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Optimal machine operation planning for construction by Contour Crafting

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ABSTRACT

Contour Crafting is an emerging technology that uses robotics to construct free form building structures by repeatedly laying down layers of material such as concrete. The Contour Crafting technology scales up automated additive fabrication from building small industrial parts to constructing buildings. Optimal machine operation planning for Contour Crafting benefits the technology by increasing the efficiency of construction, especially for complicated structures. The research reported here has aimed at providing a systematic solution for improving the overall Contour Crafting system efficiency in building custom-designed buildings. An approach is first presented to find the optimal machine operation plan for the single nozzle Contour Crafting system. Other approaches are then presented to determine collision-free operation plans for machines with multiple nozzles. The models developed incorporate physical constraints as well as some practical construction issues.

1. Introduction

1.1. The Contour Crafting technology

Contour Crafting [1] can automatically construct custom-designed structures by repeatedly layering down construction material (Fig. 1). Contour Crafting (CC) is an additive fabrication technology that uses computer control to exploit the superior surface-forming capability of troweling in order to create smooth and accurate planar and free form surfaces out of extruded materials. Some of the important aspects of CC are lower construction cost, superior construction speed, flexibility of architectural design, safety and friendliness to the environment.

Extensive experiments have been conducted over the last few years to configure the CC process to produce a variety of small and full scale objects. Small and medium sized 2.5D and 3D parts with square, convex, and concave curve features have been fabricated from a variety of thermoplastic and ceramic materials, as shown in the pictures on the left side of Fig. 2.

Larger Contour Crafting machines such as the one shown in Fig. 3 have been developed to build larger structures. These machines combine an extrusion process for forming the object surfaces and a filling process (by pouring, or extrusion) to build the object core. Several wall specimens have been constructed using CC machines that can produce hollow walls with corrugated internal structure (Fig. 4). This design is expected to be a good initial candidate for concrete wall construction as is in a way equivalent to the current CMU based walls which are widely used in various construction applications. The CC machines are light weight and can be quickly assembled, disassembled and transported by a small crew. The construction operation can be fully automated requiring minimum supervision.

1.2. Process planning and optimization in Contour Crafting

Operation planning and optimization play important roles in improving the overall CC system efficiency by generating optimal nozzle/trowel paths for the given structure designs. Multiple-nozzle or multiple-gantry systems would be suitable for construction of larger community and multi-residence structures to reduce the construction time and cost. Two types of Multi-Machine CC systems are considered in this study: *Overhead multi-nozzle* and *multi-gantry*. In both cases specific schedule and workload are to be assigned to individual nozzles or gantries for collaborative operation. Collision between nozzles should be avoided without significantly compromising the overall constructing efficiency.

2. Objectives

The reported work has aimed at the development and verification of a systematic methodology for process planning and optimization for most efficient construction of complicated large-scale structures by Contour Crafting for single and multiple machine scenarios through the following steps:

1. Describe system characteristics and define tool path elements of Contour Crafting
2. Develop practical tool path planning and an optimization method for the single nozzle CC system

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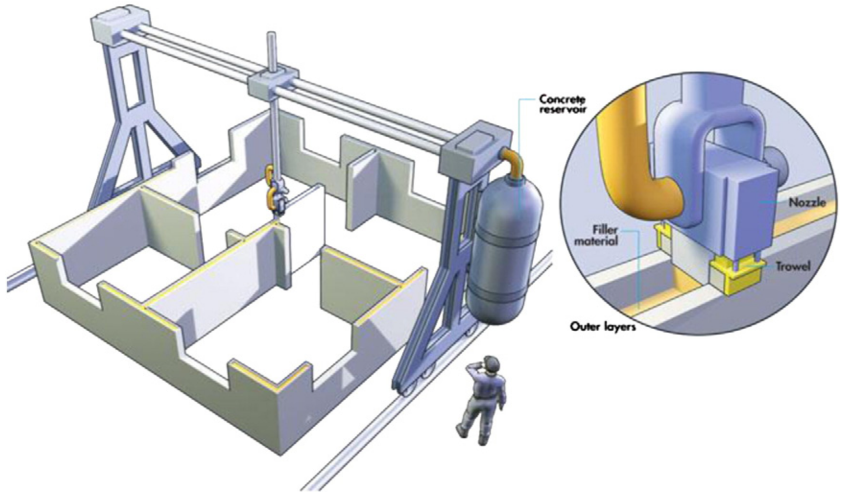

Fig. 1. Contour Crafting in construction operation.

3. Develop practical tool path planning and optimization methods for multi-nozzle systems based on the optimization method for the single nozzle case.

3. System characteristics and physical constraints

3.1. Operational facts

The scale of the optimization problem may be too large when all aspects of the technology are considered. Operational facts should be established according to the limitation and features of the system. The following are the operational facts for the system:

1. The focus here is on finding the optimal tool path for 2.5 D structures. Layers are similar to each other except at the points where openings for windows or doors are located. Generally the nozzle will try to start and end at the same point in each layer.
2. In the construction process a nozzle or nozzles have to completely finish a layer before moving on to the next layer.
3. For each layer the CC nozzle has to finish depositing one wall segment completely before starting a new wall segment so that it will travel only between end points of each wall segments.
4. In order to avoid collision between the nozzle and the previously deposited walls the nozzle should be lifted up (by at least one layer height) when traveling between end points.
5. The nozzle will be idle while traversing the places where windows or doors are located. This traversal time is called “air time”.
6. The deposition flow rate can be perfectly controlled (i.e., concrete flow can start and stop) at any time.
7. Acceleration and deceleration times of the system are considered as fixed delays in the optimization analysis.
8. The focus is on developing a practical optimization method to generate tool paths for general structures. The maximum vertex number in a structure layout would be less than 10,000. This allows for handling fairly large and complex structures.
9. In the multi-nozzle case the nozzles always work on the same layer. It is assumed that allowing the nozzles to work on different layers at the same time will not increase the system efficiency.

3.2. Tool path definition

Contour Crafting can save considerable time and cost as compared with the traditional way of construction. The cost of construction is related to time and energies spent by the machine and the amount of materials consumed for the structure. The total construction can

Fig. 2. CC in operation and representative 2.5D and 3D shapes and full scale concrete structures.

Fig. 3. Current Contour Crafting machine.

be evaluated once a tool path has been defined. The building model is first sliced into layers, and then the layout of one single layer is converted into a model which consists of edge and vertices. Edges represent the walls, and the vertices represent the intersections, corners or the end points of wall segments. Fig. 5 illustrates a sample of a Contour Crafting tool path for the structure shown.

A tool path of Contour Crafting for a specific structure must describe the position, orientation, velocity, and deposition rate of the nozzle in the entire construction period. This information is converted into a sequence of machine tasks and then fed to the Contour Crafting machine. If time or energy spent on each machine task (such as deposition, nozzle traveling or nozzle rotation) is defined as cost of construction, then process optimization means finding a path with the minimum total cost associated with every machine task. Therefore, costs of deposition, traveling and rotation need to be defined for calculating the overall cost associated with the tool path.

Cost of deposition depends on the flow rate of deposition and the velocity of the machine. However, since the nozzle has to traverse along all the deposition edges once and only once, the overall deposition time is fixed once a structure is given. Therefore, the cost of deposition does not affect the result of tool path optimization. Once the machine parameters have been defined, cost of deposition for each wall segment can be calculated according to its geometrical information.

Cost of traveling between edges is related to the cost of moving between vertices and the cost of rotation along the edges. This cost can be estimated according to the relevant position of edges. Each edge has two end points; therefore, there are a total of four possible traveling costs from one edge to another edge. Since the nozzle of the Contour Crafting machine has to orient itself to be perpendicular to the tangent of the wall segment, the nozzle may need to be re-oriented when traveling between edges. For instance, in order to construct a corner, the nozzle must rotate 90° between the constructions of two wall segments. There can be different construction sequences for the nozzle.

Fig. 6 shows the top views of a wall corner being constructed. Four possible options to construct the corner are shown in this figure. In the top left option the nozzle first builds one wall segment while moving toward the corner. At the corner the nozzle make a 90° turn and then completes the other wall segment. In the top right option the nozzle starts from the corner, builds one wall segment, diagonally moves to the beginning of the other wall segment while rotating 90° and builds the segment while moving toward the corner. In the lower

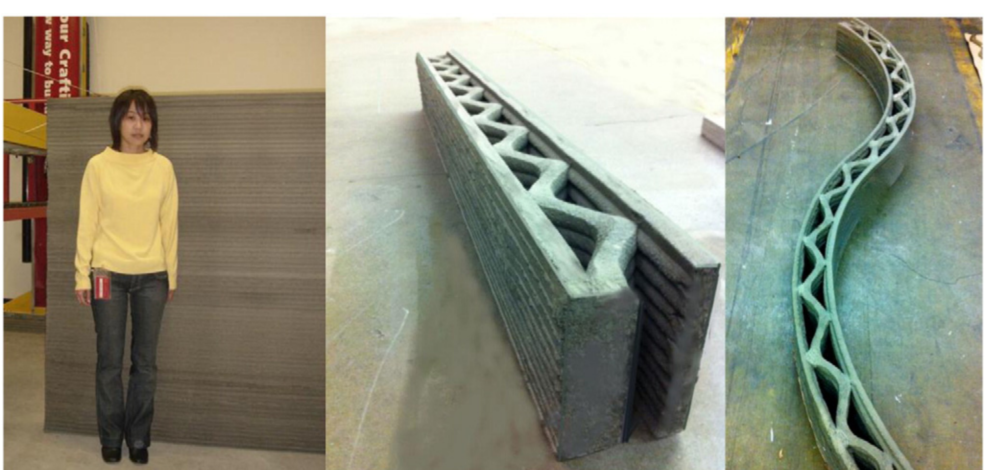

Fig. 4. Wall sections built by Contour Crafting machine.

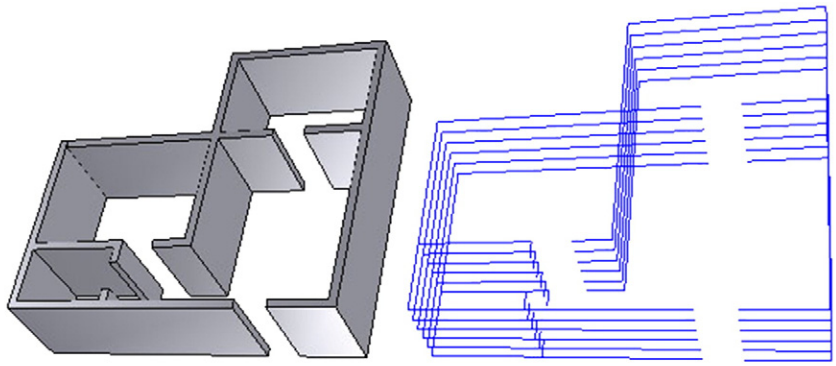

Fig. 5. A structure and its CC tool path.

left option the nozzle starts building one segment while moving toward the corner and then travels to the beginning of the other segment while rotating 90° and starts constructing the segment while moving toward the corner. In the lower right option the nozzle starts at the corner and builds one wall segment while moving away from the corner then travels back to the corner while rotating 90° and then builds the other segment while moving away from the corner. In order to choose the best tool path option the cost of traveling, cost of moving (Euclidian distance) and cost of rotation must be calculated.

