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Reconfigurable Multi-material Layered Manufacturing

S.H. Choi[1], Y. Cai[2] and H.H. Cheung[3]

[1]The University of Hong Kong, shchoi@hku.hk
[2]The University of Hong Kong, chairekk@gmail.com
[3]The University of Hong Kong, hhoicheung@gmail.com

ABSTRACT

This paper proposes integration of reconfigurable manufacturing (RM) with layered manufacturing (LM) for development of reconfigurable multi-material layered manufacturing (MMLM) systems for fabrication of large, complex objects. We present a virtual prototyping system with reconfigurable actuators (VPRA) that can increase the number of materials, speed, and build volume to improve the efficiency and flexibility of MMLM. The VPRA system offers a test bed for design, visualization, and validation of MMLM facilities and processes. It takes advantage of the convenient graphics platform of SolidWorks™ for constructing a virtual MMLM facility by selecting reconfigurable actuators from pre-defined templates. The characteristics, including the dimensions and relative spatial constraints, of the actuators can be conveniently configured to suit design requirements. Besides, a practical approach for toolpath planning of vector-based MMLM processes with multiple robotic actuators is proposed. It classifies and models the operational spatial constraints of possible actuator collisions, and indexes the deposition priorities of materials. The contours within each layer of a multi-material object are sorted according to material deposition priorities, material distribution on the actuators, and the spatial constraints for collision avoidance. The sorted contours are then arranged into a series of deposition groups for subsequent concurrent fabrication. The resulting toolpaths can then be simulated and validated through digital fabrication of complex objects. Case studies show that it can greatly improve the concurrency of material deposition, and hence reduce the build time of large, complex multi-material objects substantially. It can be practically adapted for control of LM processes with multiple robotic actuators.

Keywords: reconfigurable manufacturing, multiple robotic actuators, multi-material layered manufacturing, virtual prototyping, concurrent toolpath planning, digital fabrication

1. INTRODUCTION

Despite recent advances in layered manufacturing (LM) technology, which is now often called 3D printing, most practicable systems can fabricate objects of only a single material or relatively simple objects of a limited number of materials. There has indeed been pressing demand for complex multi-material objects to facilitate advanced product development and biomedical applications.

Some experimental multi-material layered manufacturing (MMLM) systems [26, 28, 31–33] have been adapted from vector-based LM processes for fabrication of multi-material objects. Vector-based LM processes drive tools or nozzles in linear motions to deposit fabrication materials. They offer versatile choice of materials, better control of material composition, high material utilization, and convenient maintenance. However, there are several shortcomings, particularly with respect to fabrication materials, speed, and build volume.

Most current MMLM systems cannot conveniently handle more than four materials, although new fabrication materials are being explored. Attaching additional deposition mechanisms to handle more materials would not only make the system cumbersome and hamper its structural stiffness, but also incur extra costs which may not be justifiable without sufficient utilization. This limitation hinders fabrication of complex parts with more materials.

Another major problem is the relatively low fabrication speed [5, 23, 37]. Indeed, most systems have only one actuator to deposit solid contour areas with single lines of material, which is particularly slow for large, complex parts involving more materials.

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The build volume is also a limitation. Prototypes for various applications have been growing in both size and complexity, taking larger envelopes to build. However, with a single actuator, the end-effector often needs to travel long distances to deposit materials, delaying fabrication of each layer [36]. Moreover, a system with a large build volume may become wasteful if it is not sufficiently utilized. In fact, it is difficult to determine an appropriate build volume for an MMLM system to meet changing product demands.

For vector-based MMLM, a way to improve the fabrication speed is to introduce multiple actuators for concurrent deposition of materials. Indeed, there have been attempts to employ multiple actuators for vector-based LM, although the corresponding toolpath planning technique has yet to be further developed. For FDM, Wachsmuth [36] grouped a few extrusion heads to fabricate prototypes with large cross sections. Zhang and Khoshnevis [40] introduced contour crafting using multiple nozzles for building large constructions. They presented three corresponding toolpath planning algorithms, which were basically focused on single-material objects and could not be applied for MMLM directly. Zhu and Yu [41] proposed a spatio-temporal approach to toolpath planning for small, simple multi-material assemblies. Choi and Cheung [15] proposed a topological hierarchy-based method to group the contour toolpaths within a layer into toolpath sets for concurrent deposition of different materials. Choi and Zhu [16] enhanced this approach by separating a toolpath set into individual toolpaths. They [17] further developed a dynamic priority-based approach for concurrent multi-material deposition based on the decoupled method in multi-object motion planning. However, more operational constraints should be considered to handle practical situations and ensure process safety.

To mitigate the above shortcomings in MMLM systems, we adopt the concept of reconfigurable manufacturing (RM) to improve vector-based MMLM systems. Since its emergence in the late 1990s, RM has been successfully applied in manufacturing to improve process efficiency, capability and cost-effectiveness [24,25, 29, 39]. It has indeed been identified as among the six major challenges for competitive manufacturing in the coming years [6].

In recent years, robotic arms or actuators have been introduced to develop vector-based LM systems [4, 19–21]. In comparison with the traditional X-Y-Z stage mechanism, robotic actuators seem more flexible for vector-based LM. They offer larger work envelopes and facilitate realization of hybrid process and multi-actuator collaboration.

Indeed, robotic arms have long been used for collaborative manufacturing, like welding and product assembly. Toolpath planning for collision avoidance and efficiency improvement has been extensively studied for these applications [1, 2, 7, 22, 38]. However, toolpath planning for multiple robotic actuators in LM is significantly different, and the current methods cannot be used directly. It should not be presumed that toolpath planning of 2.5D actuator motion for LM may be simpler than 3D motion for non-LM applications. Firstly, the actuator motion for non-LM is mostly fixed for a particular job which can be defined with a few critical positions, such as the start and end points and some mid-points. But in LM, the toolpaths are determined by many layer contours of significantly varying shapes and layouts. As such, the toolpaths for non-LM are generally repetitive and pre-programmable by human operators, while those for LM vary considerably from layer to layer which can only be practically processed by complex algorithms with sufficient intelligence. Secondly, robotic actuators are usually used for pick-and-place tasks in non-LM applications without much consideration of tool velocities; in contrast, LM tools have to follow specific deposition paths and velocities determined mostly by material properties to ensure fabrication quality. Thirdly, it is necessary to consider material deposition priorities in LM. Some materials may have to be deposited prior to others for various quality reasons like strength, thermal shrinkage and warpage. However, robotic actuators for sequential tasks in non-LM applications are often pre-programmed to strictly follow some fixed sequences with little flexibility essential for LM. In summary, toolpath planning of robotic actuators for LM is different from and somewhat more complicated than for non-LM applications, and it remains a critical issue to be addressed.

