A Toolpath Design Platform for Multi-material Layered Manufacturing

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ABSTRACT

Toolpath planning is vital to multi-material layered manufacturing (MMLM), particularly for improvements in fabrication efficiency and quality of prototypes. This paper proposes a toolpath design platform (TDP) for planning and validation of toolpaths in MMLM. The TDP consists of three constraint modelling modules to represent common operational and mechanical constraints of an MMLM process, and subsequently generate feasible and efficient toolpaths for digital fabrication of multi-material prototypes in a built-in virtual prototyping (VP) module. The material deposition speeds and priorities can also be adjusted to suit various material properties and optimize the toolpaths. Simulations show that the TDP is an effective tool to model and simulate MMLM processes, and accordingly generate practicable toolpath strategies for different application requirements.

Keywords: toolpath planning, constraint modelling, virtual prototyping.
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1 INTRODUCTION

Layered Manufacturing (LM), also known as Rapid Prototyping (RP), is an additive manufacturing technology widely adopted in manufacturing, jewellery, and bio-medical industries [7][10][15] for fabricating prototypes to help save cost and time of product development. In recent years, attempts have been made to adapt LM to fabricate functional components and end-use products. Moreover, high value-added products and bio-medical objects often involve complicated designs with multiple materials to exploit superior properties unparalleled by a single material. There is therefore an imminent need to develop multi-material layered manufacturing (MMLM) technology.

MMLM refers to a fabrication process of an object or an assembly of objects consisting of multiple materials layer by layer from a CAD model with sufficient material information. Some researchers have explored different techniques to fabricate multi-material objects, and experimental MMLM systems have been adapted from the LM technology. However, these MMLM systems usually tended to be of low efficiency and could not fabricate large, complex objects. Besides requisite efforts on hardware design, it is particularly imperative to develop an integrated toolpath planning system for MMLM. This is because toolpath planning controls the motion sequence of an array of tools to fabricate a prototype effectively without collisions [4], and it has a huge impact on the overall efficiency and the fabrication quality of MMLM.

This paper therefore proposes a toolpath design platform (TDP) for toolpath planning and validation in MMLM. The TDP is a simulator consisting mainly of three constraint modelling modules, which are distance-based, position-based, and region-based respectively. These modules can model common operational and mechanical constraints in an MMLM process, and subsequently generate a feasible and efficient toolpath strategy with necessary modelling parameter input. The speeds and priorities of material deposition can be adjusted to suit different material properties and optimize toolpaths. Moreover, digital fabrication of a prototype can be simulated in a built-in virtual prototyping (VP) module to visualize and validate the toolpaths. Simulations show that the TDP can conveniently model practical constraints in an MMLM process, and generate effective toolpath strategies to suit specific requirements of different applications.

2 LITERATURE REVIEW

2.1 Multi-material Layered Manufacturing

Some researchers have tried to develop multi-material layered manufacturing (MMLM) systems based on raster-based LM processes, in which contours of material are selectively generated out of an entire layer. Examples of this type of MMLM systems include Stereolithography (SLA) [2], Selective Laser Sintering (SLS) processes [1][17] and 3D Printing [18]. Such raster-based MMLM systems require a more efficient material deposition sub-system and an advanced software system to process complex parts and to enhance efficiency.

On the other hand, other researchers have focused on adapting vector-based LM processes, in which a tool is driven along a predefined path to deposit fabrication material, for MMLM applications. The Fused Deposition Modelling (FDM) system has been extended with additional nozzles, each depositing a specific material [11], for fabrication of ceramic and biomedical objects [8][9]. Besides these extrusion-based ones, some MMLM systems based on local laser-sintering have also been developed to fabricate parts with functionally graded materials, in which a laser was focused onto a substrate to create a melt pool, and metal powder was injected into the melt pool to increase the material volume [12][14].

Although such extrusion-based and local laser-sintering processes are relatively slow in build speed, they exhibit higher flexibility in build material selection and better reliability on material deposition. They can also be adapted from existing LM systems, and many emerging commercial MMLM systems tend to belong to this category. The proposed TDP is therefore developed for these two types of vector-based MMLM processes.

2.2 Toolpath Planning

Toolpath planning is a key issue of MMLM because it affects prototype quality and fabrication efficiency hugely. For vector-based MMLM, it mainly concerns with planning the motion sequence of an array of tools to deposit materials on specific contours. Since vector-based MMLM processes are inherently slow in forming a whole layer, it is greatly desirable that the array of tools containing different materials can deposit concurrently to reduce build time while eliminating tool collisions.

Some researchers have attempted to develop tool sequencing strategies for MMLM with consideration of collision avoidance and fabrication efficiency. Zhu and Yu [19] proposed a collision detection and toolpath planning method for simple multi-material assemblies with spatio-temporal modelling. This method was intuitive and effective for a small number of contours, but would become very complex when more contours and materials were involved. Choi and Cheung [4] proposed a topological hierarchy-based multi-toolpath planning approach, where the toolpaths of the contours within a slice were grouped into toolpath sets according to their materials, and an entire envelope-based concurrent planning algorithm was used to arrange the deposition sequence of the toolpath sets. Based on this approach, a toolpath set was further divided into individual toolpaths and deposition of a contour would begin when no overlap between its envelope and others was detected [6]; moreover, a dynamic priority-based approach was developed for concurrent multi-material deposition based on the decoupled method in multi-object motion planning. However, their approaches required hardware mechanism in the form of mobile robots equipped with nozzles, which might not be used directly in the current stage.

