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Toolpath Planning and Optimization for Single and Multiple Gantry Contour Crafting System

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Abstract: *Contour Crafting is an emerging technology that uses robotics to construct free form structures by repeatedly laying down layers of material such as concrete. The Contour Crafting technology scales up the additive fabrication process from building small industrial parts to constructing buildings. Tool path planning and optimization for Contour Crafting benefit the technology by increasing the efficiency of construction of complicated structures. This research has intended to provide a systematic solution for improving the overall system efficiency and realizing the automation of the Contour Crafting technology for building custom-designed houses. An approach is presented to find the optimal tool path for the single nozzle Contour Crafting system incorporating the physical constraints of the technology and construction considerations. Several algorithms are given to find the collision-free tool path for the multiple nozzle system based on the single nozzle approach.*

Keywords: *Tool path planning, optimization, contour crafting*

1. INTRODUCTION

Contour Crafting (CC) [1] is a mega-scale fabrication process that aims at additive fabrication of large scale parts directly from computer models. It is a hybrid method that combines an extrusion process for forming the object surfaces and a filling process (by pouring, or extrusion) to build the object core. Contour Crafting uses computer control to exploit the superior surface-forming capability of 2troweling in order to create smooth and accurate planar and free form surfaces out of extruded materials[2]. Unlike many other automatic additive fabrication technologies such as 3D printing, SLS, SLA, FDM, which can only deliver relatively small size of three-dimensional structures (normally 1 cubic foot maximum)[3], Contour Crafting has the capability to fabricate with thick layers using various materials and without compromising surface quality. The goal of Contour Crafting technology is to build large structures (such as custom-designed houses) in a short time (such as a day).

Toolpath planning and optimization play important roles in realizing the automation of the technology and improving the overall system efficiency by generating optimal nozzle/trowel paths for the given structure designs. Multiple-nozzle or multiple-gantry systems may be involved for construction of larger community and multi-residence structures to reduce the construction time and cost. There are two kinds of Multi-Machine Contour Crafting systems: Overhead multi-nozzle and multi-gantry. In both cases, specific schedule and workload are assigned to individual nozzles or gantries for collaborative operation. Collision between nozzles should be avoided without compromising the overall constructing efficiency. This paper intends to present a systematic methodology for Contour Crafting process planning and optimization 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
3. Develop practical tool path planning and optimization methods for multi-nozzle system based on the optimization method for single nozzle

2. METHODOLOGY

The research activities for Contour Crafting tool path planning and optimization can be categorized into three groups: Preliminary Research, Developmental Research and Analytical Research (Figure 1).

Under preliminary research the characteristics of the Contour Crafting system are studied. Hypotheses are generated according to the features and limitations to simplify the problem so that the Contour Crafting tool path model can be constructed. The Contour Crafting tool path element can be defined systematically once the hypotheses are stated. Physical constraints and the utility functions are converted from the hypotheses and are appropriately interpreted in the forms of the tool path elements.