This paper therefore proposes a deposition group-based toolpath planning approach with multiple robotic actuators to facilitate development of reconfigurable MMLM systems. Operational spatial constraints of possible collisions between robotic actuators are classified as distance-, position- and region-based and modeled accordingly. Layer contours are sorted according to three criteria of collision avoidance, material deposition priorities, and material distribution on the actuators. The contour areas eligible for concurrent deposition are arranged into a deposition group. While the groups in a layer are processed sequentially one by one, the contours inside each group are deposited concurrently by multiple actuators. As such, the approach facilitates fabrication of large, complex multi-material objects, by reducing the build time considerably while ensuring process safety. We have incorporated the proposed toolpath planning approach into a virtual prototyping system with reconfigurable actuators (VPRA), which provides a simulation platform for design, synthesis, visualization, and validation of the resulting reconfigurable MMLM mechanisms. As such, the costs and risks in development of physical MMLM facilities can be greatly alleviated. Besides, integrated with RM features, the actuators together with the nozzles of an MMLM system can be flexibly reconfigured conveniently to build complex multiple material objects efficiently. As a result, the overall efficiency, build volume, and number of fabrication materials of MMLM can be improved significantly.

2. RECONFIGURABLE MULTI-MATERIAL LAYERED MANUFACTURING

2.1. Multi-material Layered Manufacturing

MMLM refers to a fabrication process where an object or an assembly of objects consisting of multiple materials is built layer by layer from its corresponding CAD model, which contains sufficient material information in addition to the mere geometrical information in LM. Such multi-material (or heterogeneous) objects can be classified into two categories based on the distribution of materials within an object [35], namely (a) discrete multi-material (DMM) objects with distinct material domains and (b) functionally graded material (FGM) objects with continuous material variation along with the geometry.

With multiple materials, a prototype for design validation or surgical planning will be more intuitive, for example, telling different components in an assembly model, or distinguishing various organs in an anatomical model. In the manufacturing industry, the FGM feature is particularly desirable for parts frequently subject to extreme temperatures and high loads, such as those in modern aircraft and space shuttles. Ceramics are suitable for coating due to their excellent thermal resistance, but they cannot bear strong forces. In contrast, aluminium possesses good strength but high sensitivity to severe temperatures. Gradual material transition from aluminium interior parts to ceramic exterior surface coatings can meet both requirements of strength and thermal resistance [18]. In the medical industry, one important feature of living tissues is functional gradation, and they accordingly developed a graded biomaterial for knee joint implants [34]. The bio-inspired implant structure consisted of a mechanically rough material called high density polyethylene (HDPE) at the center, and a biocompatible surface of ultra-high molecular weight polyethylene (UHMWPE). The MMLM technology is deemed effective for fabrication of multi-material objects that satisfy these various requirements.

In recent years, the great potential of MMLM has attracted researchers to develop practicable MMLM techniques, mostly by extending existing raster-based or vector-based LM processes [37]. A few commercial MMLM machines have also come into the market. Though such developments have made important contributions to MMLM, some problems still need to be addressed to improve current MMLM systems for shop floor manufacturing and hence extend their further applications, especially for the vector-based ones. As discussed above, the limitations of current MMLM systems include the relatively low fabrication speed, limited types of materials and constrained build size of an object. To mitigate these shortcomings, we propose to adopt the concept of reconfigurable manufacturing system (RMS) to improve the responsiveness and capabilities of MMLM systems.

2.2. RM for Reconfigurable MMLM

The proposed reconfigurable MMLM system, which integrates RM with LM, can significantly enhance the overall efficiency, build volume, and the number of fabrication materials of MMLM. The actuators together with the nozzles with the MMLM system can be flexibly reconfigured for concurrent deposition of multiple materials. This would not only avoid clumsiness of attaching many nozzles to a single actuator, but also facilitate effective fabrication of objects larger than the work envelope of a single actuator.

2.2.1. Critical Issues

Practical integration of RM with LM warrants consideration of two main issues regarding deposition mechanism and process planning.

2.2.1.1. Deposition mechanism Traditional vector-based MMLM systems often make use of the XY-stage mechanism based on precise lead screws, taking advantage of their relatively low cost, high precision, and simple control. While similar mechanisms may still be used in reconfigurable MMLM systems, some researchers have attempted to use robotic arms for LM processes [4, 19–21]. Although robotic mechanisms may be more expensive and complicated in control, they exhibit more flexibility in material deposition and work envelope during fabrication, as well as easy concurrent fabrication by multiple units. Therefore, we incorporate both the XY-stage mechanism and robotic arms for integrating RMS with MMLM in the proposed VPRA system.

2.2.1.2. Process planning Process planning plays an important role in exploiting the hardware to improve fabrication speed and quality. In MMLM, the main steps generally include determination of build orientation, design of support structure if necessary, model slicing and toolpath planning [28]. Toolpath planning is particularly important because it impacts hugely on the overall fabrication efficiency and quality. It includes contour filling and tool sequencing strategy to ensure deposition continuity while avoiding tool collisions. Contour filling determines the internal pattern for filling a contour area, and has been well-studied in LM. Tool sequencing, on the other hand, coordinates the motions of multiple tools (nozzles) to build an object safely and efficiently, and has yet to be fully addressed in MMLM [11]. Intuitively, fabrication speed can be increased by concurrent deposition of actuators. Indeed, toolpath planning approaches with multi-actuators have been developed