Nowadays, most vector-based MMLM systems are based on the traditional translation mechanism widely used in milling machines, or on robotic arms with 3 degrees-of-freedom or more. Concurrent deposition of multiple nozzles is often constrained by interferences between mechanical structures. Moreover, the tool sequencing problem may become more complicated by the need to change deposition speeds or priorities of the tools to satisfy different material properties. All these constraints should be taken into consideration in toolpath planning.

2.3 Virtual Prototyping

Virtual prototyping (VP), often conducted in a virtual reality (VR) environment, is an effective simulation technology for product development by creating digital prototypes in lieu of physical ones. VP can be used to evaluate product design, validate manufacturing processes and test product functionality.

Xu *et al.* [16] developed a virtual rapid prototyping system (VRPS) to optimize process parameters in the SLS process. Qiu *et al.* [13] proposed a simulator for virtual fabrication of multi-material prototypes. The simulator could not only generate optimal toolpath for multiple materials, but also help detect and remove faults in the MMLM process. Choi and Chan [3] developed a virtual prototyping system to simulate both dexel-based and layer-based LM processes, and to study the surface accuracy of prototype. However, this system could only simulate single-material LM processes. It was further developed into a versatile multi-material VP system for processing relatively complex objects [5]. This multi-material VP system consisted of two modules for design and process planning of discrete multi-material objects and functionally graded objects respectively, and a virtual reality simulation module for digital prototype fabrication in either a semi- or full-immersive VR environment. It fabricated digital prototypes with toolpaths valid for appropriate material deposition mechanisms.

Therefore, to facilitate detailed verification and subsequent optimization of toolpath planning on a specific MMLM hardware configuration, the proposed TDP incorporates VP for simulation of the MMLM process.

3 OVERVIEW OF THE PROPOSED TOOLPATH DESIGN PLATFORM

As a simulator, the Toolpath Design Platform (TDP) proposed in this paper is aimed to model practical constraints in a vector-based MMLM process, and to generate feasible and efficient toolpaths for subsequent digital fabrication of multi-material prototypes under these constraints. Such constraints mainly come from the operational aspects, such as the types and layout of the manipulators in an MMLM system, the number of materials each manipulator can hold, and the potential collisions between the manipulators. Material deposition speeds and priorities could also be adjusted to suit different material properties.

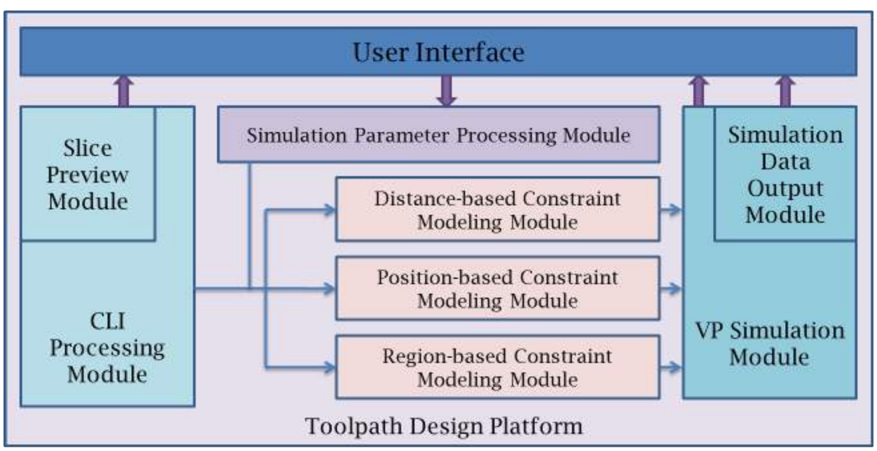


Fig. 1: The components of the TDP.

As shown in Fig.1, the TDP consists of a number of functional modules for different operations. The CLI Processing Module reads in Common Layer Interface (CLI) files of prototype containing geometry and material information, and generates the topological hierarchies of the slice contours [4]. The Slice Preview Module provides a preview of the slices on the user interface. The User Interface allows users to input constraint modelling and process parameters, and transfers them through the Simulation Parameter Processing Module to the three key modules of the TDP for constraints analysis and toolpath generation. These three modules integrate these parameters and the slice information above, execute sorting operations on the slice contours, and generate corresponding feasible and efficient toolpaths. The VP Simulation Module visualizes these toolpaths, and provides relevant process data through the Simulation Data Output Module, such as slice build time and working status of manipulators. Fig.2 shows how the TDP may benefit MMLM system designers and users.