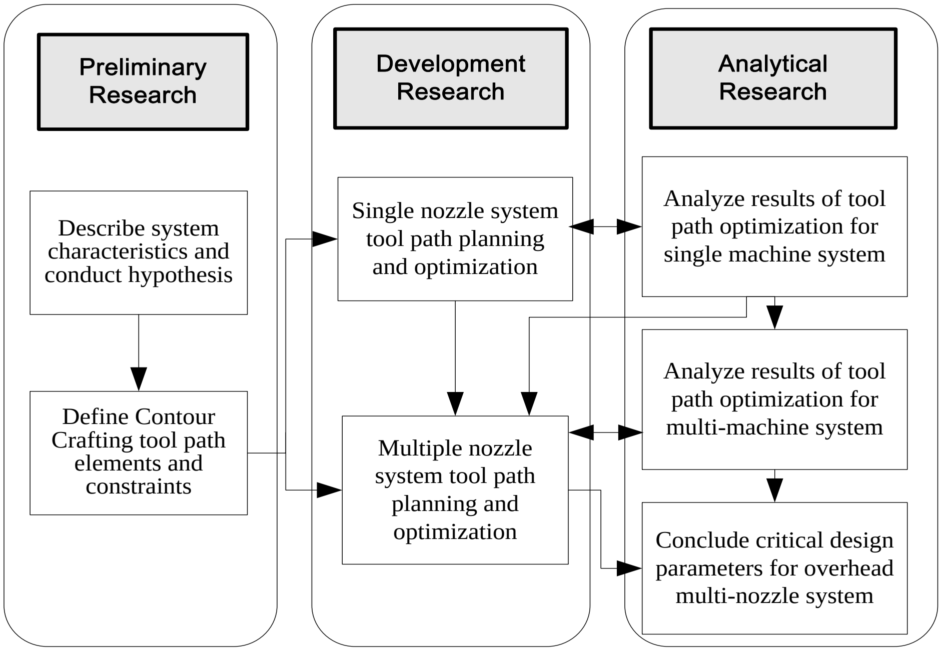

Figure 1. Research Methodology

Approach for tool path planning and optimization for the single nozzle Contour Crafting system are proposed in the development research. 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 system.

Three approaches that follow the two-step procedure are developed and illustrated in detail.

Under analytical research, experimental and numerical investigations are performed to analyze the feasibility and efficiency of tool path planning and optimization for both single and multiple nozzle systems. A simulation test bed is implemented for the purpose of simulation.

3. IMPLEMENTATION

3.1 Tool path elements of Contour Crafting

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

Cost of deposition is related to the total length of wall segments, the deposition flow rate and the moving speed of the machine. *Cost of airtime* is related to the cost of moving between wall segments and the *cost of rotation* along wall segments. *Cost of moving* between two segments can be determined once the distance between end points and the velocity of the machine are known. *Cost of rotation* between segments can be evaluated according to the relative orientation of the two segments. However, the nozzle cannot rotate without limitation to prevent damaging the cables and wires attached to it. For that reason, a stopper is assembled on the rotation union to prevent the nozzle from turning more than 360 degree clockwise or counterclockwise. 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 on not only the rotation degree but also on the starting and end positions of the stopper on the rotation union.

3.2 Tool path planning and optimization method for the single nozzle CC system

Once the costs of different machine tasks and physical constraints have been defined, optimization can be performed to find the most efficient tool path for the single nozzle system. The approach presented here is to convert the CC path model to a standard TSP (traveling salesman problem) [4].

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 $X_{ij} = 1$ (when i,j are the index of the vertices), if edge (i,j) is in the optimal tour; otherwise $X_{ij} = 0$, and $D_{ij} = d(i,j)$, when d is the traveling cost between vertices i and j.

Thus we have:

$$\text{Min} \sum \sum D_{ij} X_{ij}$$

$$\sum X_{ij} = 1 \qquad \text{for all } j$$

$$\sum X_{ij} = 1 \qquad \text{for all } i$$

$$\sum \sum X_{ij} >= 1 \qquad \text{for every } S \subseteq X \text{ (when } i \in S \text{ ; } j \in X-S)$$

The graph of a structure 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. No matter how the optimal path is generated, the nozzle should traverse all the deposition edges once and only once. Therefore, 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 airtime travel (motion between two end points of two edges) is a straight line. The optimal solution minimizes the overall airtime travel.

An approach 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. Since each edge has two vertices, the approach of shrinking the edge to a single point has four possibilities to travel from one edge to another. Since *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, it cannot be determined before performing the optimization. In order to formulate the problem as a TSP, some modifications need to be done:

Let Vi1 and Vi2 denote the two end points of the ith edge (i = 1; 2; . . . ; 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 | i = 1, 2, . . . , n; k =1,2}. Between every pair of distinct vertices (Vik , Vjl) there is an undirected edge with length given by:

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

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 i = 1; 2; . . . ; n, the distance of -M between vertices Vi1 and Vi2 implies that the optimal tour must include the edge that connects them. Therefore, every deposition edge will be traversed by the nozzle. A minimum length Hamiltonian cycle in this network yields a practical optimal tour for the tool path optimization problem. Figure 2 shows the concept behind this approach