Cost of moving between end points can be determined once the distance between two points and the velocity of the machine are known. Sometimes, the nozzle has to be lifted up and lowered down to avoid obstacles, such as previously deposited wall segments. In this case, the cost of lifting up and lowering down also need to be included in the cost of moving.

Cost of rotation between edges can be evaluated according to the relative orientation of the two edges. However, the degree of rotation of the nozzle is limited because in the real system there are cables and wires attached to the nozzle to transfer signal and power to move the nozzle components (trowels, valves, vibrators, etc.). Figs. 7 and 8 show the actual CC nozzle and the nozzle rotation mechanism.

If the nozzle is allowed to rotate without limitation, cables and wires may tangle together and get damaged. For this reason, a mechanical stop is installed on the rotation union to prevent the nozzle from turning more than 360° in either direction. Nozzle rotation direction and degree of rotation need to be adjusted if the stopper impedes the re-orientation transition of the nozzle in a given direction. Therefore, the *cost of rotation* depends not only on the extent of rotation but also on the starting and end positions of the stopper on the rotation union. Fig. 9 shows the relation between the rotation degree and the position of the stopper on the rotation union.

Cost of rotation by the same degrees in clockwise and counterclockwise directions may be different due to the limitation that the stopper imposes on the rotation union. Start and end orientations of the nozzle need to be considered in order to find the rotation cost. The rotation cost of arbitrary degrees can be calculated according to the relative start and end positions of the stopper.

Once the Euclidian distance and orientation of two edges are known, traveling cost between the points can be estimated by calculating the time spent on moving and rotating. If the nozzle is allowed to rotate while moving from point to point, then cost of traveling

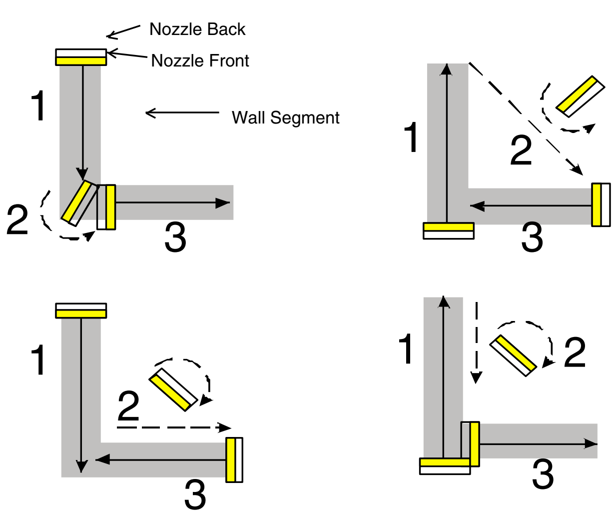

Fig. 6. Four possibilities for traveling from one edge to another (numbers show the sequence of the motion of nozzle. Solid arrows show paths of deposition while dash arrows show the airtime travel).

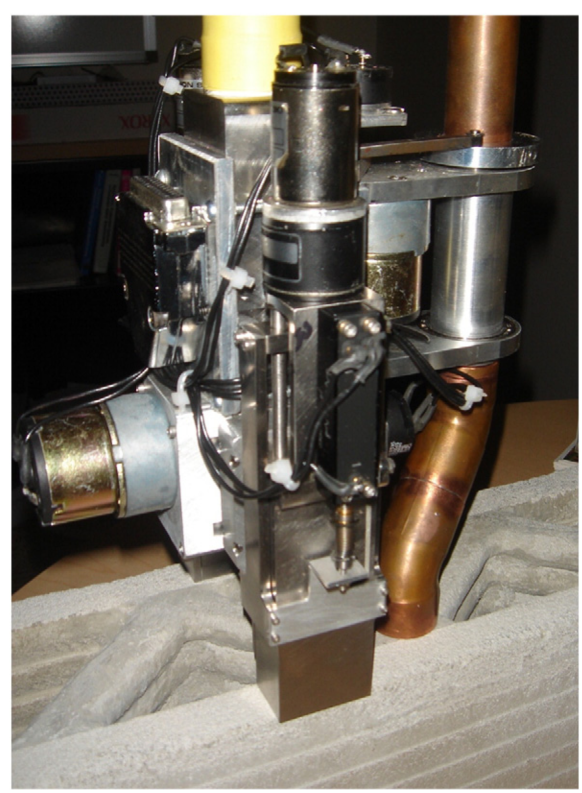

Fig. 7. Contour Crafting nozzle constructing a hollow wall.

Fig. 8. Nozzle assembly and rotation mechanism.

between two edges would be equal to the maximum of movement or rotation time, otherwise it will be the sum of the two costs.

3.3. Constraint definitions

Besides the costs of nozzle deposition and traveling, the following physical constraints also need to be considered during the entire construction process:

1. Nozzle idle time cannot be too long; otherwise concrete may solidify and clog the pipeline. The nozzle idle time cost is equal to the cost of traveling between two wall segments. Therefore, if the *cost of traveling* between any wall segments is shorter than the time it takes for the concrete in the nozzle to solidify, the requirement of this constraint is fulfilled.
2. The lower layer must be able to support the upper layer, therefore the time interval between depositing subsequent layers cannot be shorter than the critical limit.
3. Subsequent layers must be able to adhere, therefore the interval between depositing subsequent layers should not exceed the critical limit.

   Constraints 2 and 3 are both related to the time interval between depositing subsequent layers. This interval is equal to the overall time of constructing a layer, which can be calculated once the tool path of the layer has been generated. If the resulting time is shorter than the required interval in constraint 2, the machine has to wait before depositing the next layer. If this time is longer than the required interval in constraint 3, then this indicates that the structure is too large to be built by a single nozzle, and hence more nozzles or gantries would be needed for the construction.
4. When layers accumulate, the underneath layer must be solidified enough to support the overall weight of multiple layers above it. The overall weight on a layer is proportional to the number of layers above it. Hence it is proportional to the overall time of constructing a layer. Once the construction time of each layer is calculated, a chart that shows the relationship between the weight of upper layers and construction time can be used to verify this constraint.
5. Nozzle should not collide with the previously deposited layer when traveling. There are alternative ways to avoid the collision between the nozzle and previously deposited wall segments. When moving between end points of wall segments, the nozzle may have to travel in a non-straight line in order to avoid obstacles. However, although the nozzle can detour to avoid the wall segments, the routing path depends on the structure layout and the sequence of construction. In some cases, the detour may be complicated and may take too much traveling time. Since in this research it is assumed that a nozzle has to complete a layer before starting another layer , the nozzle can be lifted up one layer once it reaches an obstacle (previous wall segment) standing in its travel path. It will be lowered down before it starts to deposit material for a new wall segment. The cost of lifting up and lowering down the nozzle has been considered in tool path planning.

4. The optimal tool path for the single nozzle system

Once the costs of different machine tasks and physical constraints have been defined, optimization can be performed to find the most

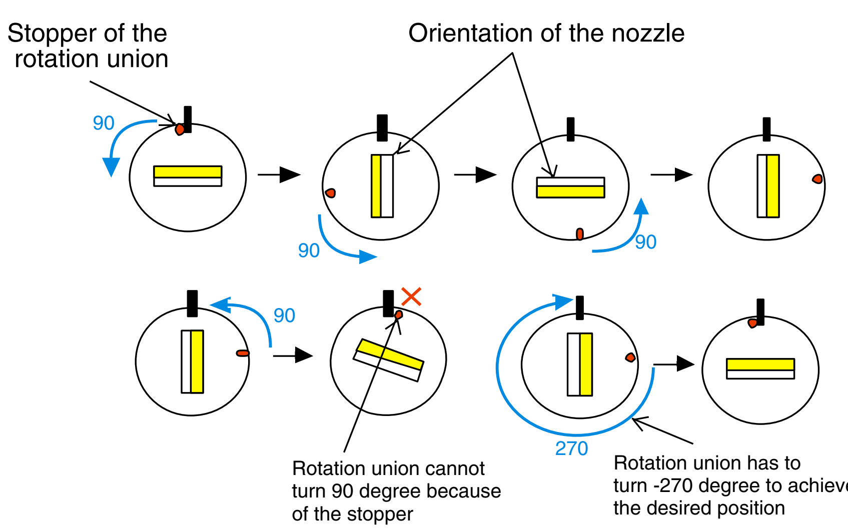

Fig. 9. Rotation union (the circle represents the rotation union, the rectangle represents the nozzle).

efficient tool path for the single nozzle system. Tool path optimization is the critical issue for several other technologies such as Laminated Object Manufacturing (LOM), laser cutting, and other layered manufacturing. P.K. Wah and his team [2] introduced ATSP-IP (asymmetric traveling salesman and integer programming) to improve the efficiency of LOM. K. Tang and A. Pang [3] introduce a greedy algorithm to deal with the application of path optimization in layered manufacturing. Trager [4] presents three different simple solutions to address nesting and (partial) tour optimization problems. In this research, the approach to find the optimal tool path is to convert the CC path model to a standard TSP (traveling salesman problem) [5]. This approach considers all the possible alternatives of construction and provides optimal solution if the TSP model is solved exactly. Heuristic TSP solvers can be used to solve large scale problem (e.g., the structure has more than 10,000 wall segments) [6].

TSP attempts to find the shortest route to visit a collection of cities at least once and return to the starting city. In the standard TSP problem vertices represent cities, while arcs are the paths between cities. A solution to the TSP must return the cheapest Hamiltonian cycle of the graph which represents the cities and paths. A Hamilton cycle is a simple path in the graph that contains each vertex. An asymmetric TSP problem can be formulated as follows: Define $Xij = 1$ (when i,j are the index of the vertices), if edge (i,j) is in the optimal tour; otherwise $Xij = 0$, and $Dij = d(i,j)$, when d is the traveling cost between vertices i and j. Thus we have:

$$\begin{aligned} &\mathrm{Min} \sum\sum DijXij \\ &\sum Xij = 1 \quad \text{for all } j \\ &\sum Xij = 1 \quad \text{for all } I \\ &\sum\sum Xij >= 1 \quad \text{for every } S \subseteq X \ (\text{when } i \in S; j \in X - S). \end{aligned}$$

The graph of a building layout cannot be directly formulated as a standard TSP problem. In the CC construction process, some edges in the graph have to be traversed by the nozzle in order to deposit concrete for building walls, which means that the CC tool path has to contain some specific edges. However, any edge can be included in the optimal path in TSP since any edge represents a path between two cities. Also, a vertex in a structure layout may have several edges incident to it, which means during the construction process, the nozzle of the CC machine will visit the same vertex more than once. However, in TSP, each vertex can be visited only once.