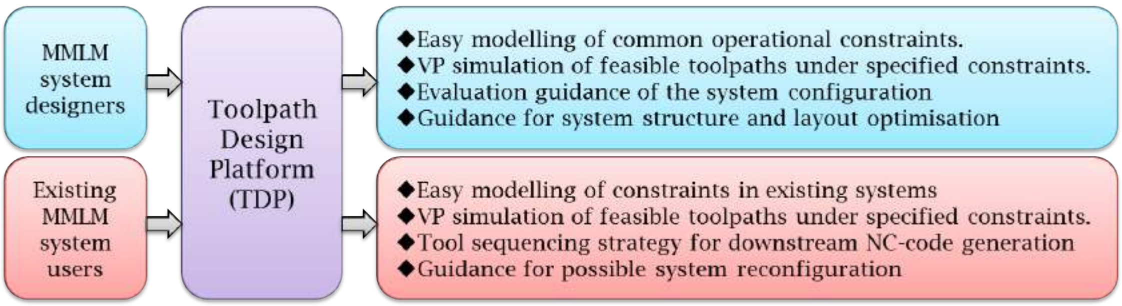


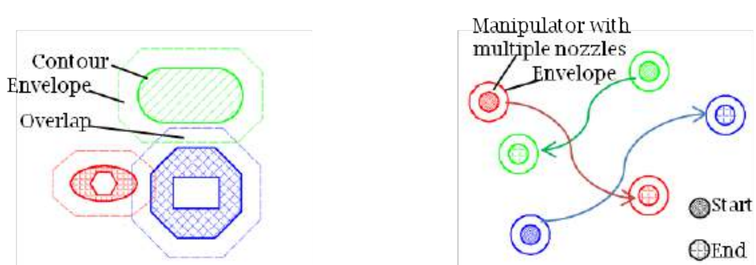
Fig. 2: Possible applications of the TDP.

4 CONSTRAINT MODELLING IN THE TDP

The TDP consists of three key constraint modelling modules, which are distance-based, position-based, and region-based respectively, for generation of feasible and efficient toolpaths for an MMLM process based on modelling of operational constraints and user requirements. These modules assume that material deposition of each slice contour can be completed in a one-off manner without pauses or disturbances. This assumption ensures better prototype quality, and makes the toolpath generation easier and more practical. The details of these three modules are as presented below.

4.1 The Distance-based Constraint Modelling Module (DCMM)

This module is based on the model in the previous work on multi-material virtual prototyping [4], in which a material-depositing mechanism consists of an array of nozzles. Each nozzle independently deposits a type of material on a specific slice contour, to which a safety distance is assigned as shown by the offset envelopes outside the corresponding contours in Fig.3 (a). Overlap tests are conducted based on these envelopes to arrange the contour deposition sequence.



(a) Slice contours with offset envelopes (b) Manipulators with safety envelopes

Fig. 3: The distance-based constraint model.

Using the TDP, users can not only simulate an array of nozzles with independent movements, but also manipulators each holding a number of nozzles as shown in Fig. 3(b), which would be a more economical way in practice. Moreover, the sorting of material deposition sequence in the TDP can be conducted at the contour level other than former material level. In other words, deposition of suitable contours will start earlier because there is no need to wait until all the contours of another material have been deposited, thus saving more time. Further, the materials within a prototype can possess different deposition priorities by assignment of an integer index. For example, a material with index (1) should be deposited prior to other materials, while a material with index (-1) should be deposited last.

A *Contour Array* in the TDP will store all the contours within each slice as its members in the material priority order, and each contour is assigned a status flag to indicate their sorting status. Status 0 means the contour has not been sorted, Status 1 means it is being sorted, and Status 2 means it has been sorted. The following steps illustrate how the DCMM generates concurrent toolpaths for the contours on a slice.

- Step 1. Perform initial sorting of the contours in the *Contour Array*, for example, by contour size.
- Step 2. For each contour in the *Contour Array*, set Status=0.
- Step 3. For the first contour in the *Contour Array* with Status=0, set Status=1, and add it into *Ready Array*, which contains the contours to be deposited.
- Step 4. For the rest of the contours in the *Contour Array* with Status=0, each of them will sequentially conduct the tests shown in Fig.4 with the contour(s) located ahead of it in the *Contour Array*. For example, firstly the second contour in the *Contour Array* will conduct the tests with the first one, and then the third with the first and second. For each contour, if the *AddFlag* remains "True" after the tests, it will be added into the *Ready Array* with Status=1.
- Step 5. For each contour in the *Ready Array*, set Status=2. These contours will be deposited concurrently and form one deposition group.
- Step 6. Clear the members in the *Ready Array*.
- Step 7. If the status of all the contours in the *Contour Array* is 2, continue the sequencing for the next slice. Otherwise, return to Step 3, and repeat the rest steps for another deposition group.