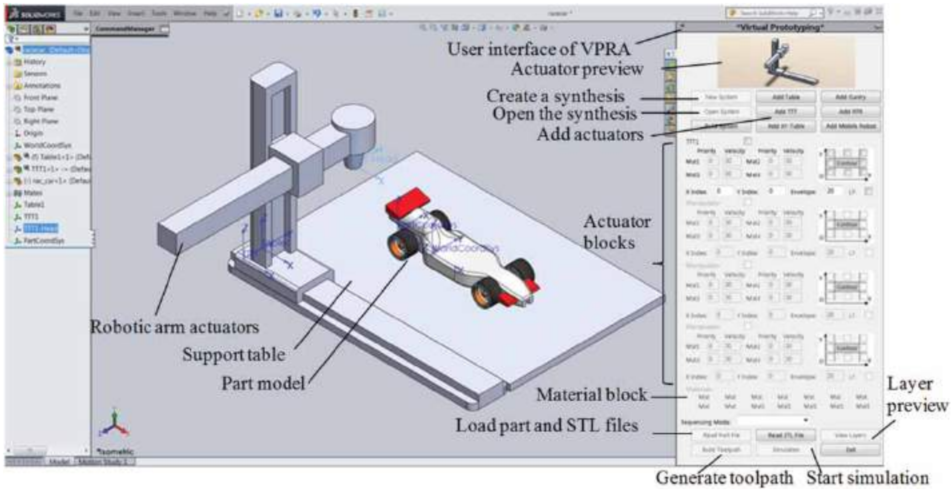


Fig. 1: Interface of VPRA.

for single-material objects [36, 40] or simple multi-material objects [41]. One main weakness of these approaches is that they consider very few operational constraints, which are essential for practicality and process safety [11,12, 16,17].

To address this weakness, this paper proposes a deposition group-based toolpath planning approach with multi-actuators. This approach classifies and models operational spatial constraints leading to possible actuator collisions, as well as indexing material deposition priorities. The contours within each layer of a multi-material object are sorted according to material deposition priorities, material distribution on the actuators, and the criteria of actuator collision avoidance. The sorted contours are then arranged into a series of deposition groups for concurrent deposition, such that deposition continuity is maintained while avoiding collisions between actuators. This approach would be incorporated into the proposed VPRA for generation of feasible and efficient toolpaths in digital fabrication. The details of this approach will be elaborated in section 4.

2.3. Virtual Prototyping for Reconfigurable MMLM

The benefits of VP for optimization of LM processes and subsequent digital fabrication of complex objects have been discussed in the literature [3, 8–15, 30]. Using VP, a virtual MMLM system can be built for visualization and simulation of the mechanism to validate and improve performance. As such, designs of new MMLM systems can also be modeled and evaluated to facilitate physical development.

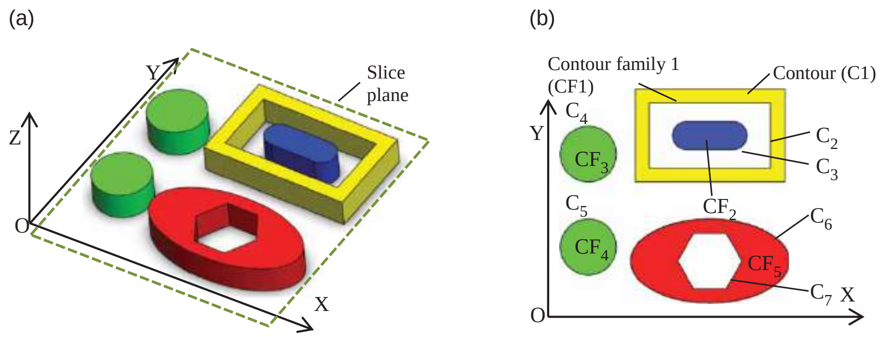
We therefore take advantage of VP to facilitate integration of RM with LM. The proposed VPRA system provides a test bed for design, visualization, validation, and subsequent improvements of vector-based MMLM facilities and processes. It is built on SolidWorks™, a commercial CAD software, to provide a convenient graphics platform for synthesizing a virtual MMLM facility with actuator templates predefined in a library as shown in Fig. 1. After planning toolpaths for an object by considering operational constraints of actuators, material attributes, process safety and efficiency, digital fabrication can be conducted to study, validate, and hence improve the performance of the virtual MMLM facility. The details of the proposed VPRA system have been presented in [10].

3. OPERATIONAL SPATIAL CONSTRAINTS OF MULTPLE ROBOTIC ACTUATORS

We now study the characteristics and modeling of three main operational spatial constraints of multiple robotic actuators, as well as indexing of material deposition priorities. Let's examine a layer of a sample multi-material part sliced by an X-Y slice plane in Fig. 2. It contains some outer contours (C1, C3, C4, C5 and C6) and inner contours (C2 and C7). A contour family (CF), formed by an outer contour together with the inner contour(s) inside it, if any, defines a solid area for deposition by a specific material [11]. There are six CFs to be deposited by multiple robotic actuators carrying four materials. Fabrication efficiency can be improved by concurrent deposition of the CFs with their corresponding actuators. However, whether two CFs can be deposited concurrently depends on factors likes the types and layout of the actuators, the materials carried by each actuator, the deposition priorities, and potential collisions between the actuators. It is essential to model various operational spatial constraints of the actuators.

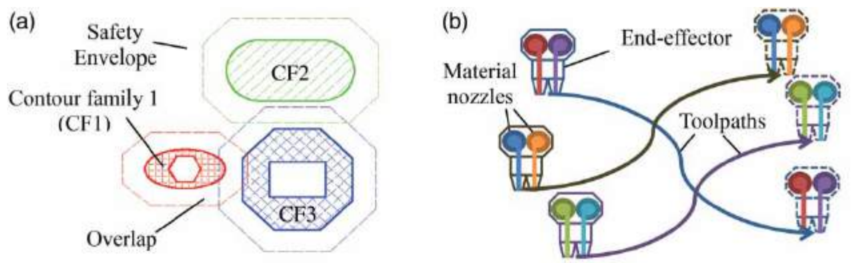
3.1. Distance-based Spatial Constraint

Let's consider depositing two CFs by two actuators concurrently. Whether this is possible depends



CAD model of the sample part A layer showing contour relationships

Fig. 2: A sample multi-material part and the contours within a layer.



