in size to the maximum length of the material stock (Fig. 3). A curve along an axis on the surface is defined as a base curve, and a point on the surface is defined as a vertex.

The sequence of data processing is illustrated in Fig. 4. Four parameters are user-specified in (a), based on which the surface function is sampled, and base curves and vertices are extracted in (b) and (c). Then, each base curve is extended with a plane depth; (d) shows the planar components obtained subsequently in two directions. Slots are generated on the components for interconnection. The maximum length of the components is less than that of the material stock. A virtual assembly generated in (e) can be used to guide manual assembly. Finally, the planar components are packed to fit within a 2D sheet, ready for machine cutting (f).

The system generates a unique label on each planar component (Fig. 5). Planes along the same axis maintain a parallel relationship. The planar components can be generated from base curves of different shapes, as shown in the three examples. A finished component is a 2D parametric object composed of a base curve, start and ending line segments, and cross-plane symbols that correspond to physical slots. The slot depth is half of the plane depth. The slots are always vertical; their openings are oriented downwards consistently in one direction and upwards in the other, which enables straightforward assembly schema.

Three models shown in Fig. 3 were fabricated by laser cutting sheets of Masonite (wood). Each model is a variation in dimension, plane depth and number of contours. The quality of a finished model is related to the starting shape and user input values. For example, the plane depth affects the strength of the structure. If the value is too low, the components may break during assembly. The number of contours affects the structural integrity; many contours would result in a high-integrity structure but it is time-consuming to assemble the model; fewer contours would result in a loose structure while easier to assemble. The methods developed for this model type of a limited size is the basis for more advanced model types.

3.2. Case 2: sub-surface

A major goal of the system is to generate a range of model sizes from the same starting shape. Isotropic scaling of the shape presented two challenges. First, how to partition a long base curve into several shorter curve sections? Second, can smaller planar components, generated from the curve sections, be assembled to create a robust large model?

Fig. 6 shows a one-meter long surface that exceeds the size of material stock; hence, a base curve cannot be fabricated in one piece. To prototype the model, the value of the longest acceptable piece (Lp) should be input to the system in addition to other parameters. Based on Lp, a base curve is partitioned into several sections, as shown in Fig. 7. An in-plane slot mechanism is applied to join the partitioned sections. The interval between two cross-plane slots should be uniform because it is the spacing between two parallel base curves and is determined by the number of contours.