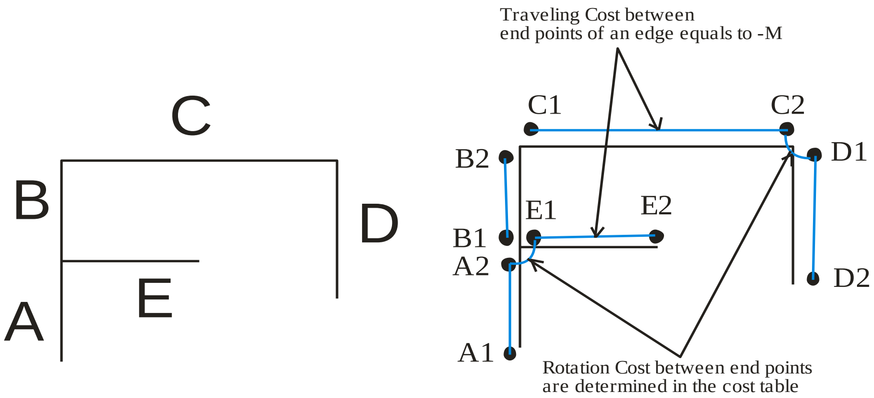

Figure 2: the concept of converting layout to standard TSP problem.

The converted CC-TSP problem can be solved by using heuristic algorithms. Most TSP solvers use effective heuristic algorithms to find the acceptable result (normally no more than 5% of the optimal solution [5]) within reasonable time. The Lin-Kernighan algorithm [5] has been one of the most successful tour-improving methods since the 1980's. The two most recent implementations of Lin-Kernighan algorithm are the Chained (sometimes also called Iterated) Lin-Kernighan algorithm by Johnson and McGeoch [6] and the modified Lin-Kernighan algorithm introduced by Helsgaun [6]. The former changes the classic Lin-Kernighan algorithm by having it iterating in several steps. Helsgaun make some improvements on the original Lin-Kernighan algorithm, mainly by revising restrictions and directing the search for tour parts probably belonging to the optimal solution. Helsgaun's application is used in this research.

3.3 Tool path planning and optimization methods for multi-nozzle

The primary concern in using multiple nozzles (or gantries) is that collision between different nozzles/gantries should be avoided. 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.

3.3.1 Step1: Iterative dividing.

The original structure layout should be separated into different sections according to the number of the nozzles. Ideally, each section contains an equal amount of work load so that the construction time of all of the sections is the same. Straight lines can cut across the original layout in order to divide it into sections with the condition that the sums of the length of all of the wall segments in different sections are equal or approximate. The single nozzle optimization algorithm (CC-TSP) is applied to find out the overall construction time of each section of the layout. If the difference between the construction times is acceptable (lower than the pre-set threshold) then the workload assignment is considered to be achieved. Otherwise, the cutting lines should be moved and split the original structure, the optimization should be performed again on each section to find the difference between the construction times. The above procedures will be performed iteratively until the best result is achieved.

3.3.2 Step 2: create collision-free tool paths between the divided parts

After dividing the structure into different sections that have almost equal work load for their corresponding nozzles, 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. Three algorithms are proposed to find the optimal collision-free tool paths. These algorithms are: (1) buffer zone; (2) path cycling; (3) buffer zone path cycling.

3.3.2.1 Buffer zone

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 Figure 3.