For Contour Crafting, the overall construction time of a specific structure is the sum of the overall time of concrete deposition and the overall nozzle airtime, in which the nozzle stops depositing material and travels between two deposition edges. No matter how the optimal path is generated, the nozzle should traverse all the deposition edges once and only once. The overall deposition time is determined once the structure is given. The overall nozzle idle time is the factor that determines the overall construction time for different tool paths. The optimal tool path is a path that has the minimum overall nozzle airtime. Since the nozzle of the machine can move freely in 3-dimensions, it can go straight between any vertices. The problem of finding the optimal tool path can be stated as follows: Given a set of edges on a layout, find the optimum sequence and direction in which: (1) each edge is traversed exactly once and (2) the traveling airtime (motion between two end points of two edges) is a straight line. The optimal solution minimizes the overall airtime.

A method to formulate the problem is to ignore the deposition edges (walls) while only considering the traveling paths between edges (the airtime of the nozzle). In this case, walls shrink to vertices (entities), when the paths between vertices represent the cost of traveling between walls. Fig. 10 shows the concept behind this approach.

Since each edge has two vertices, the approach of shrinking the edge to a single point will have four possibilities to travel from one edge to another. As defined in the previous section, the cost of traveling from one wall segment to another depends on the time spent on moving and rotating the nozzle. Cost of rotation depends on the orientation of the two edges, the traveling sequence and the starting position of the stopper on the rotation union. Cost of rotation in opposite directions may be different even with the same rotation degree. Therefore, cost of rotation cannot be determined before performing the optimization. Some modifications are needed in order to formulate the problem as a TSP:

Let $Vi1$ and $Vi2$ denote the two end points of the i^{th} edge ($i = 1, 2,\ldots, \mathrm{n}$). Let $C(x, y)$ denote the traveling cost between points x and y, which is determined by the rotation cost and the Euclidean distance of point x and y. Define a complete network with vertex set $\{Vik| \mathrm{i} = 1, 2,\ldots, n;\ k = 1,2\}$. Between every pair of distinct vertices (Vik, Vjl) there is an undirected edge with length given by:

$$\begin{aligned} C(Vik, Vjl) &= -M && \text{if } i = j \\ &= \text{Traveling cost of } Vik \text{ and } Vij && \text{if } i \neq j. \end{aligned}$$

where M is a large number (for example, M may be set equal to the total length of any feasible tour in the original problem). For $\mathrm{i} = 1, 2,\ldots, n$, the distance of $-M$ between vertices $Vi1$ and $Vi2$ implies that the optimal tour must traverse the curve connecting them. Therefore, a minimum length Hamiltonian cycle in this network yields a practical optimal tour for the tool path optimization problem. Fig. 11 shows the concept behind this approach and Fig. 12 shows the concept of converting building layout to standard TSP problem.

The converted TSP problem can be solved by using LK heuristic. Most TSP solvers use effective heuristic algorithms to find the acceptable result (normally no more than 5% of the optimal solution [7]) within reasonable time. The Lin–Kernighan algorithm [7] has been the most successful tour-improving method during the 1970s and the 1980s. The two most recent implementations of Lin–Kernighan algorithm are the Chained (sometimes also called Iterated) Lin–Kernighan algorithm by Johnson and McGeoch [8] and the modified Lin–Kernighan algorithm introduced by Helsgaun [8]. The former changes the classic Lin–Kernighan algorithm by having it iterating in several steps. Helsgaun also improves on the original Lin–Kernighan algorithm, mainly by revising restrictions and directing

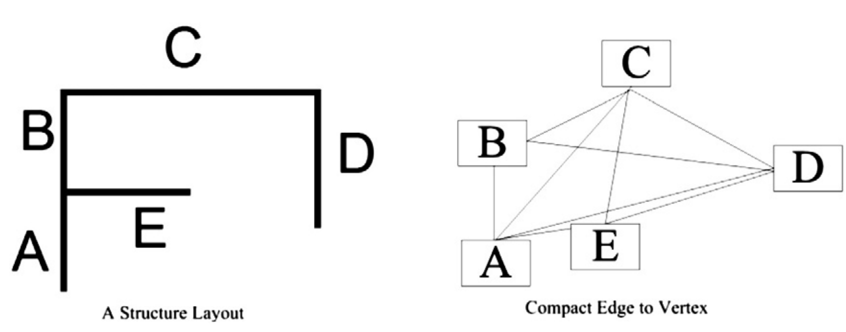

Fig. 10. Concept of shrinking edges.

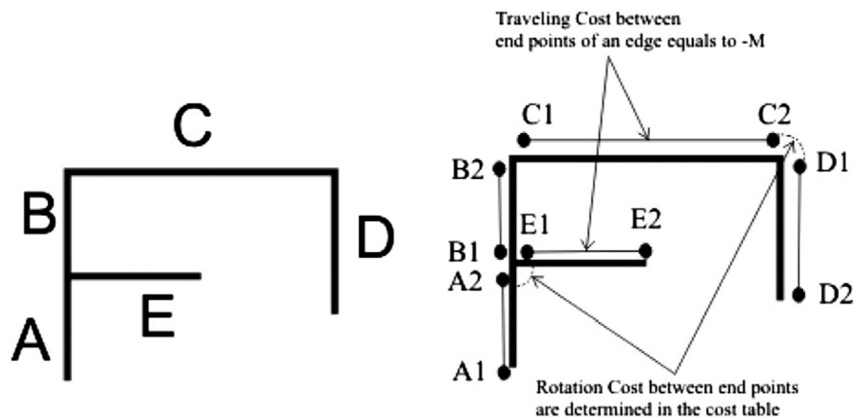

Fig. 11. Concept of assign negative traveling cost to deposit edge.

the search for tour parts probably belonging to the optimal solution. Helsgaun's application is used in this research.

5. Tool path optimization for the multi-machine system

5.1. Introduction to the Multi-Machine Contour Crafting system

Multiple machine configurations have been employed in a variety of automated systems, such as in robotic assembly of cars. Central to the success of many multi-machine systems is the conflict-free and efficient coordination of the activities of individual automated machines (e.g., robots) by implementing systematic task allocation and coordination mechanisms. Task allocation mechanisms address the question of which machine to execute which task [9]. Coordination mechanisms enable the actions performed by each machine to take into consideration the actions of the other machines in coherent manner [10]. Recent research in multi-machine systems has also addressed various approaches such the potential method [11], and coalition formation [12], which organize multiple machines into temporary subgroups to accomplish an assigned task that would otherwise be impossible to complete. Representative approaches to multi-robot task allocation are analyzed by Botelho and Alami [13], Chaimowicz et al. [14], Dias and Stentz [15], Gerkey and Mataric [16], Parker [11], Werger and Mataric [16], and Zlot et al. [17]. These approaches typically divide a task into indivisible subtasks and assign single robots to each subtask (STSR).

The Contour Crafting technology allows massive construction since it transfers construction tasks to fully automatic machine processes.

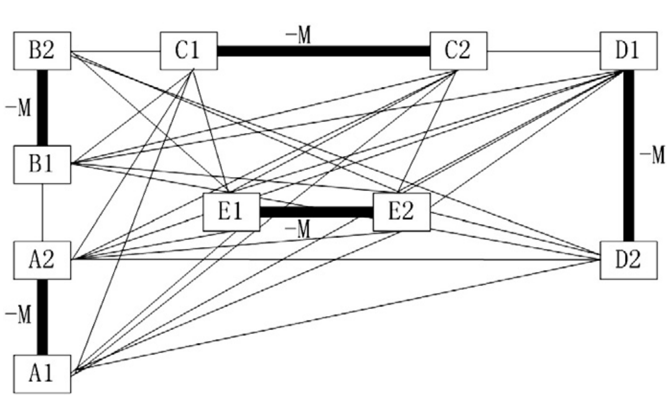

Fig. 12. Traveling cost between end points of edges (bold lines) equals to −M, Other traveling costs (thin lines) are defined in Section 3.

Multi-Machine Contour Crafting systems can be used in constructing multiple smaller structures or a large complex structure to reduce the overall construction time [18]. Using more machines means saving more time and cost. Furthermore, the current CC system is installed on rails to ensure the construction accuracy, allowing multiple machines to cooperate on the same pair of rails can also lower the installation cost.

There are two kinds of Multi-Machine Contour Crafting systems: overhead multi-nozzle and multi-gantry. The overhead multi-gantry system has an overhead platform as the carrier of several nozzles (Fig. 13). The motion of the nozzles is confined by the overhead structure. Gantries that carry the nozzle in the overhead structure cannot cross each other. The entire overhead structure will have to move up and down in order for the nozzles to build different layers. The multiple gantry system is more flexible than the overhead multiple-nozzle system. It consists of different gantries that can be operated independently. The nozzles on different gantries can simultaneously work on different layers.

Both systems have their advantages and disadvantages. The multi-gantry system can be used in most construction applications. The number of gantries used in the construction project depends on the workload and desired completion time. Many gantries can collaborate on a large construction project, yet a few gantries or even a single one can handle the small projects. Although the overhead platform system is not as flexible as the multi-gantry system (due to fixed configuration) it might conserve more energy.

Tool path planning and optimization should be performed on each layer for the overhead system since all nozzles carried by the overhead structure operate at the same height. However, in the multiple gantry system case tool path planning and optimization can be performed for layers built concurrently at different heights. In the approaches presented in this paper, however, it is assumed that all nozzles work at the same height at any point in time for both machine configurations. Tool path planning would be the same for both machine configurations if the width of the structure being constructed is not larger than the width of the overhead platform machine (i.e., if the large single gantry does not have to reciprocate on its rails). Under this scenario the following sections the tool planning algorithms that have been presented apply to both machine configurations. In Chapter 8 special treatment of tool path planning will be presented for the overhead gantry system for cases where the large gantry has to reciprocate on its rails for the nozzles to reach all areas of large structures under construction. In the earlier sections we refer to both Overhead Platform and Multi-Gantry machine types as Multi-Machine CC system.