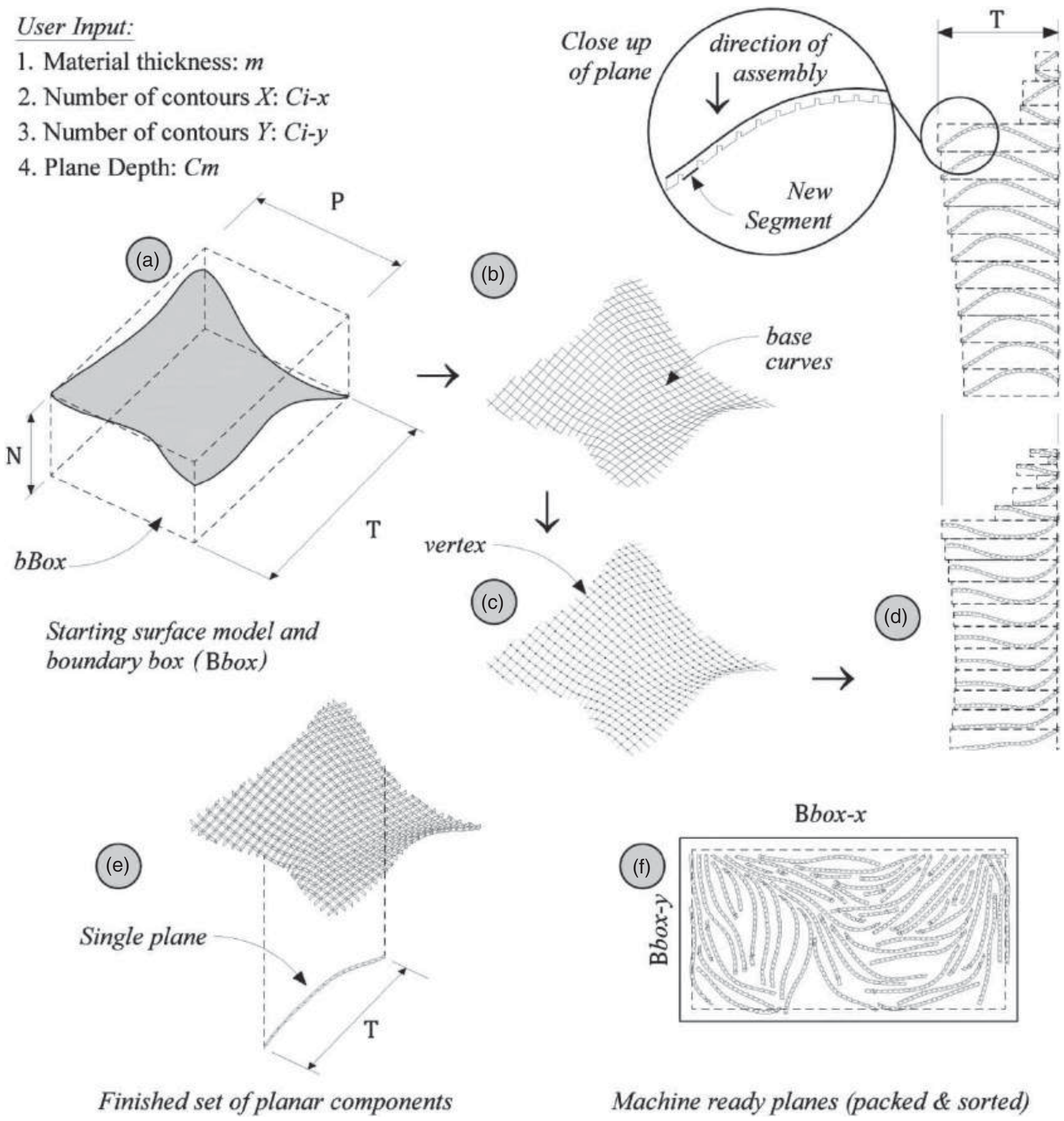

Figure 4. Core sequences of steps from initial shape to interlocking planar components.

A split vertex on a base curve is used to partition the curve. The locations of the split vertices (Fig. 7) are the key to a partitioning strategy. A simple strategy could partition all parallel base curves in one direction at the same location. This would result in a structure that can easily break at the in-plane interface because all split vertices are on the same plane. An alternative strategy depicted by the assembly schema in Fig. 7 is more robust. The locations of the split vertices oscillate on the base curves and can be expressed by

$$l_n = \begin{cases} nLp & n \text{ is even,} \\ nLp + Lp/2 & n \text{ is odd.} \end{cases} \tag{3.2}$$

where n is the index of the split vertices. In case that a split vertex and subsequently an in-plane slot is very close to a cross-plane slot, the system can shift the split vertex by a pre-set distance away from the cross-plane slot. This detail is largely implementation dependant in order to avoid a complex situation where an in-plane and a cross-plane slots are generated in the same vicinity.

The physical large-scale model was an assembly greater than one meter along one axis and half a meter along the other (Fig. 8). Most important for this study, the size meant that the model was too large to be manufactured with a common laser cutter. A set of drawings of the labelled planar components were generated based on the five user-specified variables (Fig. 6). In this example, the longest piece was limited to 45 cm, while the sheet stock was 78 cm long. The finished set contained 212 components spread out over 28 rows and 64 columns.

