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Contour Crafting Process Plan Optimization
Part II: Multi–Machine Cases

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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. Tool path planning and optimization for Contour Crafting benefit 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 system efficiency and realizing the Contour Crafting technology for building custom-designed houses. In the Part I of this paper 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. In Part II several algorithms are presented for finding the collision-free tool path for multiple machine configurations based on the single nozzle approach. The multiple machine configurations of Contour Crafting are ideal for rapidly constructing multiple adjacent structures or a large single structure because all machine modules can work in parallel to concurrently fabricate various structural parts.

***Keywords*:** Contour crafting, Tool path planning, Optimization

1. INTRODUCTION

1.1. Multiple machine systems

Multiple machine configurations have been employed in a variety of automated systems, such as in robotics 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, Brian et al. (2003). Coordination mechanisms enable the actions performed by each machine to take into consideration the actions of the other machines in a coherent manner, Farinelli et al. (2004). Recent research in multi-machine systems has also addressed various approaches such the Potential Method, Akamatsul et al. (2004) , and Coalition Formation, Parker and Tang (2006), which organizes 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

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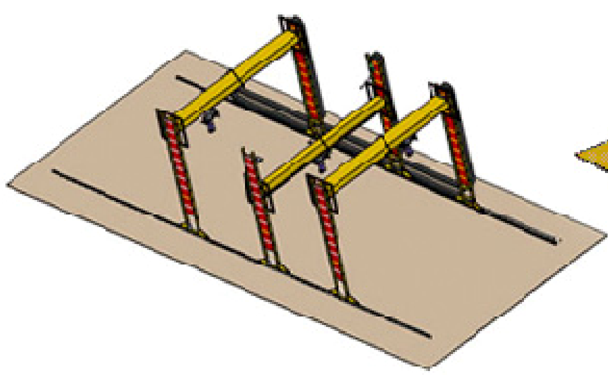
Alami (1999), Chaimowicz et al. (2004), Dias and Stentz (2003), Gerkey and Mataric (2003), Parker and Tang (2006), Werger and Mataric (2000), and Zlot et al. (2002). These approaches typically divide a task into indivisible subtasks and assign single robots to each subtask (STSR).

1.2. Multi-Machine configurations

Multi-Machine Contour Crafting systems can be used in constructing multiple basic structures or a large complex structure to reduce the overall construction time, Khoshnevis (1999, 2004), Zhang (2009). The CC system is based on a gantry structure that rides on two parallel rails. Multiple machines can ride on the same pair of rails thereby lowering installation cost while dramatically saving construction time.

As shown in Figure 1 there are two kinds of Multi-Machine Contour Crafting systems: a) *Multi-Gantry CC* and b) *Overhead Platform CC.* The Multiple-Gantry system is more flexible than the overhead multiple-nozzle system as it consists of different gantries that can be operated independently. In this configuration the nozzles on different gantries can simultaneously work on different layers. This configuration is suitable for construction of multiple structures as well as a single large structure. In the Overhead Platform system gantries each having a single nozzle can reciprocate of an overhead platform. The motion of the nozzles in this case is confined by the overhead structure. The entire overhead structure has to move up and down in order for the nozzles to build different layers. The overhead platform system is more suitable for large single structures. In both machine types gantries that carry the nozzles cannot cross each other.



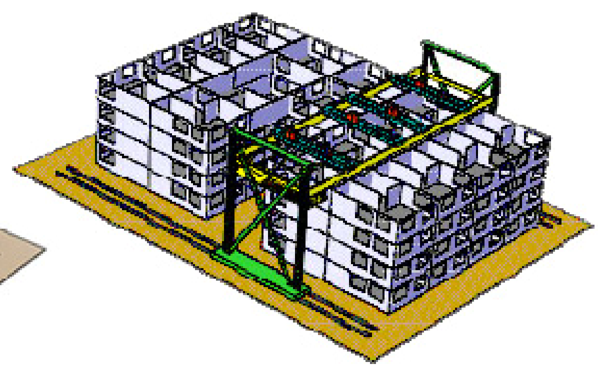


Figure 1 Multiple gantry system (system) with each gantry being an independent CC machine, and Overhead Platform which carries multiple nozzles (right)

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 work load 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 section 4 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.

2. FINDING COLLISION FREE TOOL PATHS FOR MULTIPLE MACHINE CC SYSTEM

2.1. A two-step approach

The tool path generation of the multi-machine system includes two steps. 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. Figure 2 shows the two step procedure for finding tool paths for the multi-machine Contour Crafting system.