5.2. Constraint of the Multi-Machine Contour Crafting system

There are some processes similar to multiple gantry system, such as port cranes and warehouse cranes. Research for these processes

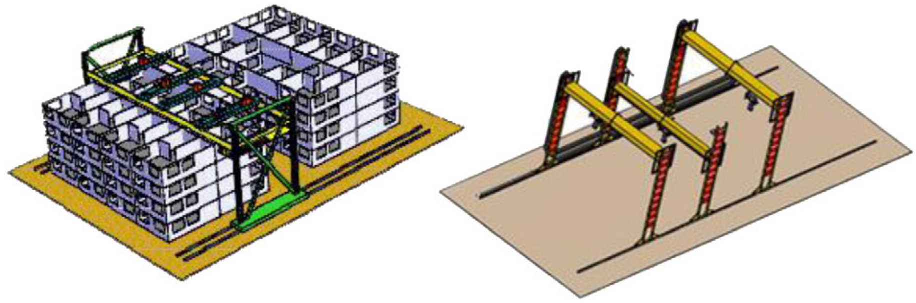

Fig. 13. Overhead gantry platform carries multiple nozzles (left) and multiple gantry system (right).

focus on avoiding the obstacle in the transfer path by using the *potential method* [11]. This is completely different from the concerns of Contour Crafting. The primary concerns of the collaboration of different nozzles and gantries in Contour Crafting are as follows:

1) Any collision between different nozzles/gantries should be avoided.
2) Any collision between nozzles/gantries and previously built walls should be avoided.

This research is focused on finding the optimal collision-free tool paths of structures in the layer-by-layer procedure. Therefore, nozzles will be lifted to avoid the collision with the layer being currently constructed when they move from one wall segment to another. Now the task of collision avoidance is narrowed down to avoidance of collision between nozzles.

5.3. The two step algorithm to find collision free tool path for multiple nozzle system under the current hypothesis

The tool path generation of the multi-machine system includes two steps: (1) iterative dividing; (2) create collision free tool paths. The first step is to separate the original structure into different sections according to the number of nozzles. The second step is to create tool paths for these sections in such a way that no collision between the nozzles occurs when they travel along the tool paths. Fig. 14 shows the two step procedure for finding tool paths for the multi-machine Contour Crafting system.

Step 1: The goal of the first step is to evenly distribute the work load among nozzles so that different nozzles complete their work on the same layer at nearly the same time. Initially the region is divided by the number of nozzles by assigning border lines to points which equally divide a selected X or Y axis. This separation may of course not equally assign work load to nozzles as some nozzles may receive relatively smaller lengths of walls to build. The single nozzle optimization algorithm, CC-TSP, presented in the previous section of this paper is then applied to find the optimal construction time for each section. If the difference between the smallest and largest construction time of different sections becomes lower than the pre-set threshold, then the nozzle workload assignment is considered acceptable. Otherwise, the section border lines are moved such that the division sizes are adjusted according to the proportion of deviation from average construction times computed in the aforementioned procedure, and optimization is performed again to determine the new construction times. This procedure is iteratively performed in a heuristic manner until the desirable result is achieved. (See Fig. 15)

Step 2: After dividing the structure into different sections that have almost equal workload for their corresponding nozzles,

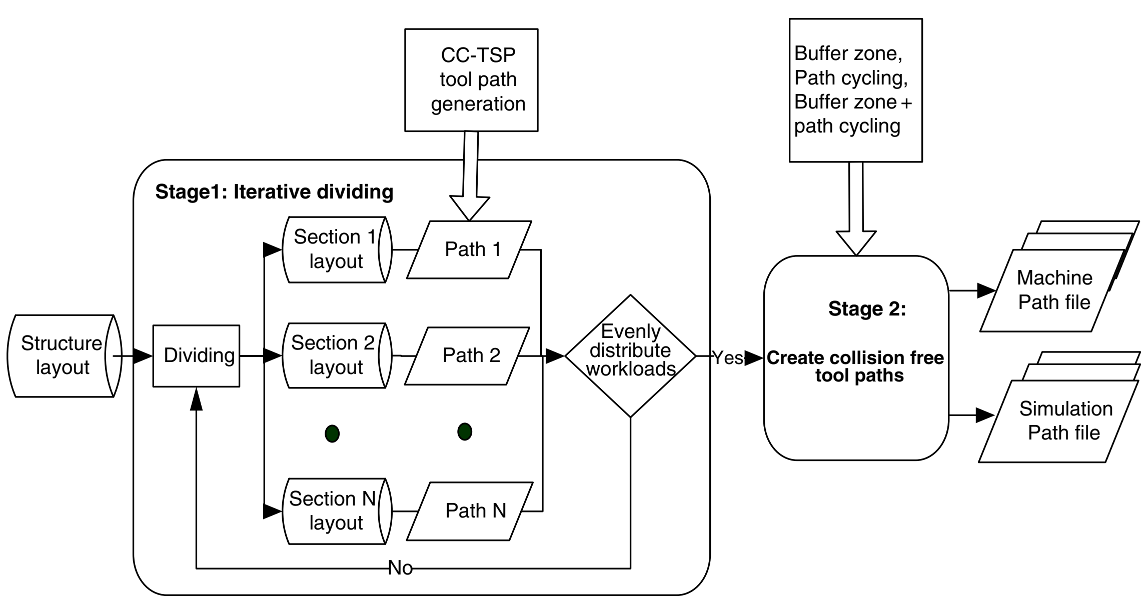

Fig. 14. Two-step procedure.

collision-free tool paths between the divided sections are created. There are two alternative methods to guarantee no collisions during the construction, which are: 1) setup buffer zones within which no more than one nozzle can operate hence preventing nozzles from getting too close to each other, and 2) adjust the x/t curve (position curve) of the gantry that carries the nozzle. These methods are explained as follows.

5.3.1. Buffer zone concept

Each nozzle in the system is responsible for constructing the section assigned to it. In most cases, nozzles work in their own working zone and shouldn't interfere with other nozzles. However, the structure layout is divided into sections with shared cutting edges or overlap areas. In both cases, collision may happen when two gantries are working at the same time near the shared borders of adjacent sections due to the width of the corresponding gantries, as shown in Fig. 16.

Buffer zones can be setup on both sides of the shared border in order to prevent collisions near the border. Buffer zones must meet the following conditions: 1) the width of the buffer zone must be bigger than the width of the gantry; and 2) the overall construction time in the buffer zone must be less than half of the construction time of the section that contains the buffer zone.

The first condition guarantees that gantries never collide when they are working outside of the buffer zones, because there is always a cushion area, which is wider than the width of a gantry between any two gantries. The second condition guarantees that nozzles spend less time inside the buffer zone than the main working zones (the rest of the section except the buffer zone area) so that two nozzles don't work in two adjacent buffer zones at any time. Under these kinds of conditions, the original layout of two adjacent sections may be divided into four areas. Let these areas be LW (left working zone), LB (left buffer zone), RB (right buffer zone), and RW (right working zone) (see Fig. 17). When one nozzle is working on LW (left working zone), the other nozzle is working on RB (right buffer zone), which is a smaller area than LW and contains less work load. The nozzle on the right side will finish the portion in RB before the nozzle on the left hand side can finish the portion in LW, so by the time the nozzle on the left side move to LB (left buffer zone), the nozzle on the right hand side is already working on RW(right working zone). These constraints assure that the two nozzles do not collide during the operation because the working areas are mutually exclusive.

5.3.2. Gantry x/t curve

In the Contour Crafting system gantries that carry the nozzle ride on rails. As such there would be no collision during the entire operation if the distance between the centers of the gantries is always bigger than a minimum limit. Let x represent the horizontal position of a gantry (or the nozzle carried by that gantry) along the rails and $x(t)$ represent the x position of a gantry at time t. An x/t curve represents the tracking curve of a gantry during the entire construction operation. If two x/t curves never cross each other and the minimal distance between these curves is never smaller than a specific amount (such as the width of the gantry), then the two nozzles will not collide with each other during the entire construction process (see Fig. 18).

Therefore, for a given layer to avoid collisions between two gantries at anytime, we must have:

$$Abs(X1(t)–X2(t))<Specific\,Distance\ (\text{e.g.,the width of the gantry}),$$

where: $0<t<$time of the end of construction of the layer
$X1(t)$, $X2(t)$ represent the X position of the two nozzles in time t, respectively.

In order to check if two x/t curves cross each other the distance between two nozzles needs to be tracked at any time t. However, given the assumption that nozzles travel in linear motion, the distance between the two x/t curves needs to be checked only when either nozzle is visiting the end point of a wall segment. Linear interpolation can be used to find the x position of a nozzle at the time that the other nozzle is visiting an end point so that the distance between two nozzles/gantries can be found (see Fig. 19).

If the two known points are given by the coordinates ($t0$, $x0$) and ($t1$, $x1$), the linear interpolation is the straight line between these points. The value x along the straight line is given from the equation.

$$\frac{x-x_0}{x_1-x_0}=\frac{t-t_0}{t_1-t_0}$$

Solving this equation for x, which is the unknown value at time t, gives

$$x=x_0+(t-t_0)\frac{x_1-x_0}{t_1-t_0}.$$

Comparing the value of xa and $xb1$ can give distance between the two curves at time t. Each extreme point of both curve will be compared to see if the minimal distance of the two curves is less than the threshold (width of the gantry). Following is the program that checks if two x/t curves cross each other.

```
for (i=0 ; I < Path1 _vertex_num ; i++)
{
for (j=0 ; j< Path2 _vertex_num-1 ; j++)
    {
    if (Path1 _vertex[i].time > Path2 _vertex[j].time) && (Path1 _vertex[i].time < Path2 _vertex[j+1].time)
            {
            X = ( Path1 _vertex[i].time – Path2_vertex[j].time)  /
            (Path2 _vertex[j+1].time – Path2 _vertex[j].time)  *
            (Path2 _vertex[j+1].x – Path2 _vertex[j].x) ;
            if (Path1 _vertex[i].x>X-width_of_machine)    // paths cross each other
                {
                return false;
                }
            }
        }
}
```

Of course the above program only checks the position of nozzle 1 at the moment when nozzle 2 visits end points. The position of nozzle 2 at the moment when nozzle 1 visits end points also needs to be

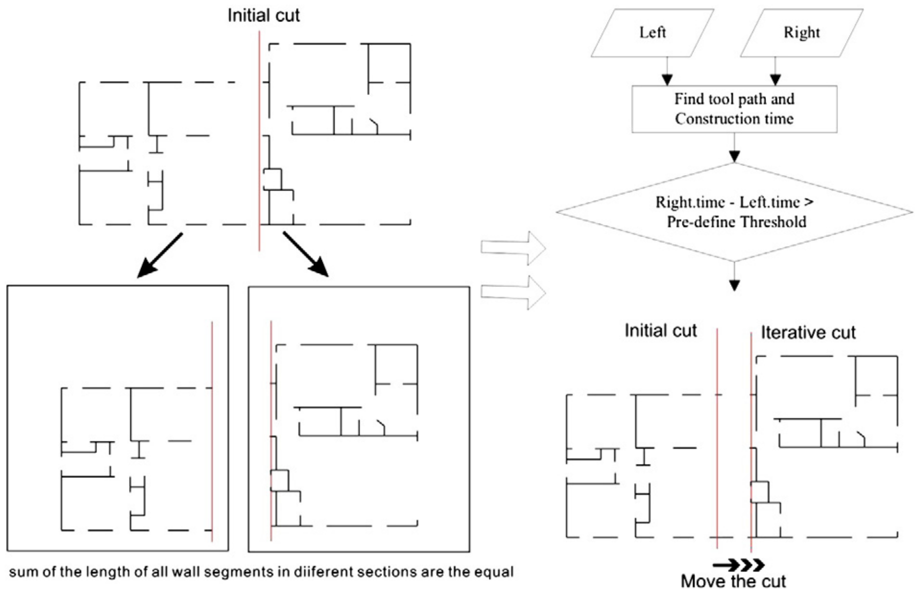

Fig. 15. Iterative dividing.

calculated and compared with the position of nozzle 1 to find out if collisions will happen. Meanwhile, if the overall construction time of the longer curve of the two is minimized, then the optimal solution for the two nozzles will be yielded.