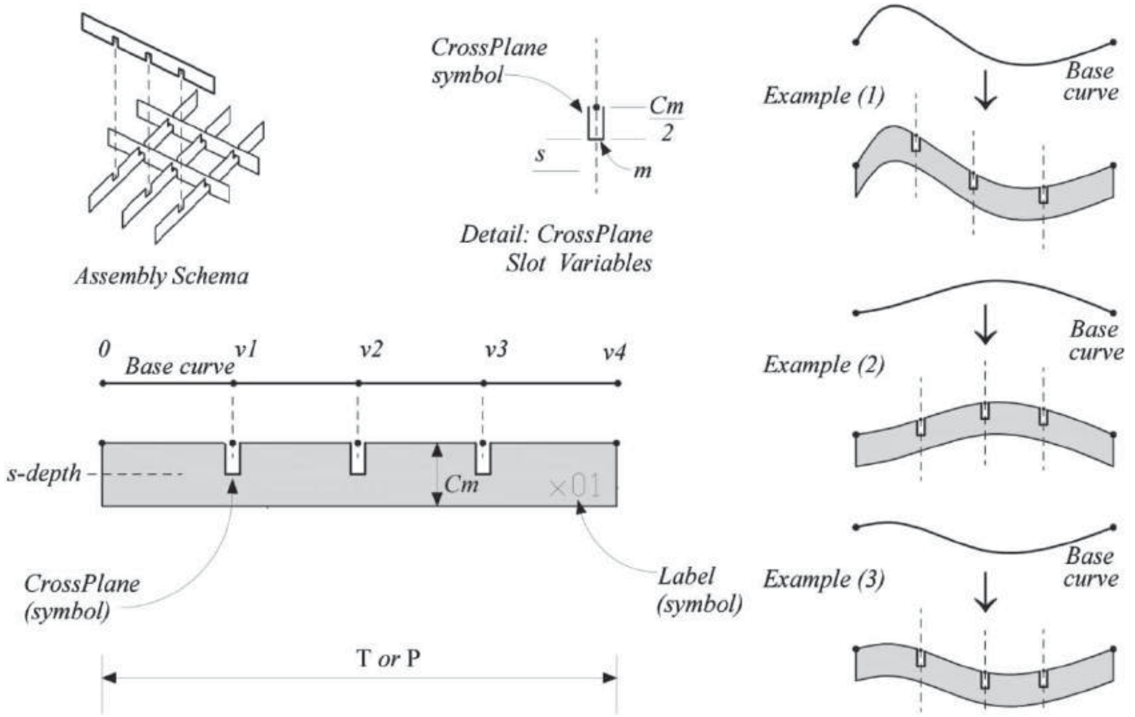

Figure 5. Anatomy of a planar component illustrating symbols (cross-plane slots) and examples of base curves of different shapes.

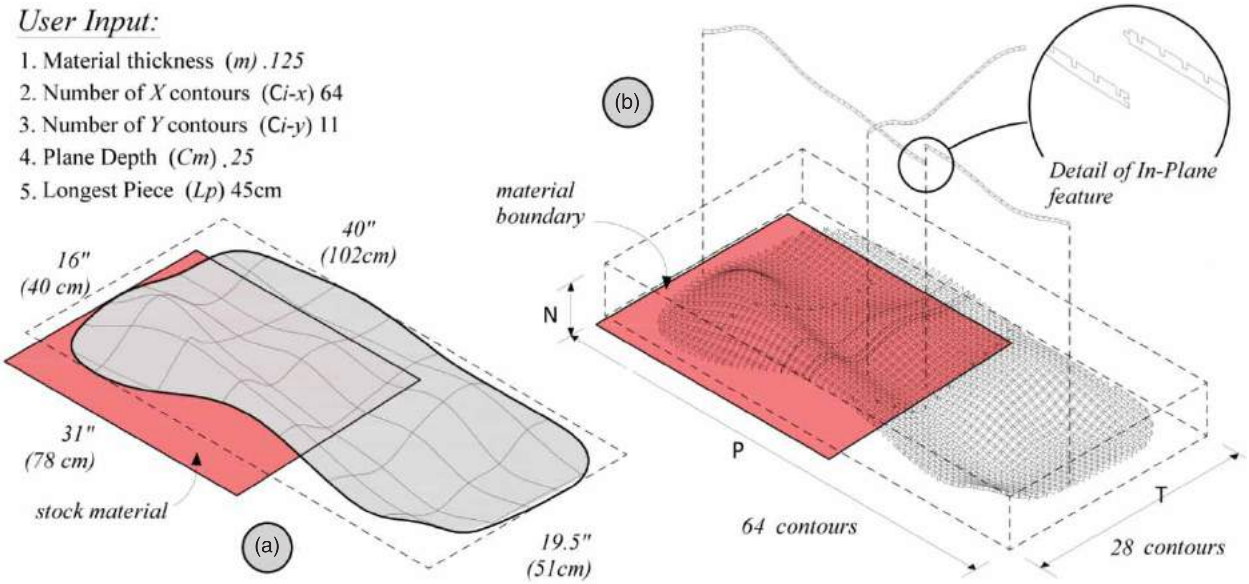

Figure 6. A surface with dimensions larger than that of the material stock. (a) The starting shape. (b) Virtual 3D model with finished parts.