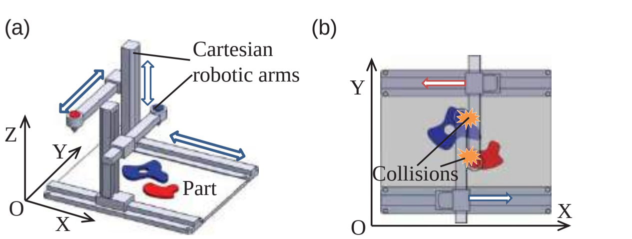
Safety envelopes of contour families End-effectors for multiple materials

Fig. 3: Modeling of distance-based spatial constraint.

primarily on the distance between the two CFs. If they are too close, there may be collisions between the end-effectors. This constraint can be modeled by assigning to each CF a safety envelope based on the end-effector radius, as in Fig. 3(a); envelope overlap tests are then conducted to plan the deposition sequence [12]. As such, CF1 and CF2 can be deposited concurrently if their envelopes do not overlap. We extend this model not only for a series of independent nozzles, but also for end-effectors that each can deposit a number of materials, as in Fig. 3(b).

3.2. Region-based Spatial Constraint

In practical operations, collisions may take place not only between the end-effectors, but also between the link arms of the actuators and between the end-effectors and the link arms. In Fig. 4, although the end-effectors of the two Cartesian robotic arms do not collide with each other, there is danger of colliding with the link arms. This problem may exacerbate for selective compliance assembly robotic arms (SCARAs) or actuators with complicated link arm postures. Therefore, a constraint model based on division of sub-regions is developed to avoid such collisions.



Fabrication layout Collisions during concurrent deposition

Fig. 4: Possible collisions between the end-effectors and the arms of two robotic actuators.

In this model, each CF is given a safety envelope with an offset distance determined by the sizes of the end-effectors and link arms. For simplicity, rectangle envelopes are adopted. Eight open sub-regions are then constructed outside the envelope along the four edges, each of which is given an ID, as shown from R1 to R8 in Fig. 5(a). According to the posture and position of a CF's corresponding actuator, one or more sub-regions are set to be the work region(s). To avoid collisions, any CFs located in these regions are not deposited concurrently with the central CF. In the example above, R7 is the work region for the blue CF because its corresponding robotic arm occupies part of this sub-region during deposition, as shown in Fig. 5(b). Since the red CF to be deposited by another actuator lies in R7, these two CFs cannot be deposited concurrently. In another example shown in Fig. 5(c), the work regions for the blue CF could be R5, R6 and R7 when it is deposited by a SCARA.

Based on this model, for any two CFs, CF1 and CF2, they are firstly given safety envelops and work regions. Subsequently, interference of work regions, i.e., whether CF1 lies in any work region of CF2 or

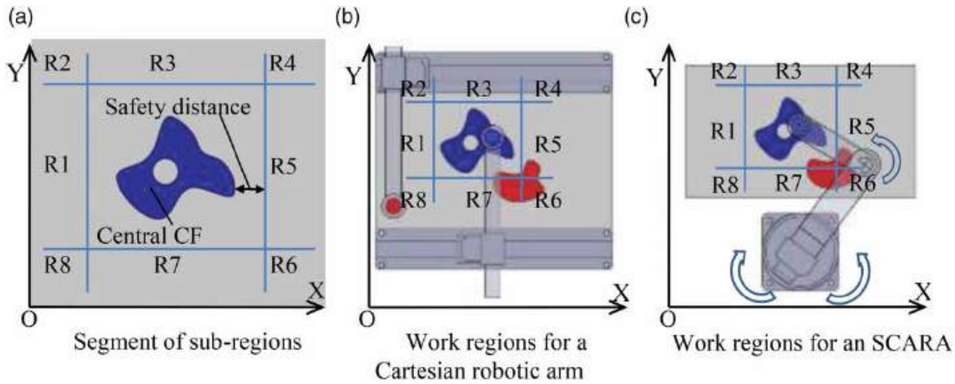


Fig. 5: Modeling of region-based constraint.

vice versa, will be checked. These two CFs can be deposited concurrently if there is no interference.

3.3. Position-based Spatial Constraint

Position-based spatial constraint exists when the actuators have to follow a position order. A typical example is the composite X-Y stage with multiple actuators. In Fig. 6(a), each end-effector (actuator) can move independently, but they must follow a position order in the X-axis and cannot get across one another.

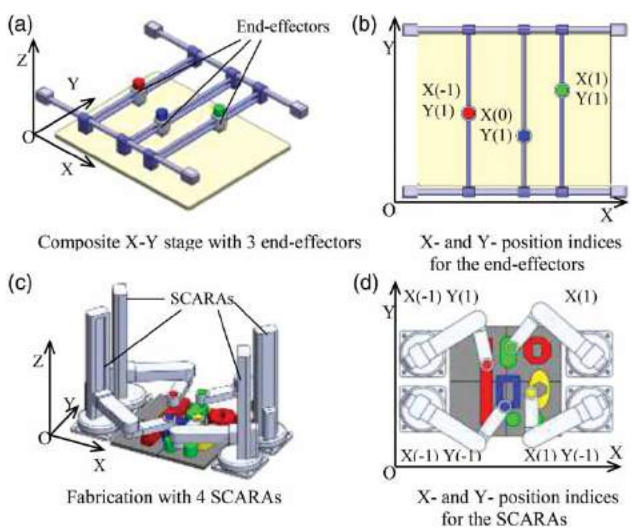


Fig. 6: Modeling of position-based spatial constraint.

In a typical coordinate system, layers of fabrication materials are deposited in the X-Y plane and stacked along the Z-axis. To model position-based spatial constraint, each actuator is given a position index to indicate its order in the X- and Y-axis. A larger X index value indicates the actuator is on the right side of those with smaller values in the X-axis, and a larger Y index indicates it is above those with smaller values in the Y-axis. For the composite X-Y stage in Fig. 6(a), the three end-effectors can be given position indices X(-1), X(0), and X(1) to indicate their position order in the X-axis respectively. Since they do not have a restricted position order in the Y-axis, their indices are all set to be Y(1), as in Fig. 6(b).

This constraint model also applies to some robotic arm actuators. For another example in Fig. 6(c), the four SCARA robotic actuators can be assigned indices X(-1)-Y(-1), X(-1)-Y(1), X(1)-Y(-1), and X(1)-Y(1), respectively, to model their position constraints as in Fig. 6(d).