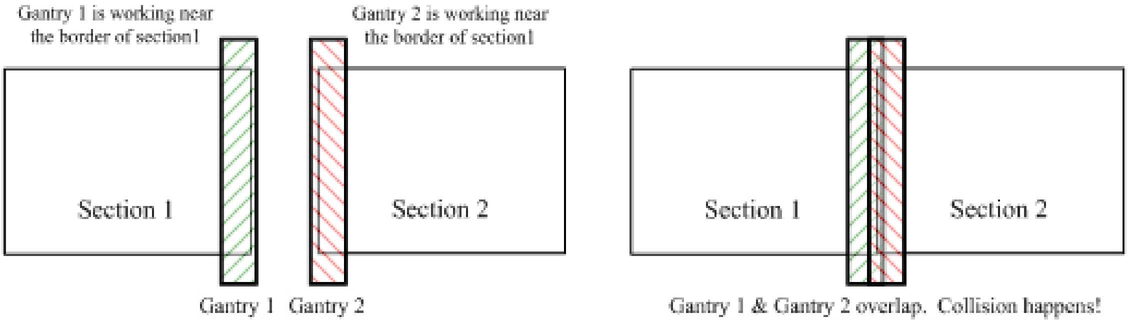

Figure 3: Possible collisions between two gantries

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; 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. When more than two gantries are working together, each divided section needs to have two buffer zones. The concept of auxiliary buffer zone can be used to reduce the number of buffer zones (See figure 4). First a buffer zone is 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. These constraints assure that the working areas of any two nozzles are mutually exclusive during the entire operation; therefore, collisions can be avoided.

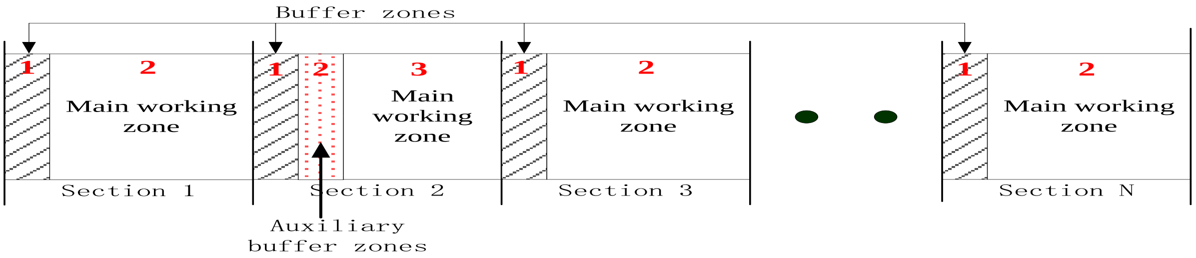

Figure 4: Auxiliary buffer zone. (Numbers are the construction sequence)

3.3.2.2 Path cycling

In the Contour Crafting system gantries that carry 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 the width of the gantry. 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 in 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. If the overall construction time of the longer curve is minimized, then the optimal solution will be yielded. (See figure 5)

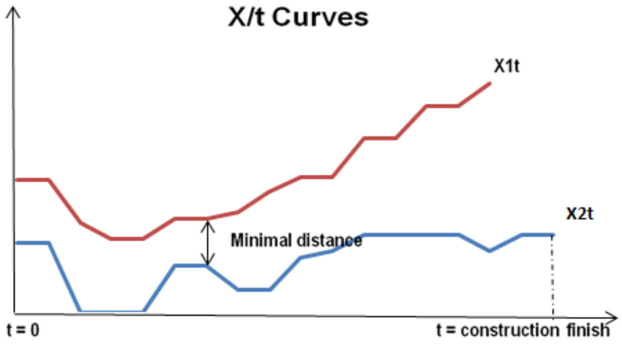

Figure 5: x/t curves

$x1(t) - x2(t) <$ Specific Distance When $0<t<$ end of the construction

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. Figure 6 shows the concept of Path Cycling.

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. Figure 21 shows the concept of cycling multiple paths in order to find a set of collision-free tool paths for N machines.