5.4. Solution methodology

Three algorithms are proposed to find the optimal collision-free tool paths by following the two-step procedure mentioned previously. Some algorithms have a higher chance of converging to a feasible solution than do others; however, the extent of optimality of their solutions might be lower. The proposed algorithms are: 1) auxiliary buffer zone; 2) path cycling; and 3) buffer zone path cycling.

5.4.1. Auxiliary buffer zone algorithm

A buffer zone can prevent two gantries from getting too close to a common border at the same time. However, when more than two gantries are working together, each gantry should avoid colliding with the gantries on either side. In a multi-gantry system one approach is to setup two buffer zones for each middle gantry. Two straight cuts are suggested to create left and right buffer zones in one section. The gantry always works according to the order: 1) the left buffer zone, 2) the main working zone and 3) the right buffer zone (see Fig. 20).

In the above case, each section has two buffer zones. Extra buffer zones reduce the construction efficiency and increase the number of wall segments that have to be split into two sections; they also impose additional constraints which result in increased problem complexity. Auxiliary buffer zones can be introduced to reduce the number of buffer zones being used. To setup an auxiliary buffer zone, first a buffer zone needs to be generated for each section, and then the construction time of each buffer zone should be calculated. If the construction time of a buffer zone in a specific section is more than that of the buffer zone in the next section this signifies that no additional buffer zone is needed. Otherwise, auxiliary buffer zones should be generated for that specific section. The nozzle should work according to the order of the original buffer zone, auxiliary buffer zone and the main working zone (See Fig. 21).

There are only two constraints in this approach: 1) the width of the (original) buffer zone must be bigger than the width of the

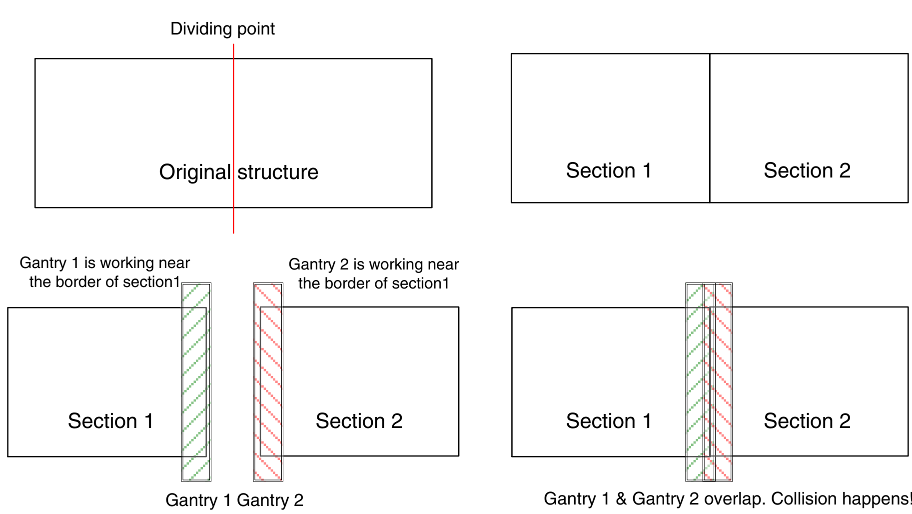

Fig. 16. Possible collision between two gantries.

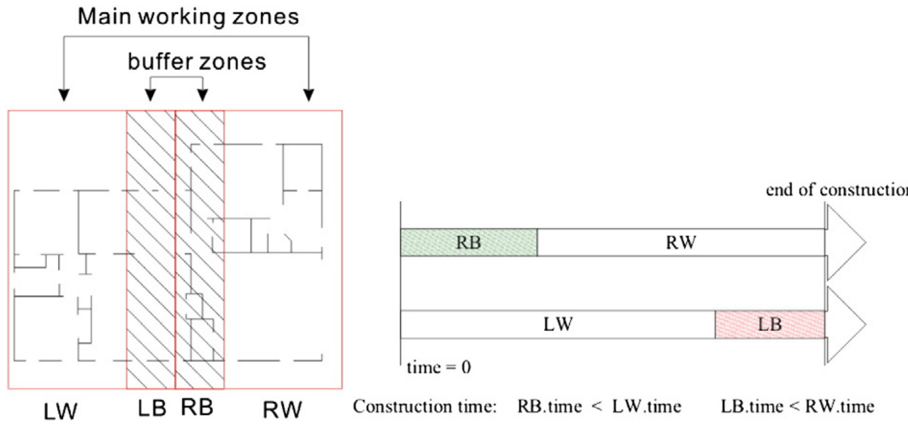

Fig. 17. Buffer zone concept.

gantry; and 2) the overall construction time of the original buffer zone and its auxiliary buffer zone is more than the construction time of the buffer zone in the next (adjacent on the right) section. According to the second constraint if the construction time of a buffer zone is more than that of the buffer zone in the next section, then no auxiliary buffer zone is needed. By using the auxiliary buffer zone method each section of the structure has at least one buffer zone, and it may or may not have the second buffer zone, therefore, the construction efficiency can be increased by the introduction of the auxiliary buffer zone concept.

5.4.2. Path cycling

Path cycling focuses on manipulating the *x*/*t* curve of the tool path to avoid collision. As shown in the previous section of the paper the generated tool path for a given layer is always a loop (i.e., the nozzle eventually visits the starting point at the end). The choice of starting point does not affect the fabrication time of the layer. In the path cycling method the start point (which is also the end point) of fabrication of each layer is changed for every new layer. This provides an opportunity for two adjacent nozzles, which would otherwise collide for a given pair of starting points, to avoid collision under changed cycles. Therefore, one of the two paths can be cycled to increase the chance of finding a pair of *x*/*t* curves that do not collide. To cycle a path the starting position is shifted to the next vertex in the sequence, and the sequence of the vertices remains the same in the tool path. If the altered path still collides with the original unaltered path of the other nozzle then the starting point is shifted again to the next vertex in sequence. Fig. 22 illustrates the concept of cycling a tool path (the numbers in the sequences represent the vertex numbers).

Linear interpolation is used to check if the two paths collide in each cycling step. If no collision is found, then the pair of the tool paths is collision-free and hence the cycling process can be stopped, otherwise the cycling process should be continued until collision-free tool paths are found. If the sequence of the tool path returns to its original pattern without finding collision-free tool paths then the path cycling method is not suitable for the given problem scenario and other methods should be attempted. The advantage of path cycling is its simplicity of computation and hence it is advisable to be tried. If path cycling does not yield a solution then *buffer zone path cycling*, which is presented in the next section should be attempted. Fig. 23 shows the concept of simple path cycling method.

The path cycling method can easily be extended to cases involving more than two nozzles (or gantries). Let *path(i)* represent the CC-TSP tool paths of different divided sections of the original structure. The first path, *path(1)*, can be fixed when path cycling can be performed on the second tool path, *path(2)*. If *path(1)* and *path(2)* do not cross each other, then *path(2)* can be fixed and *path(3)* can be cycled to find the path without collision with *path(2)*. However, if *path(3)* has been completely cycled and no collision-free paths between *path(2)* and *path(3)* are found, then *path(2)* needs to keep on cycling so that another pair of collision-free tool paths can be found between *path(1)* and *path(2)* in which case *path(2)* will again be fixed and *path(3)* will be cycled to find a path which does not collide with *path(2)*. The process should be continued until the paths have been checked and all adjacent paths are free from collision. Fig. 24 shows the concept of cycling multiple paths in order to find a set of collision-free tool paths for N machines.

5.4.3. Buffer zone path cycling

The method of *path cycling* can create collision-free tool paths in most of the cases. However, the chance of finding the collision-free tool paths still depends to a certain degree on the geometry of the structure and the width of gantry. The chance of finding collision-free solutions is enhanced significantly if the path cycling method is combined with the buffer zone method.

In this approach one buffer zone can be set up for each divided section to isolate the working area of different nozzles. Tool paths for different working areas and the buffer zone(s) are generated

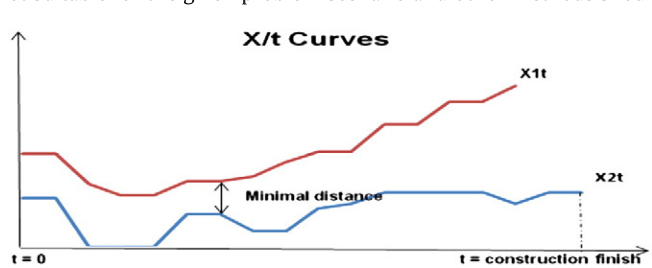

Fig. 18. Minimal distance between two *x*/*t* curves.

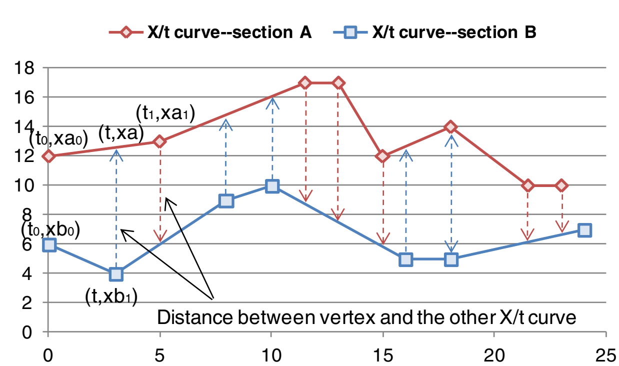

Fig. 19. Checking the distance between two *x*/*t* curves.