3.3. *Case 3: surface of a volume*

The principle of SPS generation and partition of a linear surface can be extended to create 3D objects that occupy a volume. The starting shape was obtained by an optical line-scan method [19] and can be expressed in the polar system as

$$\rho = f(\phi, h) \tag{3.3}$$

where ϕ is an angle in $[0, 2\pi)$, h is height and ρ is a radial distance. Fig. 9 illustrates the sequence of processing. An object volume is a thin walled 3D shape consisting of closed horizontal and open vertical base curves (a). Horizontal base curves are cylindrical with a central axis. Vertical base curves are linear line segments, similar to those in Case 2. Based on the user input variables (b), the vertices are extracted to form an outline of the volume (c).

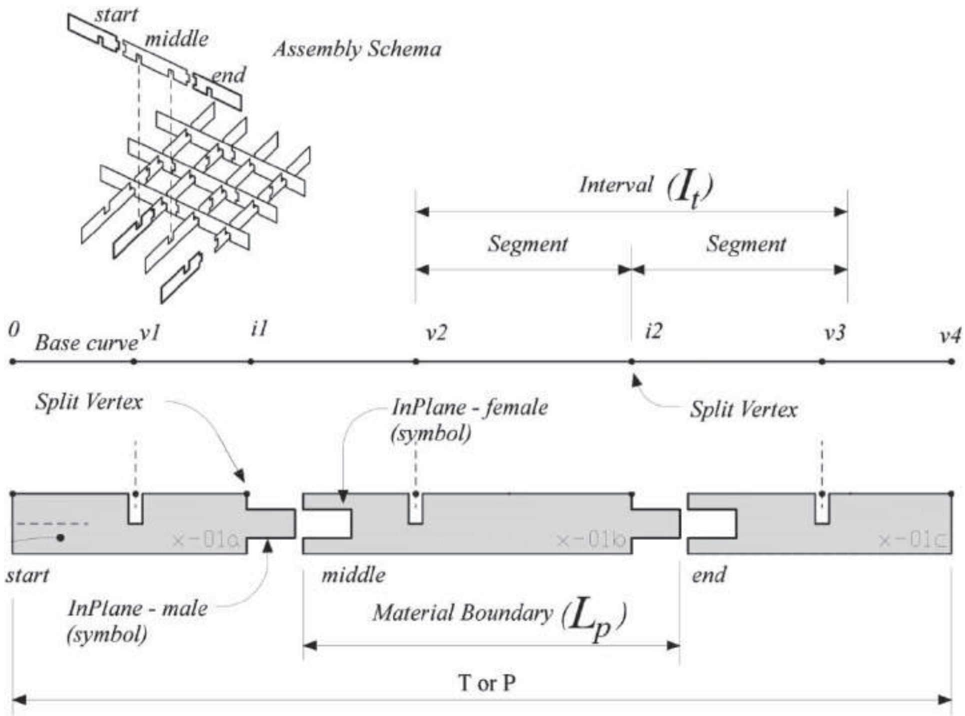

Figure 7. Anatomy of a partitioned planar component created from a base curve.

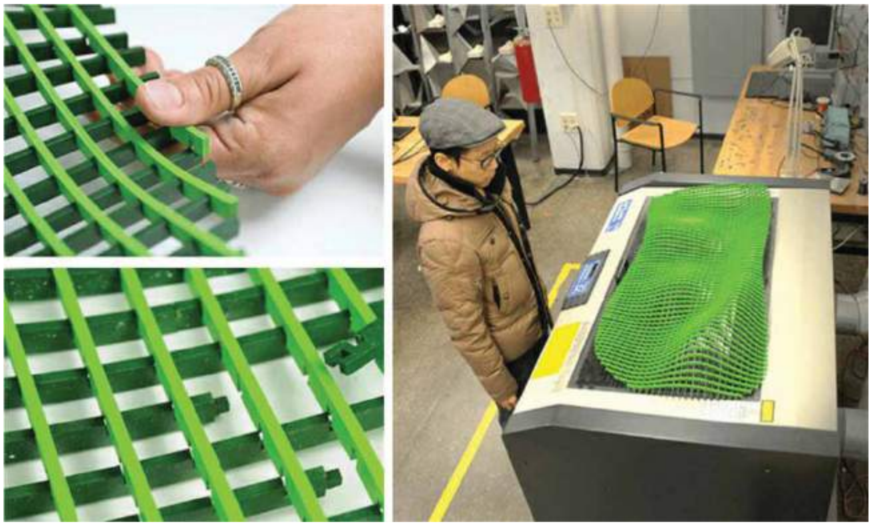

Figure 8. In-plane features of a large-scale model. Note the varying split positions in each row and the fully assembled model atop the laser cutter used.