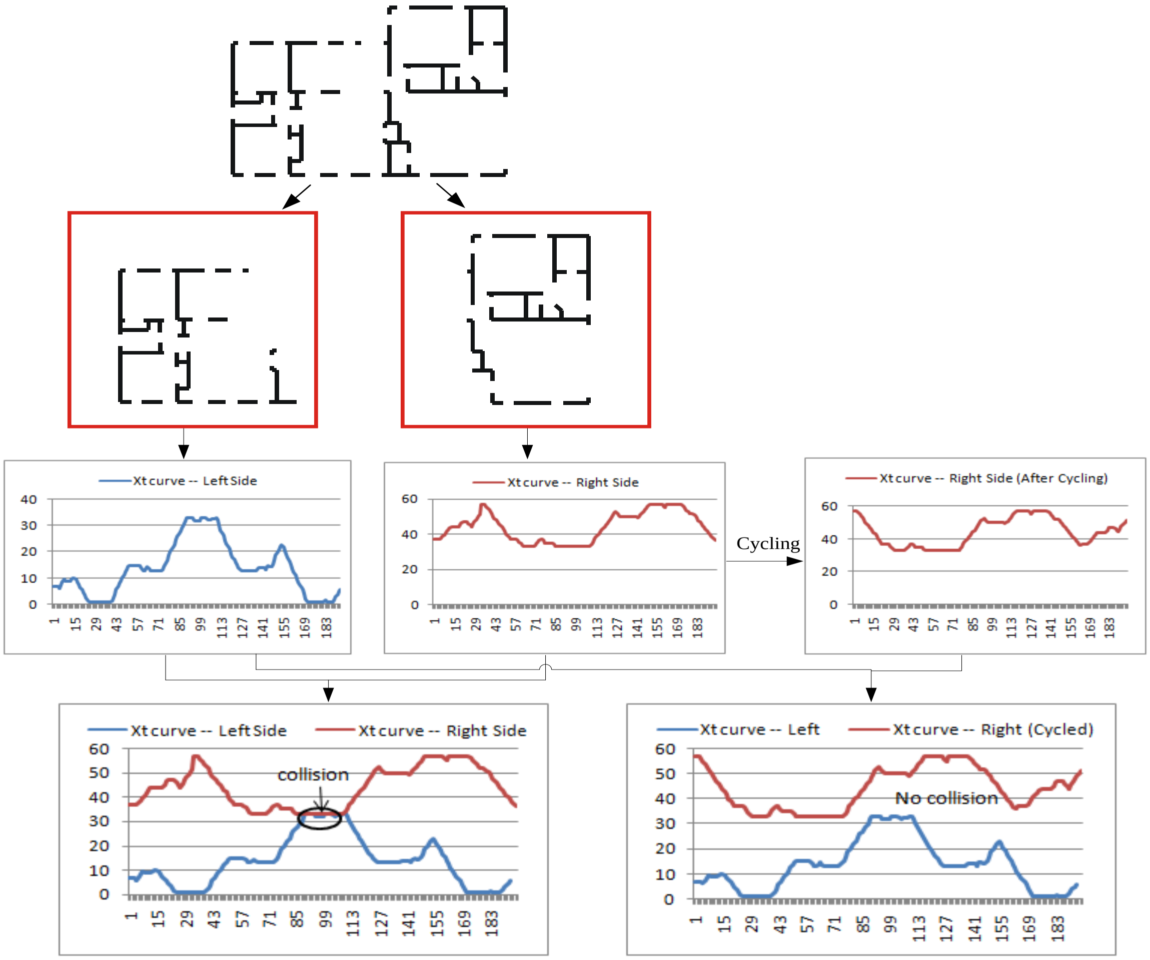

Figure 6: Concept of Path Cycling

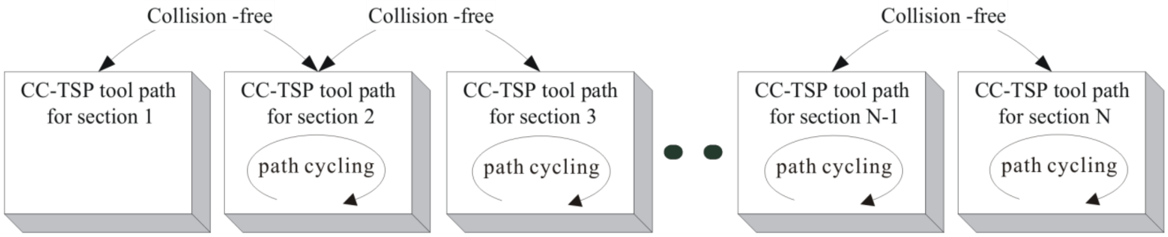

Figure 7: Concept of Applying the approach on N machines

3.3.2.3 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 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 Figure 8.