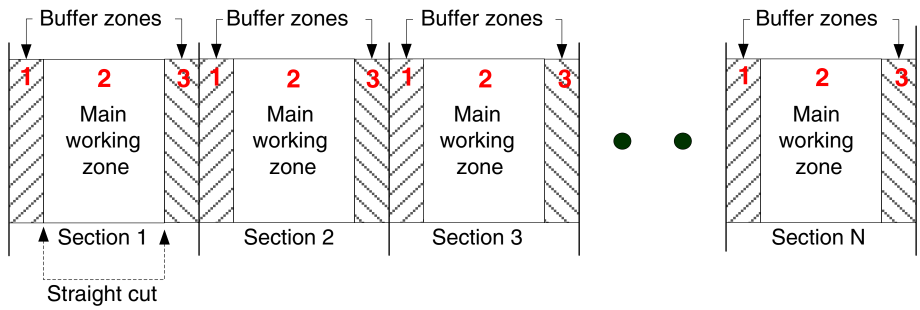

Fig. 20. Buffer zone set up.

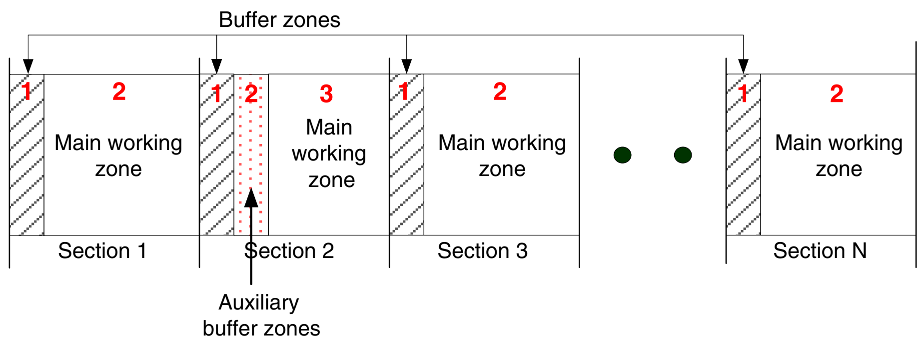

Fig. 21. Auxiliary buffer zone.

using the CC-TSP approach described in Part I of the paper. Path cycling is then performed on each main working zone to create pairs of collision-free tool paths between each of the adjacent buffer zones and working zones, as illustrated in Fig. 25.

Though it looks similar to the *auxiliary buffer zone* method, the *buffer zone path cycling* method has some advantages over the previous method. Without cycling any tool path one nozzle may need to have more than one buffer zone to keep a certain distance from the adjacent nozzles. By using the method of path cycling only one buffer zone is needed to avoid collision. Before performing path cycling the only time that collisions could happen is when a nozzle finishes its construction task on its own buffer zone and moves to its main working zone while the nozzle next to it is still working on its own buffer zone. Since both nozzles have to first finish the construction tasks on their own buffer zone, collision can only happen when the construction time in the adjacent buffer zones are different (see Fig. 26). As the construction time difference between the adjacent buffer zones is much smaller than the overall construction time of the main working zone, the chance of finding collision-free tool paths between the main working zone and the buffer zone when cycling the path of the main working zone is much greater.

When more than two machines are used in construction, unlike in the previous method (simple path cycling) the procedures for finding pairs of collision-free tool paths for adjacent zones would be independent of each other in the method of *buffer zone path cycling where* only the paired-up working zone path and buffer zone path are checked for collision. Cycling the tool path of a working zone increases the chance to create collision-free tool paths with the tool path of its adjacent buffer zone yet this cycling procedure does not cause any possibility of colliding with any other tool paths. This property dramatically increases the chance of finding collision-free tool paths when many machines are involved in construction.

6. Analysis of single and multiple nozzle tool path optimization

The results of this study are based on numerical simulation of several randomly building structures with varying designs. Structure designs have been selected with different levels of complexity as the simulation objects to generate simulation results as the sample data.

6.1. Real-time animated simulation of Contour Crafting

Integration of planning and optimization module and the real-time simulation and animation is especially important since it allows users to visualize the construction process in a virtual environment to verify the validity of the tool path for different nozzles/gantries and different structures. Integration of the strategy and planning data together with the geometrical representation of the structures can be accessed in the virtual environment [19] for monitoring or early stage planning. Users can operate the virtual machine and monitor the entire process to avoid potential problems, such as possible collisions with objects (e.g., existing structures, auxiliary equipment, etc.), which may not have been accounted for in the optimization model.

A 3-dimensional simulation platform is developed incorporating the Contour Crafting system characteristics and parameters. Tool path planning and optimization methods for single and multiple

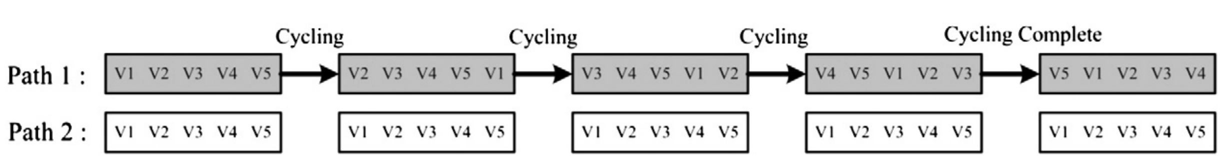

Fig. 22. Illustration of cycling a tool path.

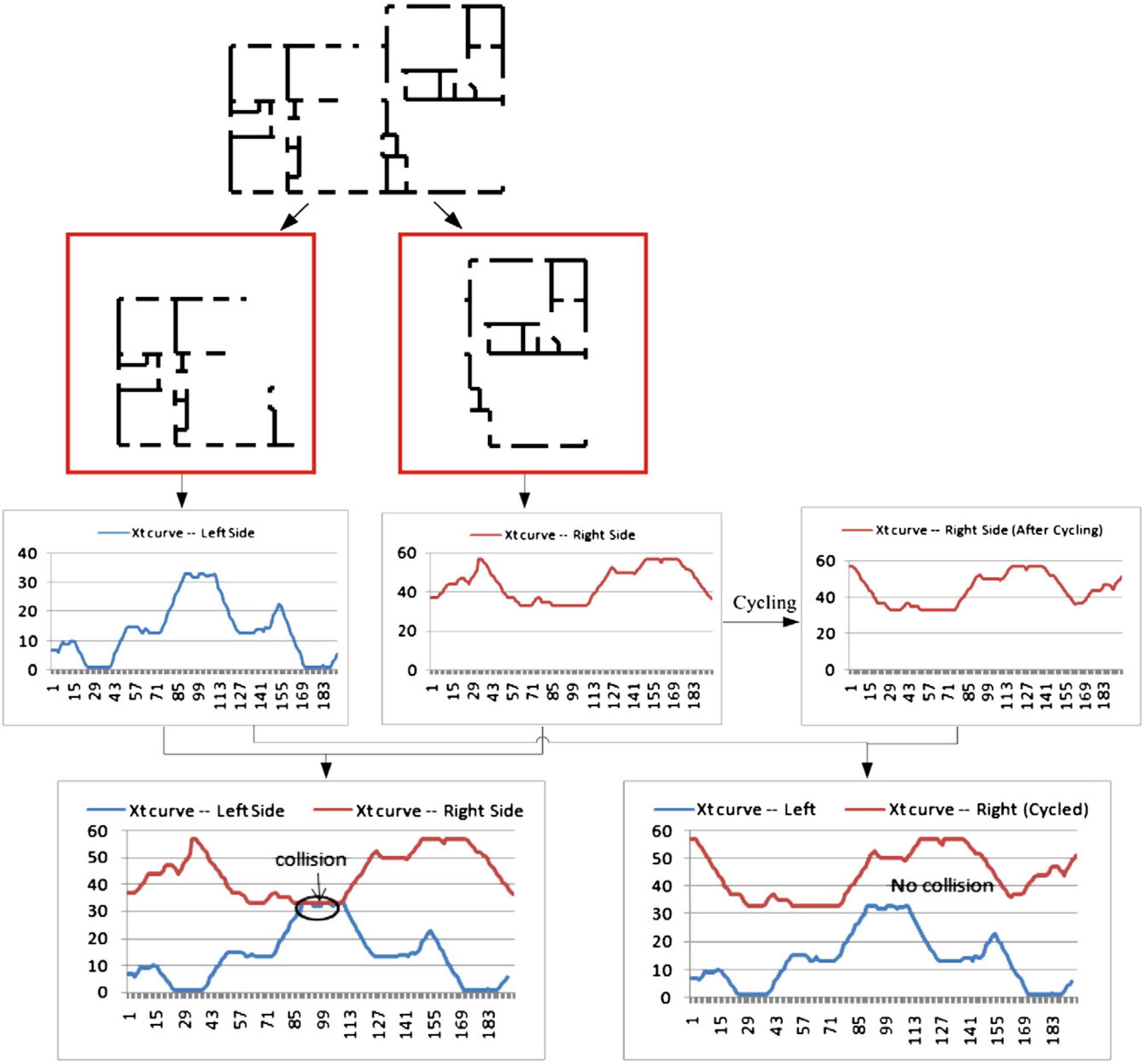

Fig. 23. Concept of path cycling.

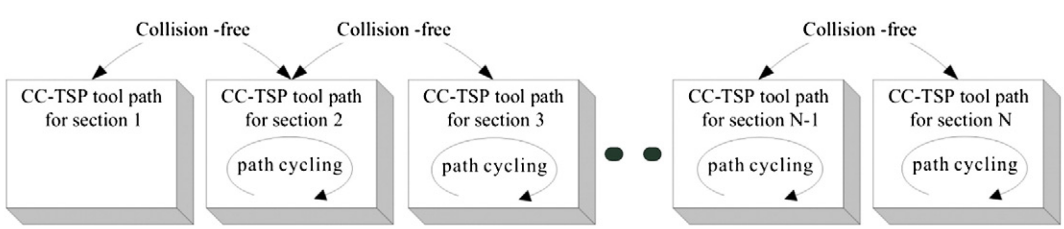

Fig. 24. Concept of applying the approach on N machines.

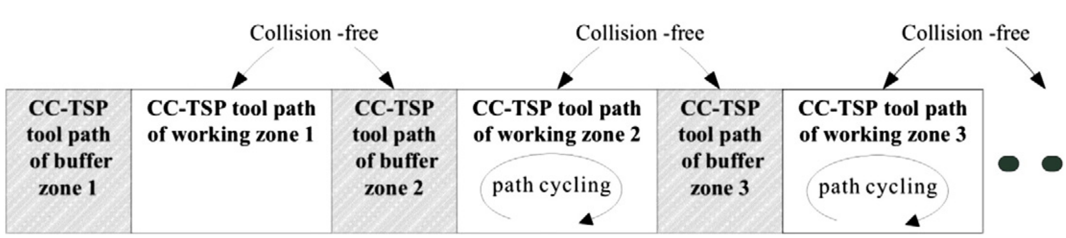

Fig. 25. Buffer zone path cycling for the N machines system.