Then, cross-plane (d) and in-plane slots (e and f) are generated. Information of line segments are processed and labels are attached to each planar component (g). The resulting components (i) can be assembled to produce a representation of the object (h).

Cross-plane slots are organized around the central axis to allow vertical components to be assembled from the outside (Fig. 10). If a vertical base curve is longer than the size of the material stock, it is linearly partitioned based on Eq. 3.2. If a horizontal base curve is too long, radial partitioning is applied. The principle of oscillation should also be incorporated in order to achieve a robust assembled structure. A feasible strategy of radial partitioning is to treat the midpoint between any two adjacent vertices as a possible split vertex (e.g. *i0*, *i1* and *i2* in Fig. 10).

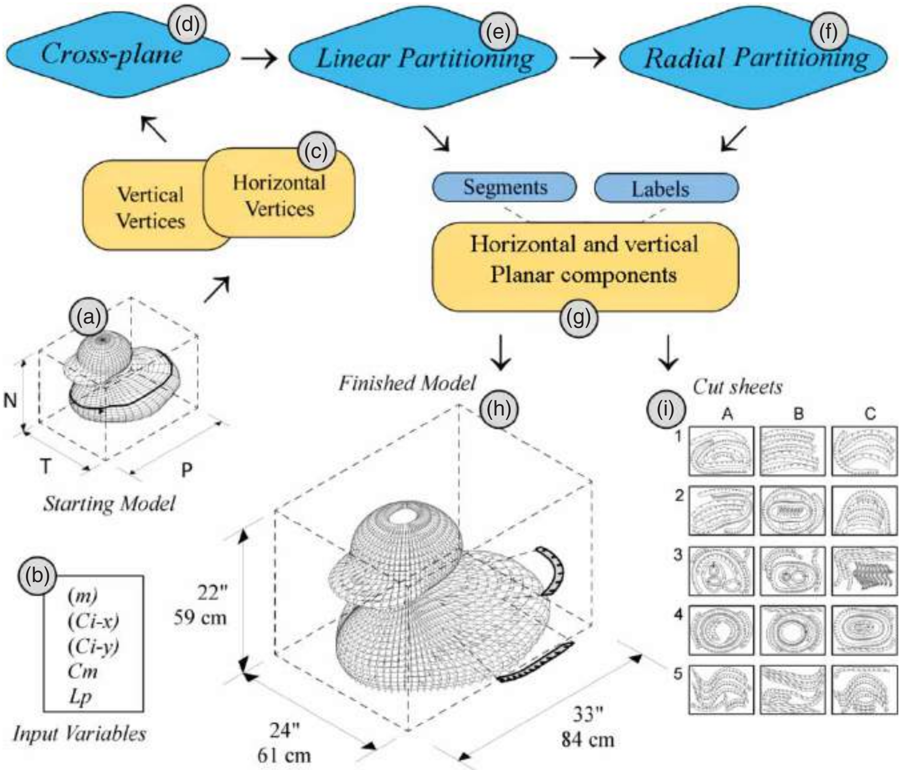

Figure 9. Core sequences of steps from initial shape to an object volume.