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. In order to create robust and collision-free system, machine behavior can be used to incorporate with the buffer zone path cycling concept [7] [8].

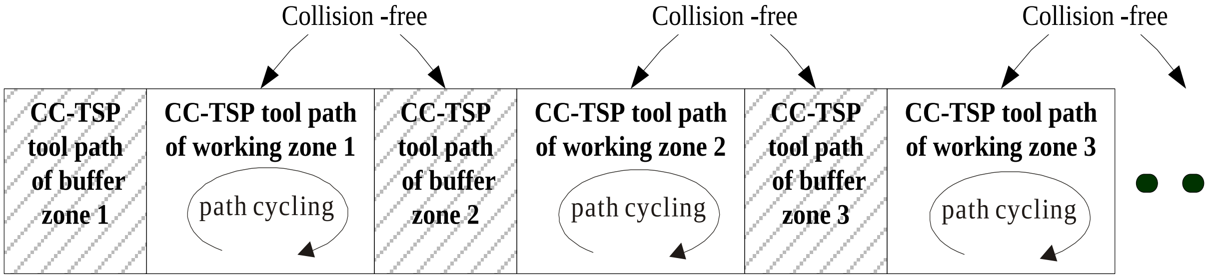

Figure 8: Concept of Buffer zone path cycling

4. RESULTS

4.1 Analysis for Single nozzle toolpath result

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 Figure 9.

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. Figure 10 shows the saved airtime percentage by CC-TSP, and the Nearest Point algorithm as opposed to the original edge sequence of the structure.

Figure 11 shows the airtime save percentage between CC-TSP and Nearest Point Algorithm. 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 that CC-TSP significantly reduces the overall airtime in construction.

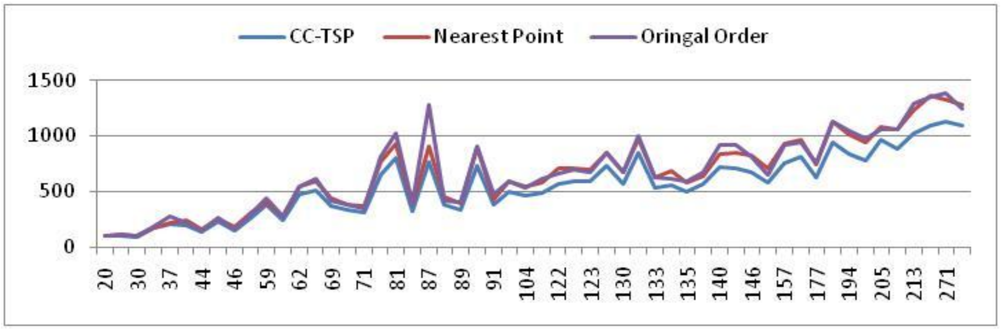

Figure 9: Total construction time comparison

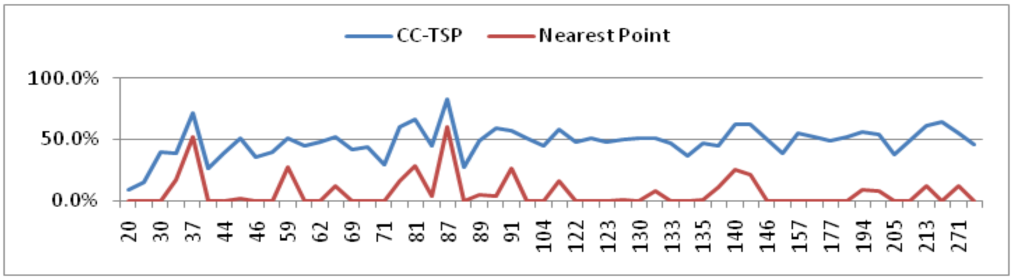

Figure 10: Airtime save percentage by CC-TSP, Nearest Point Algorithm, as opposed to the original edge sequence of the structure