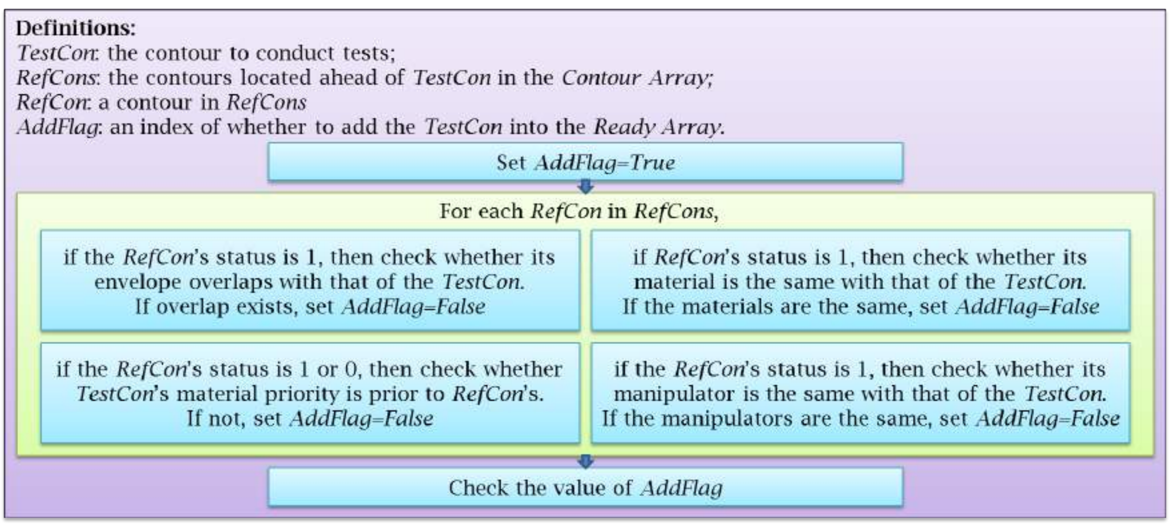


Fig. 4: The distance-based contour tests in the DCMM.

With consideration of collision avoidance, allocation of materials to manipulators and material deposition priorities, the output of the tool sequencing operation above is a series of deposition groups, each consisting of a number of contours to be deposited with different materials concurrently. Different contour filling strategies will not affect the number and the constituent contours of the deposition groups due to the fact that the sequencing is conducted based on the safety envelopes of contours. The data of the contours within a deposition group are used to calculate the duration and end time of the group, and determine the start time of the next group. The initial contour sorting in

Step 1 aims at improving the efficiency of the toolpath generated by weakening the randomness of the sequence of contours with the same material priority in the *Contour Array* and approximating the deposition durations of the contours within a deposition group. Indeed, if the deposition durations of the contours within a deposition group are closer, less idle time of manipulators will be wasted.

4.2 The Position-based Constraint Modelling Module (PCMM)

This module is built on a position-based constraint model for modelling manipulators with constant position orders. A typical example is the XY-table shown in Fig. 5(a) with multiple manipulators. In this situation, each manipulator can move independently, but the nozzles on the left manipulator cannot deposit the contours on the right side of the right manipulator while a nozzle on this right manipulator is depositing a contour. In other words, the manipulators must follow a position order in the X direction to realise concurrent deposition in this case.

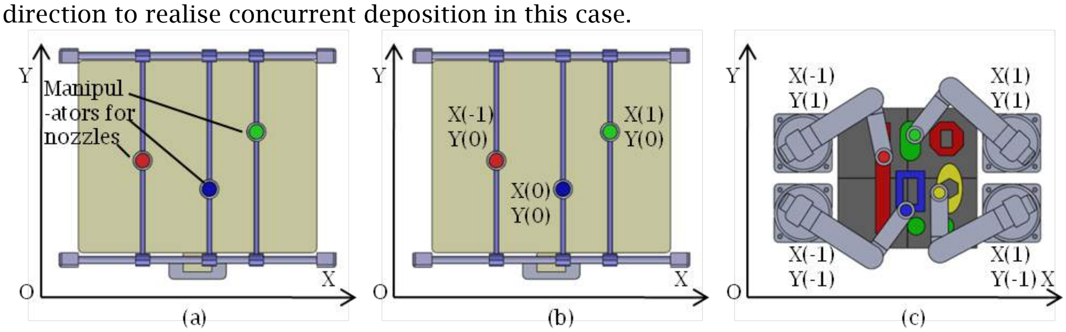


Fig. 5: The position-based constraint model: (a) An XY-table with three manipulators, (b) Assignment of X and Y index to the manipulators in the XY-table, (c) Assignment of X and Y index to the manipulators in an MMLM system composed of four robotic arms

In the proposed position-based constraint model, each manipulator is given an X-position index and a Y-position index to illustrate its relative position to each other. The index can be either positive or negative. A larger X index value indicates the manipulator is on the right side of those with smaller values in the X direction, and a larger Y index indicates it is above those with smaller values in the Y direction. For the XY-table in Fig. 5(a), the three manipulators are given position index X(-1), X(0) and X(1) respectively to indicate their position order in the X direction accordingly. Since they do not have a constant position order in the Y direction, their Y-position indexes are all set to be Y(0), as is shown in Fig. 5(b). Besides such translational mechanism, this model also applies to some robotic arm manipulators. In Fig. 5(c), the four robotic arm manipulators can be assigned indexes X(-1)-Y(-1), X(-1)-Y(1), X(1)-Y(-1), and X(1)-Y(1) respectively to model the position constraints.

if the *RefCon*'s status is 1, then check whether its contour position and its corresponding manipulator's position indexes match those of the *TestCon*.
If not, set *AddFlag=False*

Fig. 6: The position-based contour test in the PCMM.