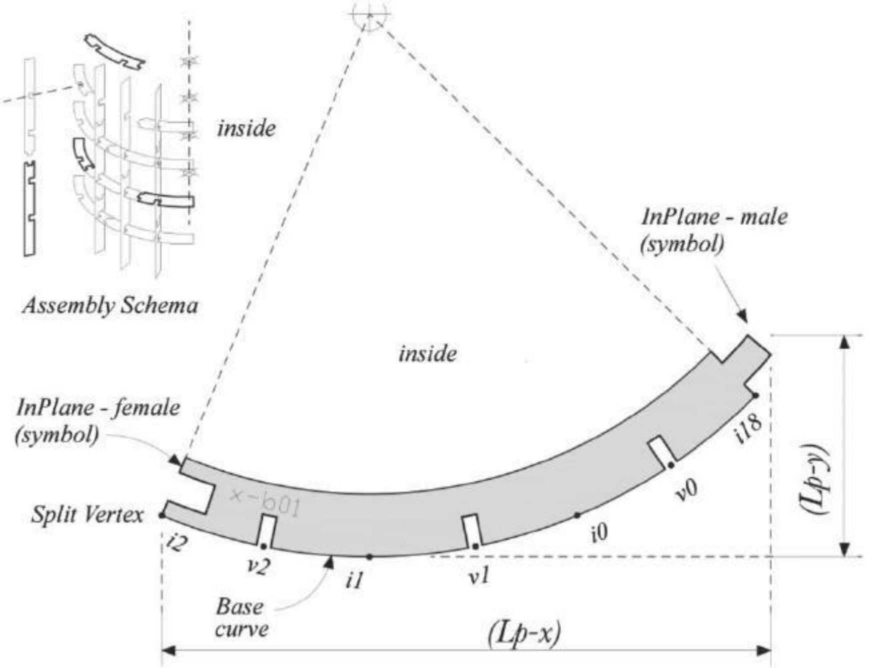

Figure 10. Anatomy of a partitioned planar component created from a horizontal base curve.

If the component is longer than *Lp*, the split vertex that is closest to the mid-section is used to partition the component into two pieces. The initial partitioning line of horizontal base curves is dependent on their index. If the index is an odd number (e.g. 1st, 3rd, etc. base curve), the line is along the x axis, as shown in Fig. 11(a); if the index is an even number, the line is rotated by an angle of θ (e.g. 30°) indicated in Fig. 11(b). Subsequent partitioning lines always go through the radial center and the split vertex midway of a component. This strategy is easy

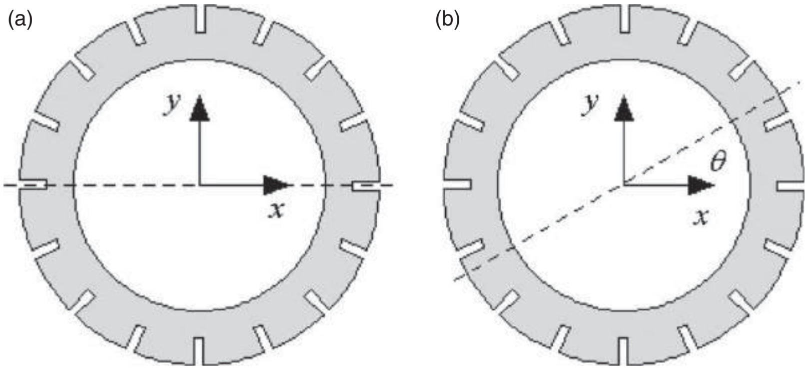

Figure 11. Initial partitioning line (dashed line) of radial partitioning. (a) The index of the horizontal component is an odd number. (b) The index is an even number.

Figure 12. (1) Middle-scale model built of 20 horizontal layers. Large-scale model: (2–3) start of assembly and base parts, (4) oscillation of in-plane slots on horizontal layers, (5) assembly of the last 30 layers, and (6) comparison in size between (a) the original model used for scanning, (b) middle-scale, and (c) large-scale models build from the same starting scan.

to program recursively and is able to produce reasonably robust structures.

Two models of varying physical sizes were created in a pilot study (Fig. 12). The purpose was to scan a toy rubber duck [Fig. 12(6a)] and fabricate a large model. The starting toy was approximately 560 cm cube. From that object, the first model (21.5 cm × 16 cm × 15 cm) consisted of 34 parts: 20 horizontal and 14 vertical planes (1). The second planar structure was a large model approximately one-meter long by half a meter wide (84 cm × 61 cm × 59 cm) built of 257 parts (2–5): 30 horizontal and 61 vertical planes. Both models were laser cut from sheets of plywood approximately 0.5 cm thick. Time taken to laser cut parts and manual assembly was not recorded. In this study, the model was laser cut and assembled by a programmer and a fabricator.

4. Experiments and results

After the pilot study, experiments focusing on SPS of Case 3 were carried out, aiming to produce objects of different shapes and to study the human factor in the design-fabrication framework. Three large models were manufactured from starting shapes scanned of a duck, a manikin and a merlion model (Fig. 13). The finished models were fabricated of Masonite with laser cutters and assembled by several fabricators (Fig. 14). The programmer managed input of variables to the system, packing parts on cut sheets, and the production of drawings for laser cutting; however, he did not participate in fabrication or assembly. The fabricators' time and energy was focused on laser cutting, assembly and cleanup.

Figure 13. Duck, manikin and merlion models.

Figure 14. Finished large-scale models built from scanned information.