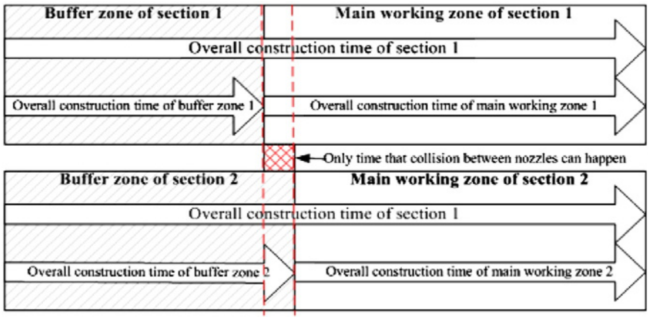

Fig. 26. Collisions occur in the overlap time of construction.

nozzle systems are implemented in the platform. Fig. 27 shows sample frames of the 3D simulation software module. In simulation of the single nozzle system two virtual machines are placed side by side. Simulations show that for all sample structure layouts the virtual machine, which is using CC-TSP to generate optimal tool paths, completes the construction much faster than the other machine, which uses the nearest point algorithm. In the simulation of multiple nozzle system two virtual machines are placed in the scene to construct structures collaboratively.

6.2. Analysis of single-nozzle tool path solution

50 structure layouts with different degrees of complexity have been used to test the results of different algorithms. The parameters of different sample structure layouts of the samples such as the width, height and number of wall segments in the structure are collected. Overall construction times resulting from following the tool paths generated by CC-TSP, Nearest Point, and the original order of the line segments in the structure are compared and showed in Fig. 28. In this figure the numbers on the horizontal axis represent the wall segments in the structure layout, and the numbers on the vertical axis represent the overall construction time for the corresponding structure. The complexity of a structure is proportional to the number of wall segments in it. The nearest point algorithm is a greedy algorithm that seeks the nearest vertex to visit when the nozzle is looking for the next destination.

The performance difference between CC-TSP and Nearest Point is more obvious if the total air time rather than the construction time is considered. Fig. 29 shows the saved airtime percentage by CC-TSP, and the nearest point algorithm as opposed to the original edge sequence of the structure. Fig. 30 shows the percentage of saved airtime when CC-TSP and the nearest point algorithm are compared.

The red line is the trend line of the average percentage of airtime saved, which increases along the horizontal axis representing the number of wall segments in the structure. Compared to the nearest point solution, the CC-TSP performs better with structures that are more complex. According to the above figures, it can be concluded that CC-TSP significantly reduces the overall airtime in construction.

6.2.1. Conclusion

By defining tool path elements the problem of tool path planning is converted into typical graph problems. The approach is to transfer the problem to a TSP (traveling salesman problem) structure by introducing a negative value to every two end points of each edge to obligate the optimal tool path to include every edge of the original structure in the entire path. The *Lin–Kernighan* heuristic algorithm is used to find the TSP solution in this research. The heuristic TSP solver is used because at reasonable speed it can find a solution within 5% of the exact solution even for large-scale TSP problems with up to 10,000 vertices. In general, the solution found by the CC-TSP algorithm saved 45% of nozzle air time compared to the nearest point algorithm. More time is saved when the level of complexity of a structure is increased.

6.3. Analysis of multi-nozzle tool path solutions

50 structure layouts with different levels of complexity were used to compare the results of different approaches. The performance of the three algorithms, auxiliary buffer zone, path cycling and buffer zone path cycling was then compared. Success rate of finding the tool paths and overall construction time were evaluated as performance metrics of these algorithms. Performance of the same algorithm with different number of nozzles (2 or 3) was also evaluated. The results of the analyses are presented in the following sections.

6.3.1. Success rate of different methods

Different approaches have different success rates of finding collision-free tool paths. Fig. 31 shows the success rates of different approaches in the two nozzles (left) and three nozzles (right) case.

In this chart, the success rate bars are shown in different method groups. In each group, there are three bars representing the success rate with different gantry widths. The *auxiliary buffer zone* algorithm has the highest success rate while *path cycling* has the lowest success rate. The number of nozzles that are utilized to construct the specific layout is another factor that affects the success rate. The success rate for the three-nozzle case is lower than that of the two-nozzle case when the same structure layouts are used. This indicates that generally it would not be advisable to construct small structures with too many nozzles (or gantries).

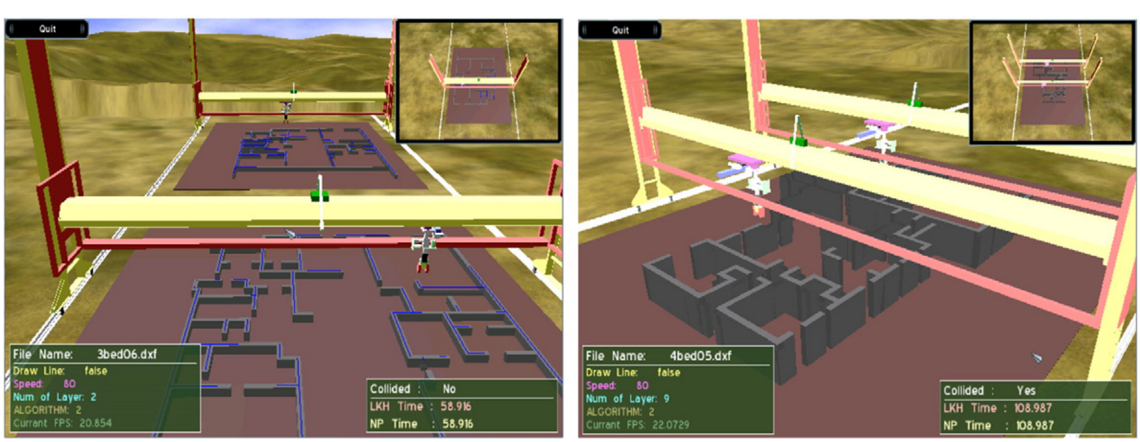

Fig. 27. 3D simulation platform.

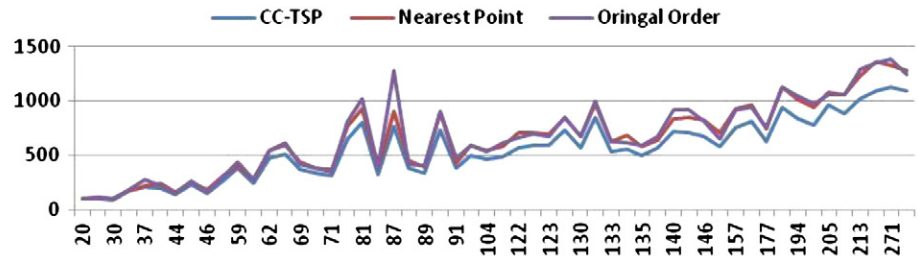

Fig. 28. Total construction time comparison.

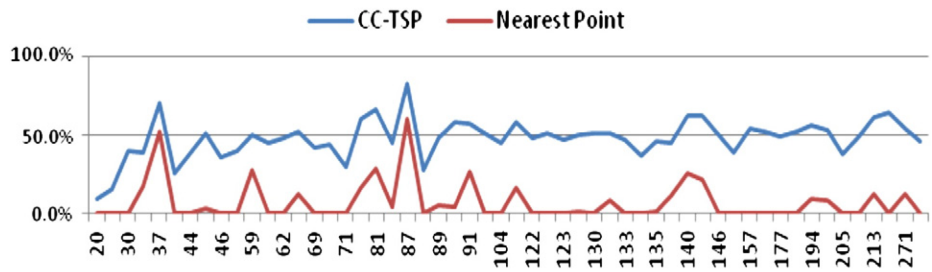

Fig. 29. Airtime save percentage by CC-TSP, NP, CC-CPP as opposed to the original edge sequence of the structure.

6.3.2. Performance of different methods

Fig. 32 below compares percentage of the total construction time saved over the single-nozzle case by the three algorithms. The construction time of the single-nozzle system is calculated using the CC-TSP algorithm. The vertical axis in the figure represents the percentage of time saved; the horizontal axis represents the number of wall segments in the structure layout from small to large.

As shown *path cycling* saves more time than do *auxiliary buffer zone* and *buffer zone path cycling* methods. The average percentage saved in *path cycling* is about 47% (ranging from 42% to 49%). The average percentage saved in *buffer zone path cycling is 37% (range from 18% to 43%)*. The average percentage saved in *auxiliary buffer zone* is 35% (ranging from 22% to 42%).

The performance differences in the three-nozzle case are similar to the differences in the two-nozzle case. Fig. 33 shows the performance differences among the different approaches, yet the pool of sample data is smaller since the three nozzle case has a smaller success rate.

6.3.3. Total construction time with different number of nozzles

According to the earlier discussion of the performance of different methods we have found that *path cycling* and *buffer zone path cycling* have high success rates and better performances. Following figures show the total construction time with these two algorithms for different number of nozzles.

In Figs. 34 and 35 the top curve represents the construction time calculated by the CC-TSP algorithm for different structure layouts that have different numbers of wall segments. The middle curve in these figures represents the construction time using *path cycling* and *buffer zone path cycling* for the two-nozzle system, respectively; and the lower curve represents the construction time by using *path cycling* and *buffer zone path cycling* for the three nozzle system, respectively.

There are spots in Figs. 34 and 35 where the value of the lower curve reaches zero, which means that solutions are not found for particular structures when a three-nozzle system is used. The difference between the lower curves in the two figures indicates that the *buffer zone path cycling* method has higher success rate in finding a solution. However, the method of *path cycling* saves more construction time than does *buffer zone path cycling* in both two-nozzle and three-nozzle cases.

6.3.4. Summary of findings about algorithms for multiple nozzle system

Given the foregoing discussions on the simulation results, we can conclude that *path cycling* methods could save more construction time than *buffer zone path cycling* methods. *Buffer zone path cycling* always performs better than *auxiliary buffer zone*, and the success rate of these two methods is almost the same. However, *buffer zone path cycling* method has a higher success rate of finding the solutions than *path cycling*. Also, the larger number of wall segments a structure has, the easier it is to find the solution for the multi-nozzle system.

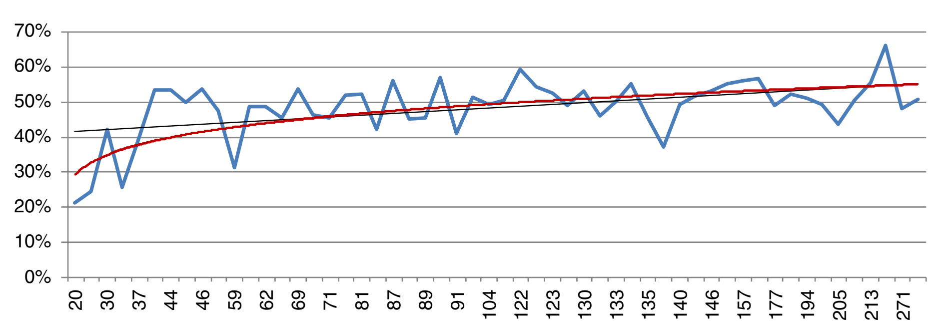

Fig. 30. Airtime save percentage between CC-TSP and nearest point algorithm.