Based on the position-based constraint model above, the PCMM will follow similar tool sequencing steps presented in the DCMM, and a new test in Fig.6 is added. In this new test, the module will check whether the *TestCon*'s position and its manipulator's position indexes match those of the *RefCon*. For example, if the value of the X-position index of *TestCon*'s corresponding manipulator is larger than that of the *RefCon*'s, it means *TestCon*'s manipulator should be on the right of *RefCon*'s. Therefore, if the *TestCon* is located on the left of the *RefCon*, it would be impossible to deposit materials on these two contours concurrently. Within this new test, the module will also consider whether there is enough space for the arrangement of manipulators based on safety envelopes. For example, for two manipulators with X(-2) and X(2) respectively, there should be enough space for the manipulators located between them with X(-1), X(0) or X(1), even though these manipulators do not deposit in the same deposition group.

4.3 The Region-based Constraint Modelling Module (RCMM)

In practice, collisions may not only take place between the working heads of manipulators, but often between the links of the manipulators, as well as between the working head and the links of the manipulators. As is illustrated in Fig. 7(a), although the working heads of the two translational manipulators, which hold nozzles for different materials, do not collide with each other, there is a danger of collision between the working heads and links. The problem may become even worse in robotic arm type manipulators, which tend to have more complicated link structures. In this module, a constraint model based on sub-region division is developed to avoid such collisions.

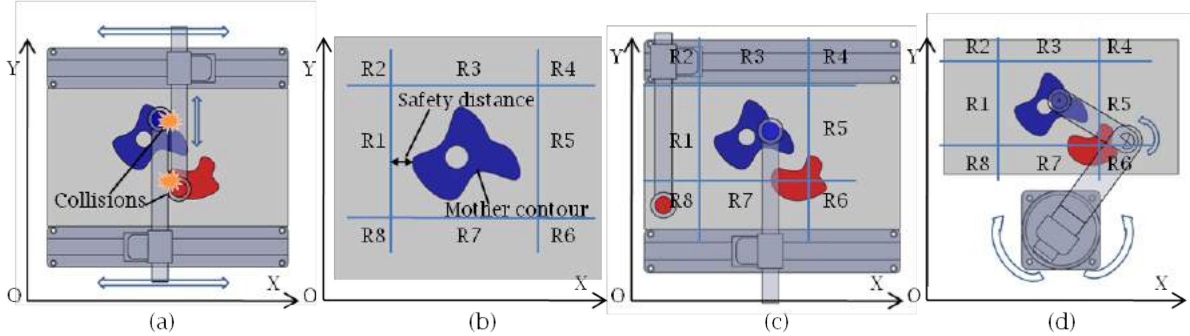


Fig. 7: The region-based constraint model: (a) Collision between two translational manipulators, (b) Distribution of the sub-regions of a contour, (c) Distribution of sub-regions and work regions of a translational manipulator, (d) Distribution of sub-regions and work regions of a robotic arm manipulator

In this region-based constraint model, each slice contour is first given a safety envelope as those in the DCMM, but the safety offset distance should be determined with consideration on both working head size and manipulator link's geometrical size. For simplification reason, rectangle envelopes are adopted. Then eight sub-regions are divided outside the envelope along the edges, each of which is given an ID, as shown from R1 to R8 in Fig. 7(b), and the contour in the envelope is called the mother contour. According to the mechanical structure and the geometrical size of the contour's corresponding manipulator, one or more of these sub-regions are set to be the work region(s). To avoid potential collisions, any contours located in these work regions cannot be deposited concurrently with the mother contour. In the previous example, R7 is the work region for the blue contour because the link of its corresponding manipulator occupies part of this sub-region during deposition of it, as is shown in Fig. 7(c). Since the contour of another manipulator (the red one) lies in R7, these two contours cannot be deposited together, otherwise collision may occur. In another example shown in Fig. 7(d), the work regions for the contours of a manipulator in the form of a robotic arm could be R5, R6 and R7.

if the *RefCon*'s Status is 1, then check whether *TestCon* and *RefCon* interfere with each other's work regions. If interference exists, *AddFlag=False*

Fig. 8: The region-based contour test in the RCMM.

Based on the region-based constraint model above, the RCMM will follow similar tool sequencing steps presented in the DCMM, and another new test in Fig.8 is added. In this new test, the module will check whether *TestCon* and *RefCon* interfere with each other's work regions, that is, whether *TestCon* lies in the work region(s) of *RefCon*, or *RefCon* lies in those of *TestCon*. If interference exists, these two contours cannot be deposited concurrently. If envelopes other than rectangles are adopted, or more sub-regions are divided outside the envelope, better accuracy and more efficient tool sequence may be attained at the cost of heavier computation burden. Moreover, the contours of the same manipulator can have different work regions based on different manipulator postures to achieve higher modelling accuracy. However, this may require specific structural information of the manipulator and intensive computation.