Based on this model, for two CFs, CF1 and CF2, the proposed approach will check whether the positions of CF1 and CF2 match the position indices of their actuators. Specifically, it examines whether the CF whose actuator has a larger X index is located on the right side in X-axis, and that with a larger Y index is on the upper side in Y-axis. For example, if the X index of CF1's corresponding actuator is larger than that of CF2's, it means CF1's actuator should be on the right of CF2's. Therefore, if CF1 is located on the left of CF2, these two CFs cannot be deposited concurrently.

3.4. Material Deposition Priorities

The properties of materials for multi-material objects may vary significantly. To ensure fabrication quality, some materials may have to be deposited in a specific order or prior to others. This is vital for fabrication of cell-seeded biomedical scaffolds in tissue engineering, where certain materials have to be deposited first to construct scaffolds before live cells are placed. To model material property constraint, a priority index is assigned to each of the materials of an object to indicate the deposition priority of the related CFs. A material with a smaller priority index indicates that its CFs should be deposited before those of other materials with larger indices. For example, the CFs of a material with priority index (1) should be deposited prior to those of all other materials, and the CFs of a material with index (2) should be fabricated before those of another material with index (4).

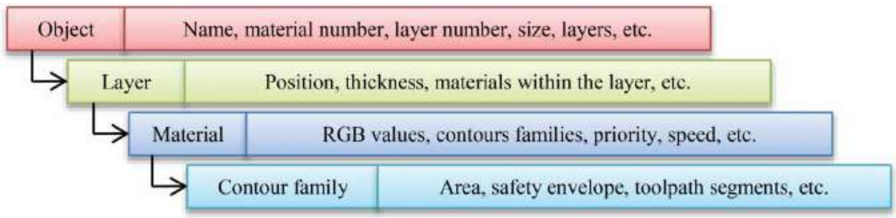


Fig. 7: Hierarchical structure for management of contour data.

3.5. Management of Contour Data

After slicing, sorting, and hatching operations [12], the contour data of an object are arranged according to their topological relationships into a hierarchical structure in Fig. 7 to facilitate subsequent toolpath planning. An entity in a higher hierarchy may consist of a number of entities of the adjacent lower hierarchy. For example, a layer may have to be deposited by several materials, each of which is assigned a unique RGB value.

3.6. Operational Data Structure of Actuators

The operational data of an actuator are structured as a comprehensive descriptor, as shown in Fig. 8. The geometrical data store the main dimensions of the actuator, including the length of a screw lead and the diameter of the end-effector. The position data indicate the actuator's position and posture during fabrication. The material data contain the RGB values of the materials on the end-effector. In previous works [26, 28], the end-effector of an actuator can generally deposit at most four kinds of materials, which can satisfy most common applications while avoiding clumsiness of the deposition mechanism. We therefore follow this restriction. The constraint data specify the operational spatial constraints of the actuators, such as X- and Y-position indices. The actuator ID is used in the sorting procedures to be presented below, where each layer CF would be assigned such an ID to indicate which actuator would deposit it.

Fig. 8: Operational data structure of an actuator.

With the data structure above, the relation between a multi-material object and the actuators can be established. By matching the RGB information in the object and the actuators, we can identify which actuator will deposit the CFs of a specific material. Moreover, the constraint data, position data, and ID of an actuator can be associated with the corresponding CFs with the same material for subsequent sorting. Using multiple actuators can also improve fabrication efficiency of large single-material objects by replacing the materials on their end-effectors with a single material for concurrent deposition of the object. However, the relation between the single-material object and the actuators cannot be determined with the data structure above, for the RGB data of all the actuators are the same. This will be dealt with in Section 4 below.

4. TOOLPATH PLANNING FOR RECONFIGURABLE MMLM

Fig. 9 shows the data structure for representing a multi-material object. An Object may be composed of a number of layers of materials (Layers), which form an array of layers (LayerArray). A Layer may contain several fabrication materials (Materials), which form an array of materials (MaterialArray). A Material may comprise some Contour families (CFs) forming a CFArray. Each CF is assigned an index Status to indicate its sorting status. Status 1 means the CF has been sorted, and 0 otherwise.

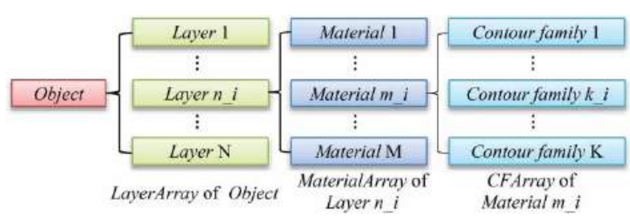


Fig. 9: Data representation of a multi-material object.

We assume that deposition of a CF is completed in a one-off manner without pauses or disturbances. This ensures better fabrication quality and makes the toolpaths more practicable. Based on the relationship between an object and the actuators in Fig. 10,

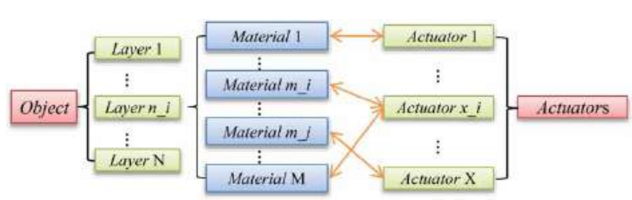


Fig. 10: Relationship between a multi-material object and the actuators.

the following procedure elaborates the generation of concurrent toolpaths for the CFs in a specific layer.