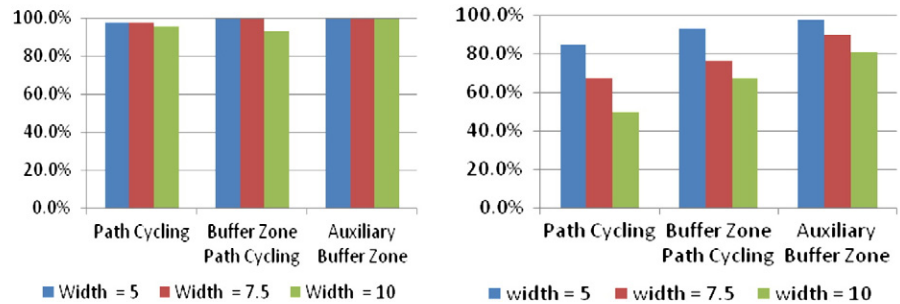

Fig. 31. Success rates of different approaches in the two nozzle case (left) and three nozzle case (right).

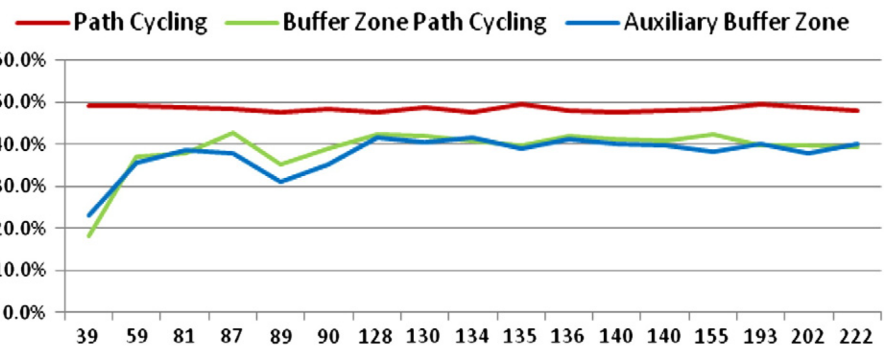

Fig. 32. Percentage of construction time saved with four approaches in two nozzle cases.

Compared to the single nozzle case, the percentage of construction time saved in building larger structures using the multi-nozzle system is higher. Furthermore, the width of the structure layout is the critical factor for the success rate.

7. Conclusion

This research reported here was intended to provide a systematic methodology for CC machine operations planning and optimization in order to efficiently construct complicated large-scale structures by Contour Crafting systems using single or multiple machines and other hardware configurations.

2.5D building structures have been considered. Structure models are first horizontally sliced into different layers and then tool path planning and optimization are performed on the layout of each layer of the structure. It is required that the CC nozzles complete the construction of each entire layer before moving to the next one. Under these premises, edges and vertices are defined as the basic elements of the Contour Crafting tool path when edges represent the wall segments and vertices represent the intersections, corners or end points of the wall segments. Physical constraints of the technology are incorporated with construction considerations to define other tool path elements, such as cost of deposition, cost of traveling, cost of moving and cost of rotation.

By defining tool path elements, the problem of tool path planning is converted into typical graph problems. The approach is to conform the problem to the structure of a TSP (traveling salesman problem) by assigning a negative value to every two end points of each edge to obligate the optimal tool path to include every edge of the original structure. The *Lin–Kernighan* heuristic algorithm is used to find the TSP solution. The heuristic TSP solver is used because it can find a solution which is no more than 5% worse than the exact solution. Solutions are found in a reasonable time for even large scale TSP problems (fewer than 10,000 vertices). In general, the solutions found by the CC-TSP algorithm saved 45% of nozzle airtime as opposed to the nearest point algorithm. More time is saved when structure complexity is increased.

Based on the optimization method for the single nozzle system, a two-step procedure is introduced in order to generate collision-free tool paths for the multi-machine Contour Crafting systems. In the first step, the original structure is first evenly divided into different sections according to the number of nozzles used. The nozzle workloads contained in each section are evenly allocated so that the waiting time of moving to the next layer is minimized for each individual nozzle. In

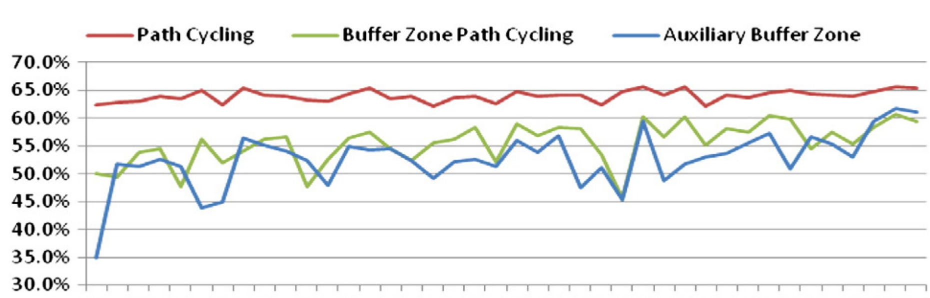

Fig. 33. Percentage of construction time saved with four approaches in three nozzle cases (path cycling: top curve; buffer zone cycling: middle curve; auxiliary buffer zone: lower curve).

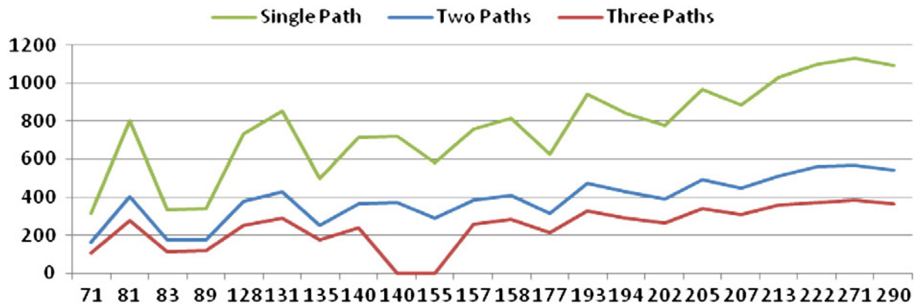

Fig. 34. Construction time difference among single nozzle, two nozzles and three nozzles (path cycling).

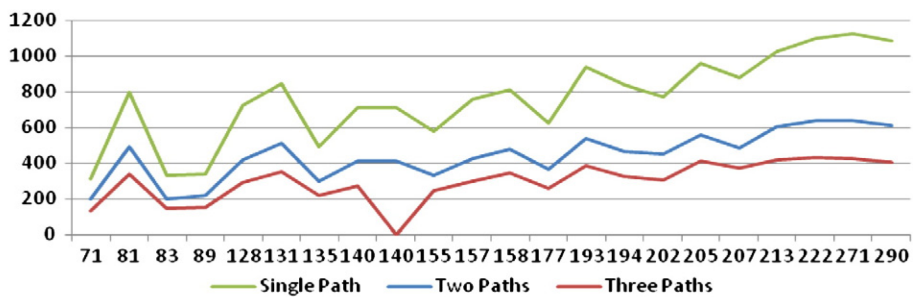

Fig. 35. Construction time difference among single nozzle, two nozzles and three nozzles (buffer zone path cycling).

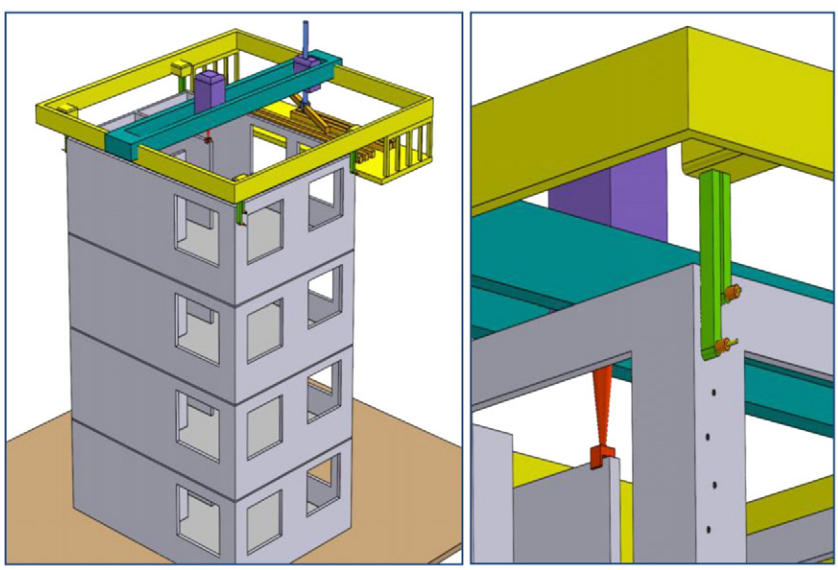

Fig. 36. Construction of multi-story building using climbing machine.

the second step the concept of buffer zones and path cycling are introduced to create collision-free tool paths between sections. The buffer zone concept sets up a cushion area to prevent every two adjacent nozzles from getting too close to one another; the path cycling concept simply manipulates the construction sequence without compromising the construction efficiency. Three approaches that follow the two-step procedure are developed: *path cycling*, *buffer zone path cycling* and *auxiliary buffer zone*. These approaches progressively have a higher chance of converging towards a feasible solution. However, the extent of optimization of their solutions progressively declines. Machine behavior is also incorporated with the buffer zone concept in order to guarantee a robust and collision-free system.

A 3-dimensional simulation platform is developed incorporating the Contour Crafting system characteristics and parameters to test the result. 50 structure layouts with different levels of complexity were used to compare the result of different approaches. The results indicate that the individual path cycling and buffer zone cycling are methods with higher success rates and reasonable optimality. With a gantry width of 5 ft, the average percentage saved in path cycling is about 47% (range from 42% to 49%). The average percentage saved in buffer zone path cycling is about 37% (range from 18% to 43%). The average percentage saved in auxiliary buffer zone is about 36% (range from 22% to 42%). Construction by Contour Crafting is expected to be significantly faster than conventional methods of construction due to the novel technological features of the process. The algorithms introduced in this article can add to the intelligence of the Contour Crafting machine control software to add even more efficiency to this already efficient construction technology.

It should be pointed out that although the models presented here may seem to apply to single story construction, implementation for multi-story buildings will be possible by repeating the solution procedure for the specific floor plan of each level in a multi-story building. A variation of Contour Crafting machine will be able to build multi-story buildings by climbing the building under construction, as shown in Fig. 36. As shown in the right side frame in the figure, in the course of layering process metallic pipe segments are placed at designated locations around the building. Once the layer cures these tubular segments can be used as stable anchor points for insertion of pins used by the climbing mechanism to elevate the machine platform to a higher stage after a given number of layers are deposited.

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