4.1. Visual evaluation

We compared by the eye, the smaller handheld models against the larger models. Complex shapes, such as the merlion prototype, were not as convincing as the duck and the manikin prototypes. The model fidelity was not high at surface details. This is not surprising because SPS is a sampled representation of the original shape. To capture the surface details of the merlion, more horizontal and vertical layers are required, which takes longer to fabricate and assemble. Due to our choice of the optical line-scan method [19], all models had an opening at the top and bottom, and the merlion model was missing a hole at the tail.

4.2. Quantitative finding

Quantitative measures were taken included time, materials, size of model, and number of parts (Table 1). A strong correlation is found between the number of parts and total time consumption. On average, production of each model took 7 minutes per part regardless of model size. All models were over a meter in length in one direction.

4.3. Physical and cognitive challenges

After construction of the three models, the fabricators were asked questions regarding the assembly of each model and the use of physical space to sort and

Table 1. Breakdown of parts and time.

	Size (cm)			Parameters			
Model	*x*	*Y*	*z*	*Ci-x*	*Ci-y*	*Cm*	*Lp*
Duck	84	61	59	61	30	0.45	24
Manikin	52	36	100	30	26	0.69	36
Merlion	29	16	100	30	28	0.69	40
	Material			Time (hour)			
	Thickness	Parts	Sheets	Cutting	Assembly	Total	Min./part
Duck	0.31 cm	257	38	12	18	30	7
Manikin	0.31 cm	89	24	5	4	9	6.07
Merlion	0.31 cm	95	24	4.5	6.5	11	6.95

pre-assemble parts. They were also questioned about the quality of material, personal fatigue, structural integrity, and ease of assembly. They expressed that complications in assembly were based on material choice and that Masonite was not durable enough to sustain the load. In contrast with the first duck model (Fig. 12) fabricated of plywood, the programmer and fabricators noted that model assembly was extremely complicated and physically exhausting.

Assembly as a manual process, as opposed to using fully automated machines (e.g. 3D printers) found in additive manufacturing, revealed a range of issues. The greatest concerns expressed by the fabricators involved challenges in material handling, pre-assembly of parts, and structure stability during assembly. The partition of a large component affected the structure strength and handling of parts. Labels on the components presented a challenge to the efficiency of assembly and created confusion between parts. On several occasions, the fabricators could not understand the orientation of a component and expressed that the labels alone were not enough to organize the order or to determine the direction of assembly. The fabricators also reported that sorting the laser cut parts is time-consuming.

4.4. *Fabricator suggestions*

Various suggestions were made by the fabricators mostly related to the nature of how components could be generated and handled. First, multiple labels could be marked on a component to speed up searching. Second, manufacturing the models of flexible material such as plywood opposed to brittle Masonite. Last, one fabricator recommended the programmer to sort the components on cut sheets in an order of assembly rather than in a seemingly random order.

5. Discussion: embodied prototyping

The experiments and results indicated a need to address physical and cognitive limitations related to human intervention and model production. Initially, our measures of evaluation were set up to challenge the models by visual matching, by eye, against the original scans. Reducing the spacing and adding more material will elevate visual quality of the model details and improve matching between the scans and finished products. Structural integrity after assembly was controlled by the material thickness (m) and plane depth (Cm). Model density was controlled by the number of contours (Ci-x and Ci-y). The maximum length of each part (Lp) controlled the overall number of parts, ultimately controlling efficiency and time in assembly. All of these variables could affect the stress involved in assembly; however, it is believed that human-centered variables pertaining to cognitive factors would have greater relevance.

A set of claims from the literature on embodied cognition are discussed to provide new opportunities for human-centered actions relating to the concerns of the fabricators. The goal is to build relationship between geometry and human activity. Measures concerning the body and mind of the design-fabrication framework can address fatigue, ergonomics, cognitive overload, and environment issues. They can also provide a system of feedback to software developers. Wilson [34] identified six views in the broader field of embodied cognition. They are used here to capture and categorize human-centered activates in prototyping. The views are discussed in the context of design and fabrication.

5.1. *Cognition is situated*

Real world constraints exist, and therefore every design situation differs from another. Situated cognition is interpreted here as a need for an adaptable prototyping system. A user may choose to prototype an object in different ways depending on how the prototype will be used, evaluated or tested. For now, the SPS system processes a limited range of shapes, or objects with a central axis. It cannot process shapes with extensions such as arms as part of a human figure model. More sophisticated algorithms are under development to include more varieties of shape geometry. A situated task translated to a variable would support production of cylindrical, rectangular, developable or integratable set of shapes through interlocking or layered, or even press-fit structures. We name a human-centered variable addressing situated cognition Shape Flexibility.