- Step 1: For each CF in the Layer, set Status = 0 and associate the ID and the relevant position and constraint data of their corresponding Actuator with them respectively after matching the RGB information of the Materials they belong to and the Actuators.
- Step 2: For the CFArray of each Material in the Layer, rearrange the order of CFs in them respectively by the deposition durations of the CFs.
- Step 3: Rearrange the order of the Materials in the MaterialArray so that those with higher priorities will be listed ahead.
- Step 4: For the first Material in the MaterialArray, pick up the first CF with Status = 0 in its CFArray. Set the Status of this CF to be 1, and add it into the ReadyArray, which contains the CFs to be deposited in a group. If none of the CFs in the CFArray of this Material satisfy Status = 0, try to pick up such a CF in the remaining Materials in priority order until one is found.
- Step 5: For the remaining Materials in the MaterialArray, each CF in their individual CFArray with Status = 0 will sequentially conduct the test shown in Fig. 10 with the CF(s) in the ReadyArray. For a CF, if the index ToAdd remains “True” after the test, it will be added into the ReadyArray and should be considered in the tests for remaining CFs. Meanwhile, the tests for the rest CFs in the current CFArray will be suspended, and the tests for the CFs in the CFArray of the next Material will begin.
- Step 6: For all the CFs in the ReadyArray, set Status = 1. These CFs will form a new deposition group to be deposited concurrently.
- Step 7: Clear the CF(s) in the ReadyArray.
- Step 8: If all the CFs in this Layer satisfy Status = 1, continue sorting for the next Layer. Otherwise, return to Step 4, and repeat the rest steps for another deposition group.

It should be noted that in Fig. 11, besides the tests for the constraints based on distance, work region, position and material priorities, an additional test is conducted to check whether TestCF and RefCF are the same one on the same actuator. Two CFs on the same actuator cannot be fabricated in the same deposition group.

The initial CF sorting in Step 2 improves the efficiency of the resulting toolpaths by alleviating sequence randomness of the CFs in each CFArray. Very often, more than one CF in a CFArray may pass the collision tests in Fig. 11. The initial CF sorting in Step 2 ensures the deposition duration of the CF chosen from a CFArray into the ReadyArray, if any, is the longest among all the CFs in the same CFArray passing the collision tests. Indeed, if the deposition durations of the CFs within a deposition group are closer, less time will be wasted on actuator idling. Without this initial sorting, however, a CF added into the ReadyArray may be the one with short deposition duration in its CFArray, while other CFs in the ReadyArray may be with long durations in their individual CFArrays. In this case, the durations of the CFs in the same deposition group will have large deviations, causing more actuator idling.

The output for each layer, as shown in Fig. 12, is a list of deposition groups, each of which may contain a number of CFs. The deposition groups can be deposited concurrently with the relevant materials, because collision avoidance, allocation of materials

Definitions:
TestCF: a *CF* in the *CFArray* to conduct test;
RefCF: a *CF* in the *ReadyArray*;
ToAdd: an index of whether to add the *TestCF* into the *ReadyArray*.

```
For each RefCF in the ReadyArray,  check the following:
  if ( envelopes of TestCF and RefCF overlap ||
       material priority of TestCF < material priority of RefCF ||
       actuators of TestCF and RefCF are the same ||
       TestCF and RefCF interfere with each other's work regions ||
       positions of TestCF and RefCF violate the position indices of their actuators )
     set ToAdd = False;
  else
     set ToAdd = True;
```

Fig. 11: Tests to determine concurrent deposition of contour families.

on actuators, and material deposition priorities have been taken into consideration.

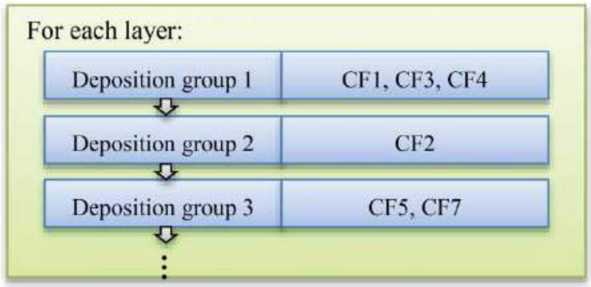


Fig. 12: Deposition groups in a layer.

Different internal contour filling styles, either zigzag or spiral, will not affect the number and the constituent CFs of the deposition groups, because the sequencing operation is based on the safety envelopes of CFs. The data of the CFs within a deposition group are used to calculate the duration and end time of the group, and to determine the start time of the next group. In comparison with the previous works [12], the proposed algorithm sorts deposition sequence at CF level, instead of at material level. In other words, deposition of specific CFs may start earlier before finishing all the CFs of another material.

5. CASE STUDIES

5.1. Toolpath Planning for a Discrete Multi-material Toy Excavator Model

A discrete multi-material toy excavator model with dimensions of 306 mm × 97 mm × 138 mm, as shown in Fig. 13, is used as the sample prototype. Fig. 8 shows the virtual MMLM facility synthesized in the SolidWorks environment for digital fabrication of the excavator, which consists of four actuators in the form of mobile robots.

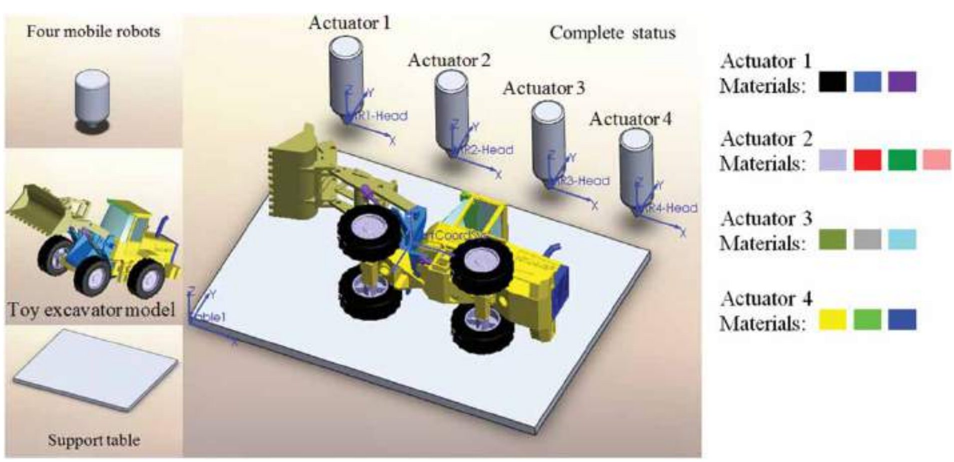


Fig. 13: Synthesis of MMLM facility for digital fabrication of a discrete multi-material toy excavator.