5 SIMULATION WITH THE TDP

Fig. 9 presents the flow chart of employing the TDP to model constraints of an MMLM process and generate feasible and efficient toolpaths for digital fabrication of prototypes. After inputting the CLI file of the prototype, a user can view the slices in the preview window, and acquire prototype information like the size and material varieties. Based on such information, the user can determine the number and types of manipulators to be used, as well as the materials to be deposited from each of these manipulators. To model the practical constraints, the user needs to input necessary parameters after choosing a toolpath generation mode based on the DCMM, PCMM or RCMM. Material deposition speeds and priorities can also be assigned at this stage. After the modelling above, a set of toolpaths will be generated. Digital fabrication based on these toolpaths can be visualized and validated with VP simulation; process data like slice build time and manipulator working status can also be analysed. If the user is not satisfied with the result, for example, the concurrency level of the manipulators are low, or the deposition of manipulators violates practical constraints, the constraints can be remodelled and the procedures above be iterated until the result is acceptable. Therefore, the user can make use of the tool sequencing output of the TDP to evaluate and optimize the design of new MMLM systems, or guide machine code generation and process planning for existing MMLM systems. Two case studies will be presented to demonstrate the functionalities of the TDP.

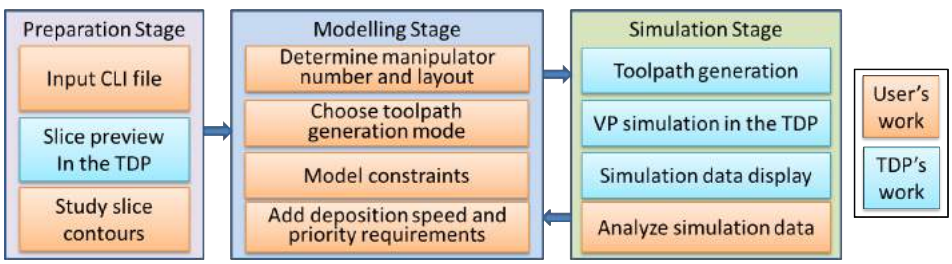


Fig. 9: The flow chart of utilizing the TDP for simulation

5.1 Virtual Prototyping of a Multi-material Toy Car

A toy car to be made of 13 materials, shown in Fig. 10(a), is chosen as the sample part in this case study. The user interface of the TPD is shown in Fig. 10(b). It provides users with preview of slice contours, material information of the part, and a number of manipulator setup blocks to model different constraints. It also allows the user to assign varying material deposition speeds and priorities, as is shown in Fig.10(c). The DCMM and PCMM will be used to model the constraints and generate feasible and efficient toolpaths for comparison. For the DCMM, four manipulators in the form of mobile robots will deposit the contours, while for the PCMM, four manipulators in the form of XY-table will do. Moreover, two different material assignments on the manipulators will be conducted in the PCMM module. Deposition parameters, like the build direction, layer thickness and hatch distance, are set to be the same in these three situations. The manipulator setups and total build time of the toy car in the three situations above are shown in Tab. 1, and the deposition sequence of the contours on the 50th layer previewed in Fig. 10(b) is also presented as a detailed example of the toolpaths generated. The build time of sequential deposition with the same deposition parameters is 10456.33s. In Tab. 1, the three toolpaths generated all take less time than the sequential deposition does, and the toolpath generated by the DCMM is more efficient than that by the PCMM with identical material distribution, because no position constraints need to be considered in it. Moreover, the two toolpaths generated in the PCMM module also exhibit different build times due to different material nozzle assignments to manipulators. Indeed, in the DCMM, if the different materials of adjacent contours can be assigned to several manipulators, such contours will have a higher chance to be deposited concurrently, thus saving the build time.

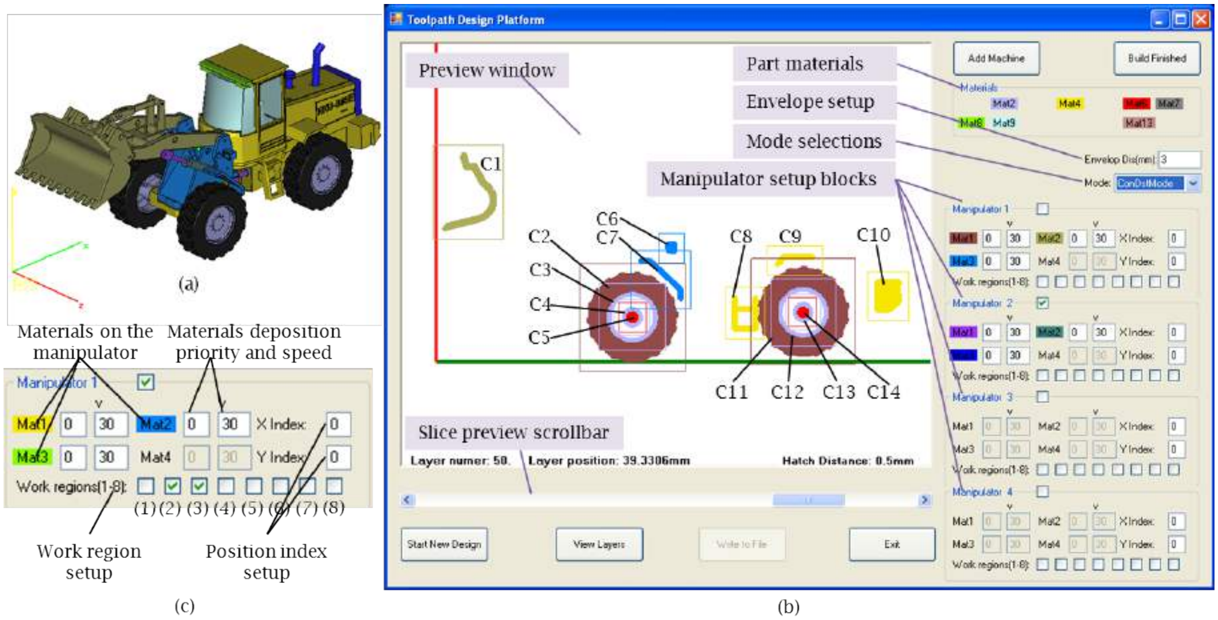
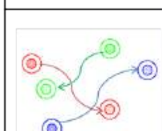
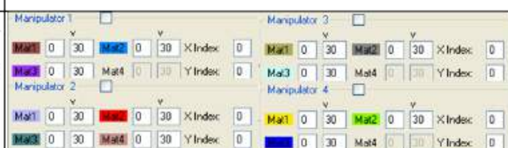
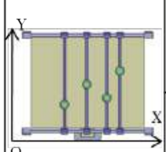
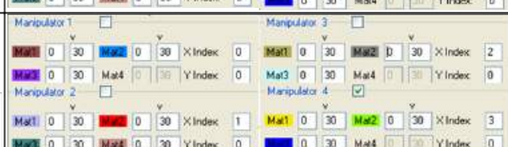
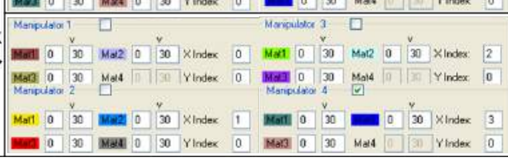