5.2. *Cognition is time-pressured*

Particular to this study it was clear that the fabricators were frustrated by the amount of time required to assemble each model. Although Table 1 presented an average time for each model, more measures related to material surface variation, friction of slots, and a fabricator's height, strength and skill level are needed to determine time. Task variables may have a dynamic relationship between a series of task choices such as available fabrication time opposed to resulting assembly time. Shape geometry, tolerance of laser cutting (friction of slots) and the maximum size of each part, all have weight in a human-centered variable: Time Ratio.

5.3. *We off-load cognitive work onto the environment*

This view translates to the designer's use of space. In this study, the fabricators used space to arrange parts, pre-assemble parts, and physically access the model (Fig. 14). Task variables relating to space could include the relationship between available space and organization of parts sorted on cut sheets. Confined space means that parts are better sorted and packed on sheets in order; during assembly, sorting the physical parts is reduced to minimum. Available physical space for part layout means that parts can be sorted on the floor; hence, packing of parts on the cut sheets should maximize the use of material while largely ignoring the order of the components. We name this variable Sorting and Packing.

5.4. *The environment is part of the cognitive system*

Fundamental principles of organization and function mean that cognition is distributed across the entire interaction between human and environment. It could be interpreted as a variable in relationship to the physical size of the artifact, environment, and access. Perhaps a small person building an artifact several meters high using SPS will have to strategize model access for assembly. For example, if the duck were manufactured as a ten-meter high artifact opposed to one meter, how would workers access the assembly? Human-centered variables can be framed in terms of accessibility or fabrication of physical scaffolding as part of the generative process.

5.5. *Cognition is for action*

In this view, tools serve as an extension of the body and come into play for activities. Researchers state that reading words on a page as an action is symbolically based recognition, and that the act of reading is a system of identifying patterns and objects. In a physical design system such as SPS where parts are read and assembled, an encoded system for reading parts as shapes should be the norm. There are many ways this system can be codified – from shape semantics, to symbols encoded on each part, to finishes such as colors. We name this variable Symbolic Action.

5.6. *Off-line cognition is body based*

This is another broadly based view that explores many forms of memory as systematic ways to control body actions. One example presents implicit memory and skill as a way to offload thinking when faced with momentary challenges. Skill recall stands in opposition to situated cognition because it states that previous situations are used to manage new situations. The designer makes the system predicable for the user. Off-line example means that components are encoded with familiar assembly systems, drawing on the user's memory. Libraries of familiar features such as snap fit assemblies found in clothing or common toys (e.g. Lego) can support successful actions. There are two tasks here. First is the development of a library of common, successful features that are encoded as symbols. Second is a library recall and application system. This variable is named Fabrication Library.

As a physical model production system SPS aims to become an efficient system of very large model prototyping. As a design system SPS expects to become a design framework that contributes to design learning and emergence. Our next steps will merge embodied tasks with generative algorithms as a way to build a broader design-fabrication framework that can transform design and making into a design continuum. Finally, it can be argued that commercial additive manufacturing machines that produce prototypes quickly provide an efficient, but not experienced, prototyping approach. Counter, the design-fabrication framework aims at producing physically larger system that engages the designer as an active participant.

6. Conclusion

Physically based prototyping has many benefits beyond the measurable feedback systems illustrated here.

Designers of products such as furniture, watercraft and buildings know the benefits of a large-scale rapid system of design production. In this paper we successfully addressed questions related to basic production by fabricating models greater than a meter in length from a common prototyping machine. Second, assumptions were made that a large physical prototype assembled by hand could be limited by cognitive and physical factors not addressed in the literature on additive manufacturing. Resulting models demonstrated many complex concerns mostly related to human factors. The discussion connected methods of production and task variables with methods of evaluation found in the field of embodied cognition. Designers interested in prototyping their ideas prior to manufacturing expect and need generative systems of rapid production. SPS is a scalable low-fidelity modeler which once developed, will work as a realistic large-scale prototyping system. Future researchers and programmers can use this work in its current state as a platform to build an embodied prototyping system inclusive of new measures for cognitive activities.

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