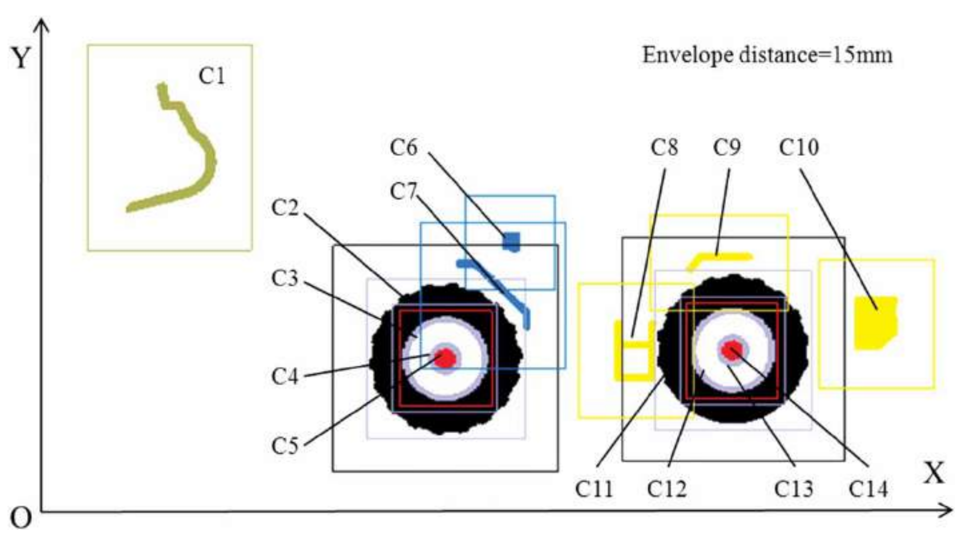


Fig. 14: Contours of a selected layer.

The color STL model of the toy excavator is sliced into 100 layers with hatch width being 1 mm after it is loaded and transformed. Its thirteen types of material are assigned to the actuators from the material blocks. Theoretically, these materials can be randomly assigned to the actuators as long as the nozzle capacity limitation on each actuator is not violated. However, to improve the efficiency of the toolpaths to be generated, the assignment of materials should be conducted following the distribution of the materials in the prototype and the constraints among the actuators. For the actuators in this virtual facility, since the constraints among them are based on the distance between contours, the contours of the materials on one actuator should not be adjacent to those of materials on other actuators. As such, the possibility of collision can be reduced, and deposition concurrency increased. The deposition speed and priority of each material are also defined. Moreover, a safety distance of 15 mm is assigned to each actuator according to their dimensions.

Fig. 14 shows a selected layer of the toy excavator, where each contour has been added a safety envelope with the distance defined before. Based on the result of the overlap test among these safety envelopes, the multi-material toolpath planning module would follow the procedures introduced previously, and generate a series of deposition groups for this layer, as shown in Fig. 15. Each deposition group consists of one or more contours to be deposited concurrently. According to these deposition groups, the digital fabrication of this layer is visualized as shown in Fig. 16.

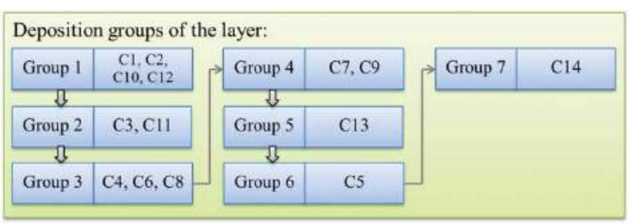


Fig. 15: Deposition groups for the selected layer.

As can be seen, except for some contours which inevitably have to be deposited sequentially, multiple actuators are capable of depositing the remaining contours concurrently without collisions during the digital fabrication of the selected layer. The total build time is about 143.34 minutes with the concurrent toolpaths, and 216.13 minutes with the sequential toolpaths; the build time saving is 33.68%.

5.2. Digital Fabrication of a Multi-material Brooch

The jewelry industry is a potential big user of MMLM technology. Fig. 17 shows a composite X-Y stage LM system consisting of two actuators for fabrication of a multi-material brooch. A total of five materials are assigned to the end-effectors according to their

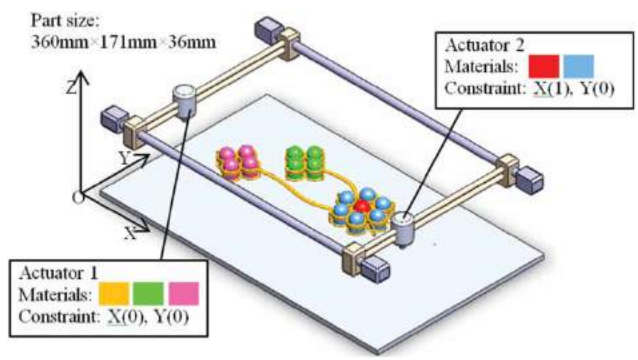


Fig. 17: A composite X-Y stage with two actuators for fabrication of a multi-material brooch.

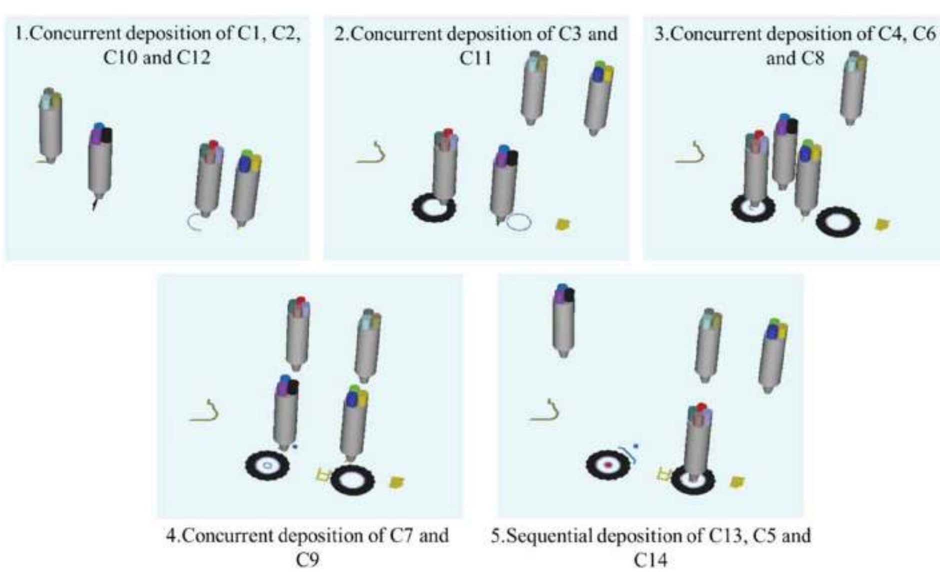


Fig. 16: Digital fabrication of the selected layer with concurrent toolpaths.