Fig. 10: Virtual prototyping of a multi-material toy car: (a) The multi-material toy car, (b) The user interface in the TDP, (c) The manipulator setup block for modelling constraints in the TDP.

Constraint Types	Manipulator setups	Deposition sequence of contours on the 50'th layer	Total build time (50'th layer time)
 DCMM		{C1, C2, C10, C12} →{C3, C11} →{C7, C8, C13} →{C4, C6, C9} →{C5} →{C14}	6378.02s (153.48s)
 PCMM		{C1, C8} →{C3, C9} →{C4, C10} →{C5} →{C2, C12} →{C11}→{C7, C13} →{C6, C14}	8263.75s (177.66s)
		{C1, C5} →{C7} →{C6} →{C2, C8} →{C3, C9} →{C3, C14} →{C10, C12} →{C11} →{C13}	9110.78s (180.97s)

Tab. 1: Virtual prototyping of the toy car in the TDP with DCMM and PCMM.

However, in the PCMM, depositing adjacent contours with the same manipulator may result in a faster outcome, because the chance of violating the position order of the manipulators may become lower. In this case study, the TDP helps the user to model different kinds of constraints in the DCMM and PCMM, and generate corresponding feasible and efficient toolpaths. It also helps to study the influence of different material nozzle assignments on process efficiency.

5.2 Configuration Optimization of a Robotic-arm-based MMLM System

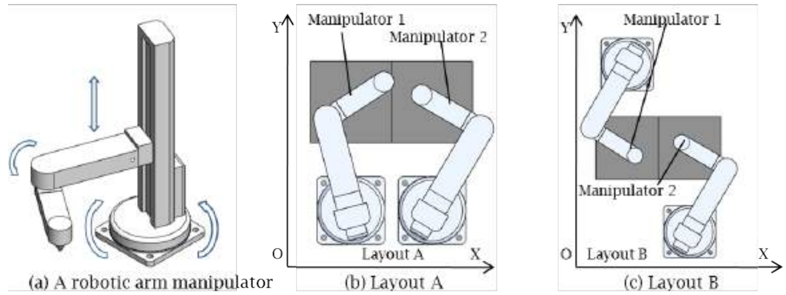


Fig. 11: A reconfigurable MMLM system.

Currently, the configuration of most LM systems is fixed, that is, the structure and layout of the system cannot be adjusted. However, system reconfiguration would bring about more flexibility and efficiency in an MMLM process in some cases. Therefore, the TPD helps the user study possible reconfiguration of an MMLM system to improve its performance. For example, for an MMLM system comprising robotic-arm-based manipulators, as shown in Fig. 11(a), it can be reconfigured by changing the positions of the two manipulators holding nozzles for different materials, as is shown in Fig. 11(b) and (c). The RCMM in the TDP is employed to model the operational constraints in these two layouts and generate corresponding toolpaths. The work regions for the contours in these layouts are shown in Fig. 12. In the first layout, the work regions for the contours of the first manipulator are R1, R7 and R8, and for those of the other R5, R6 and R7. In the second layout, the work regions for the contours of the first manipulator are R1, R2 and R3, and for those of the other R5, R6 and R7. A multi-material object shown in Fig. 13(a) is used as the sample part, and the overlaps of the contour envelopes are shown in Fig 13(b). The manipulator setups in these two layouts and the total build times of the part are shown in Tab. 2.