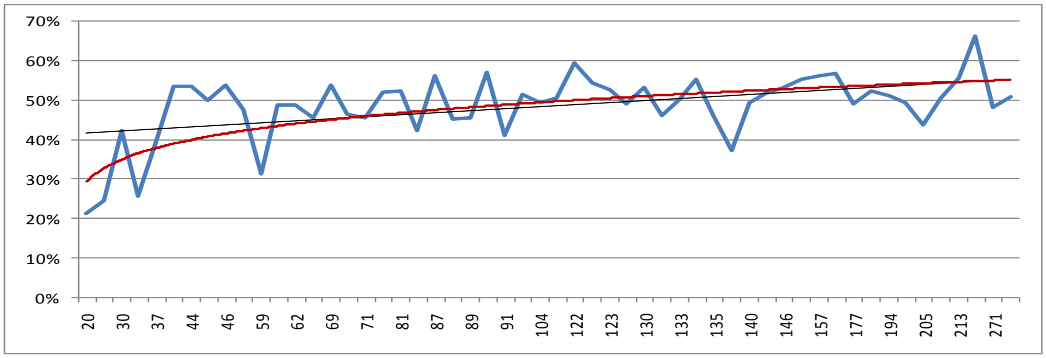

Figure 11: airtime save percentage between CC-TSP and Nearest Point Algorithm

4.2 Analysis for multiple nozzle toolpath result

Three algorithms given are: (1) auxiliary buffer zone; (2) path cycling; (3) buffer zone path cycling. The performances of these algorithms including success rate of finding the solution and the overall construction time are compared.

Figure 12 shows the success rates of different approaches in the two nozzles (left) and three nozzles (right) case. In this figure, the success rate bars are shown in different 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 when *Path Cycling* has the lowest success rate.

Figure 13 below compares percentage of the total construction time saved among the three algorithms as oppose to the single nozzle. The construction time of single nozzle system is calculated by 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. *Path Cycling* save more time than *Auxiliary Buffer Zone* and *Buffer Zone Path Cycling*. The average percentage saved in *Path Cycling* is about 47% (range from 42% to 49%), which is very close to the 50% optimum. 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% (range from 22% to 42%).

The performance differences in the three nozzle case are similar to the differences in the two nozzle case. Figure 14 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.

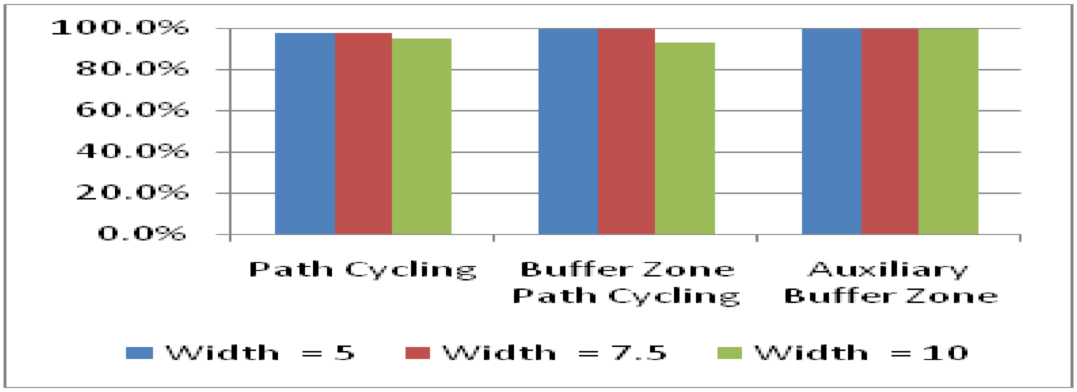

Figure 12: Success rates of different approaches in the two nozzles case (left)and three nozzles case(right)