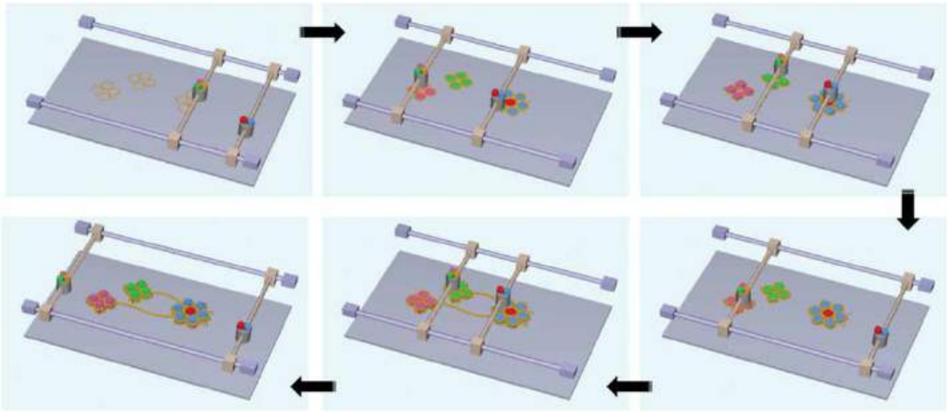


Fig. 18: Digital fabrication of the brooch.

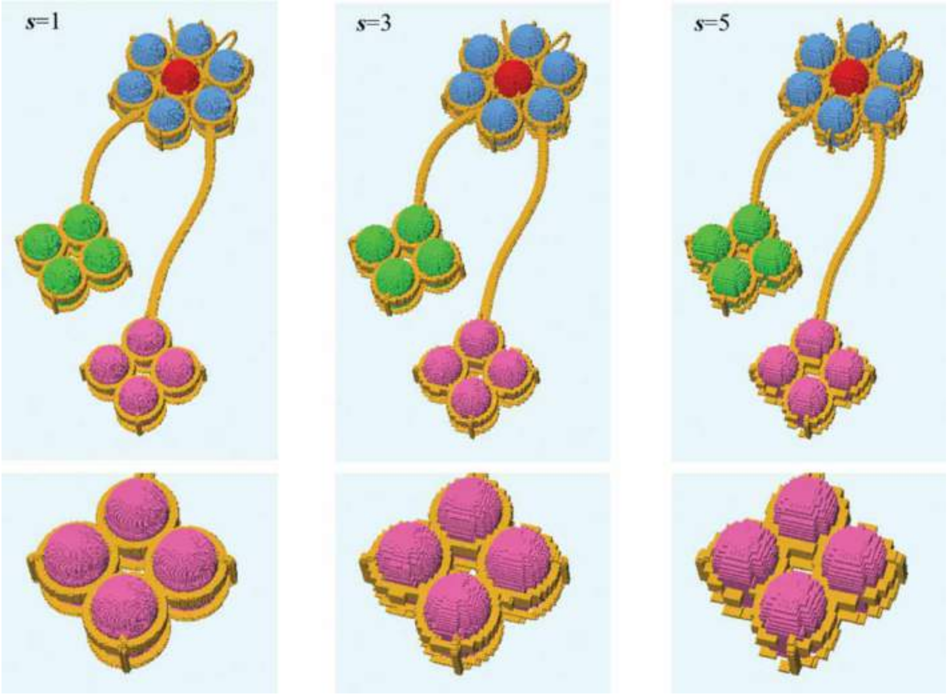


Fig. 19: Digital brooch with 3 different levels of display smoothness and simulation realness

distribution in the brooch. Since the brooch skeleton is made of orange material, it is assigned the highest deposition priority. The color STL model of the brooch is sliced into 100 layers with a hatch width of 1 mm. The position-based spatial constraint between the two actuators is as follows. Actuator 1 is assigned X(0) and Y(0) as its X- and Y-position index, respectively, while Actuator 2 is X(1) and Y(0). Moreover, a safety distance of 20 mm is assigned to each actuator according to the dimensions of their end-effectors.

Based on the settings above, concurrent toolpaths are generated for subsequent digital fabrication, several stages of which are shown in Fig. 18. Fig. 19 shows the result digital brooch displayed in three different levels of display smoothness and simulation realness.

With identical layer thickness and hatch width, the total build time for the fabrication of the brooch model in this composite XY-table is estimated to be 345.58 minutes with the concurrent toolpaths generated, while it is 543.78 minutes with sequential toolpaths. Hence, the toolpaths generated in the VPRA can help improve the process efficiency considerably.

6. CONCLUSION

This paper presents integration of reconfigurable manufacturing with layered manufacturing and proposes a practical toolpath planning approach, based on deposition groups for concurrent deposition by multiple actuators to improve the overall fabrication efficiency, build volume, and number of materials of complex multi-material objects. The operational spatial constraints causing actuator collisions are classified and modeled, and material deposition priorities are indexed. The layer contours are sorted based on actuator collision avoidance, material deposition priorities, and material distribution on the actuators. The contours eligible for concurrent deposition are arranged into a series of deposition groups, within each of which all the contours will be deposited concurrently. The proposed approach has been implemented in a virtual prototyping system with reconfigurable actuators (VPRA) for simulation and visualization of MMLM processes. The VPRA system provides insights into the characteristics of reconfigurable MMLM, which can be subsequently materialized for physical fabrication of multi-material objects. This approach highlights a possible direction for development of MMLM technology. Case studies show that it can effectively consider operational spatial constraints to avoid collisions and uphold material deposition priorities to ensure fabrication quality. This exploits the potential of multiple robotic actuators to improve fabrication efficiency of both multi- and single-material objects. It can indeed be adapted for control of physical MMLM processes.

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