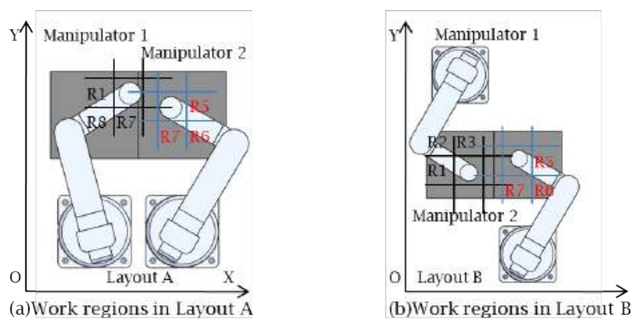


Fig. 12: Work regions of the two manipulators in the two layouts.

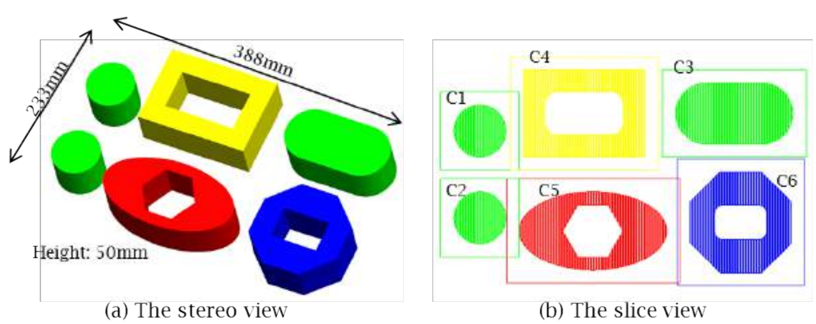
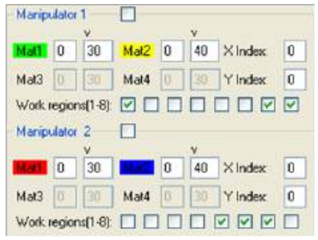
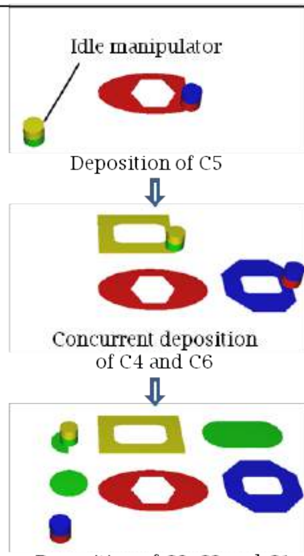
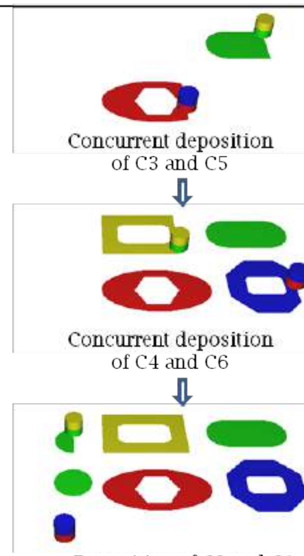


Fig. 13: A multi-material sample part.

Configuration	Layout A	Layout B
Manipulator Setup		
Build-time	100848s	72910.3s

Tab. 2: Manipulator setups and build times in the two layouts.

Configuration	Layout A	Layout B
Slice deposition process		
Slice Build-time	1008.48s	729.10s

Tab. 3: Snapshots and build time of the fabrication process of the same layer in the two layouts.

In Tab. 2, it can be seen that the second layout enables the MMLM system to fabricate the sample part in a shorter build time. For the fabrication details, the user can refer to the built-in VP simulation module in the TDP, and analyse the deposition process in each layer. Tab.3 shows the digital fabrication of the same layer of the part in the above two layouts, which helps the user to compare the layouts and decide further optimization. Nozzles on different manipulators are simplified as a number of cylinders in different colour, whose radius represents the safety distance of the envelope. It can be observed that the manipulators in the second layout exhibit more concurrent deposition of contours due to the varying work regions. In this case study, the TDP facilitates configuration improvement of an MMLM system.

6 CONCLUSIONS

In this paper, a toolpath design platform (TDP) based on virtual prototyping (VP) is proposed for planning and validation of toolpaths for multi-material layered manufacturing (MMLM) processes under different operational and mechanical constraints. Three key constraint modelling module modules, which are distance-based, position-based and region-based respectively, are developed to model these constraints and generate feasible and efficient toolpaths for digital fabrication of multi-material prototypes in a built-in VP simulation module. Material deposition speeds and priorities can also be adjusted to suit different material properties and further optimize the toolpaths.

Simulation shows that the TDP is effective in modelling these aforementioned constraints based on distance, position and region requirements in the MMLM process, and that the toolpaths generated are practicable and competent for different applications. Through VP simulations, it was found that the material nozzle assignment on multiple manipulators within an MMLM system might have a great impact on the efficiency of the deposition process. Moreover, appropriate reconfiguration of an MMLM system might help reduce the build time.

In its current stage, the TPD can assign only one nozzle to each material. However, for prototypes with large slice contour areas, it would be possible and desirable that the large contour can be deposited by two or more nozzles of the same material simultaneously, so that the efficiency can be further improved, although the toolpath planning algorithm would have to be enhanced accordingly. In future study, this function will be developed and integrated into the TDP.

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