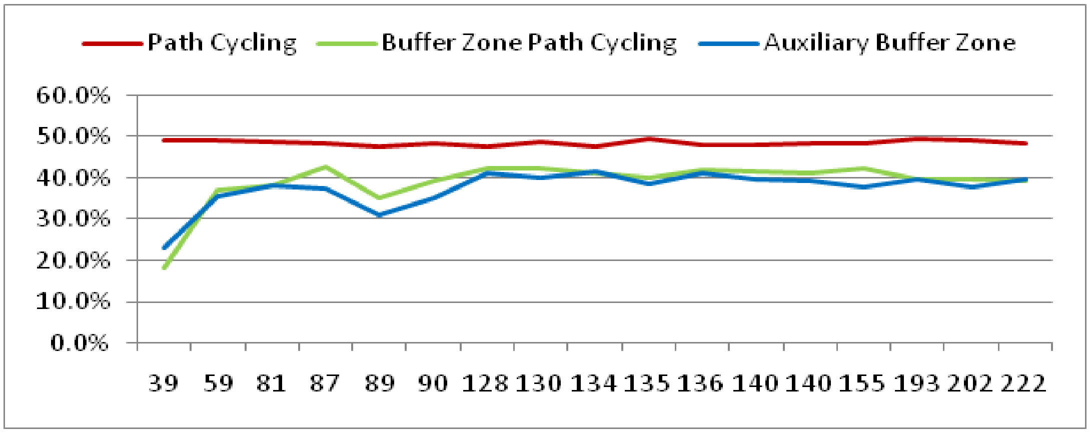

Figure13: Percentage of construction time saved with four approaches

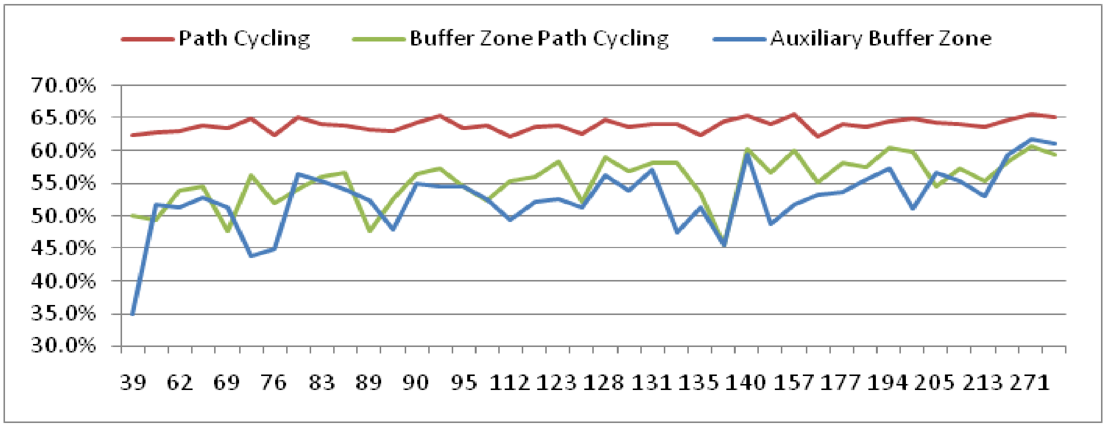

Figure 14: Percentage of construction time saved with four approaches in three nozzle cases

5. 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 (travelling 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. The *Lin-Kernighan* heuristic algorithm is used to find the TSP solution in this research. 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 system. In the first step, the original structure is first evenly divided into different sections according to the number of nozzles involved in the construction. In 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 pair of nozzles from getting too close to each other; 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.

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Behrokh Khoshnevis is a professor of Industrial & Systems Engineering, Mechanical & Aerospace Engineering and Civil & Environmental Engineering and is the Director of the Center for Rapid Automated Fabrication Technologies (CRAFT) at USC. He is active in CAD/CAM, robotics, and mechatronics related research and development projects that include the development of three novel Solid Free Form (Rapid Prototyping) processes called *Contour Crafting*, *SIS* and *MPM* as well as development of mechatronics systems for biomedical applications (e.g., restorative dentistry, rehabilitation engineering, and tactile sensing devices), autonomous mobile and modular robots for fabrication and assembly applications on earth and in space, and automated equipment for oil (petroleum) and gas industries. He has several major inventions which have been either commercialized or are in the commercialization process. His educational activities at USC include the teaching of a graduate course on *Invention and Technology Development*. He routinely conducts lectures and seminars on the subject of invention. He is a Fellow member of the Society for Computer Simulation, a Fellow member of the Institute of Industrial Engineers and and a senior member of the Society of Manufacturing Engineers.