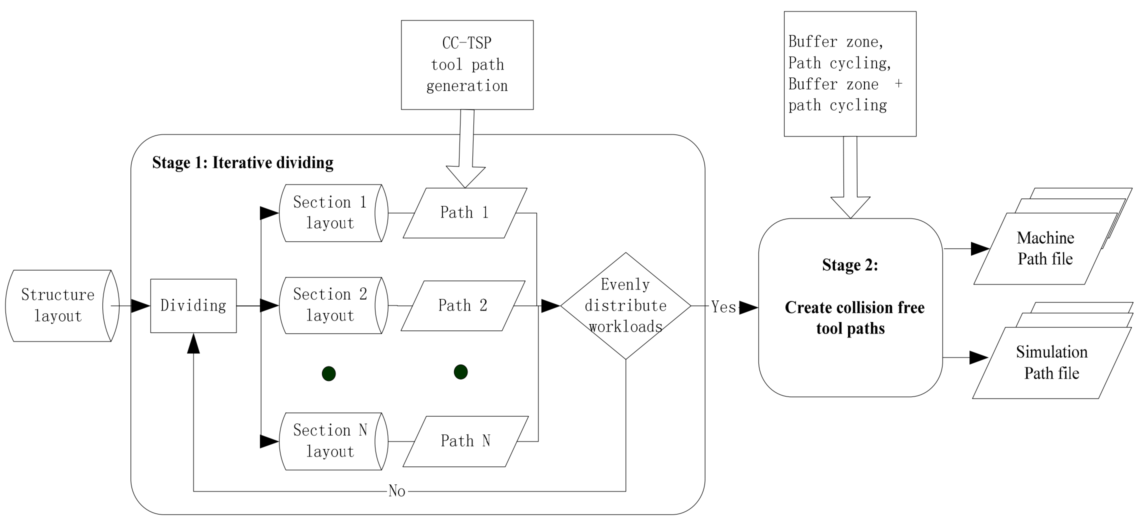


Figure 2 The Two-step Procedure

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 Part I 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.

Step 2: 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. These methods are explained as follows.

2.1.1. 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 Figure 3.

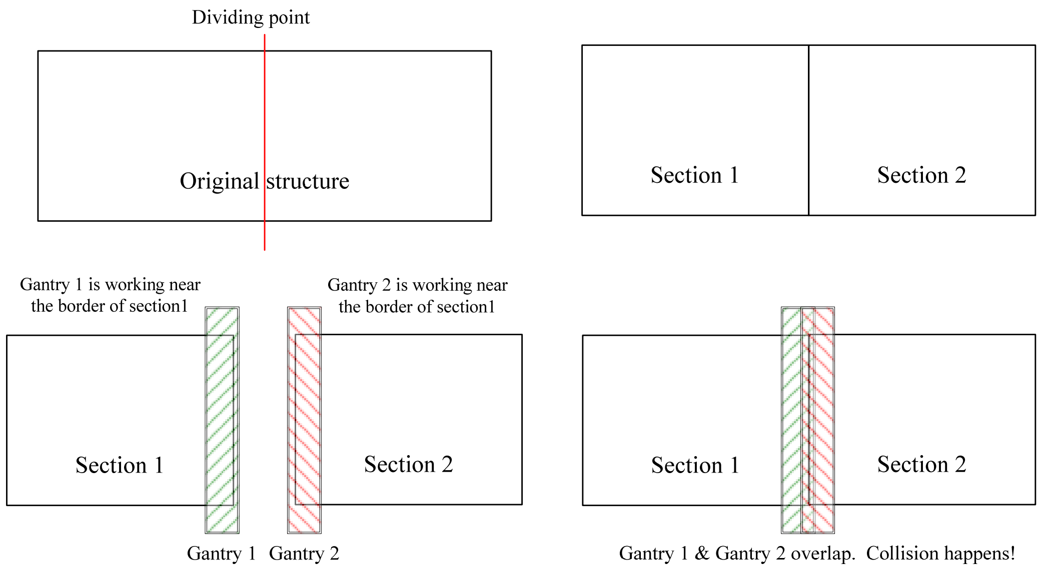


Figure 3 Possible collision between two gantries

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. These constraints assure that the two nozzles do not collide during the operation because working areas are always mutually exclusive.

2.1.2. Gantry x/t curve

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 (see Figure 4).

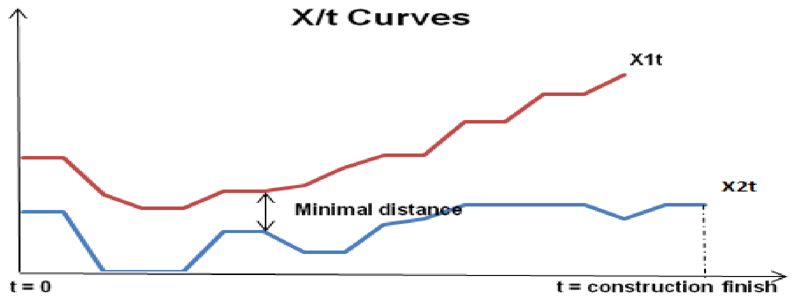


Figure 4 Minimal distance of to x/t curves

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

Abs (*X1*(t) – *X2*(*t*)) < Specific Distance (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 Figure 5).

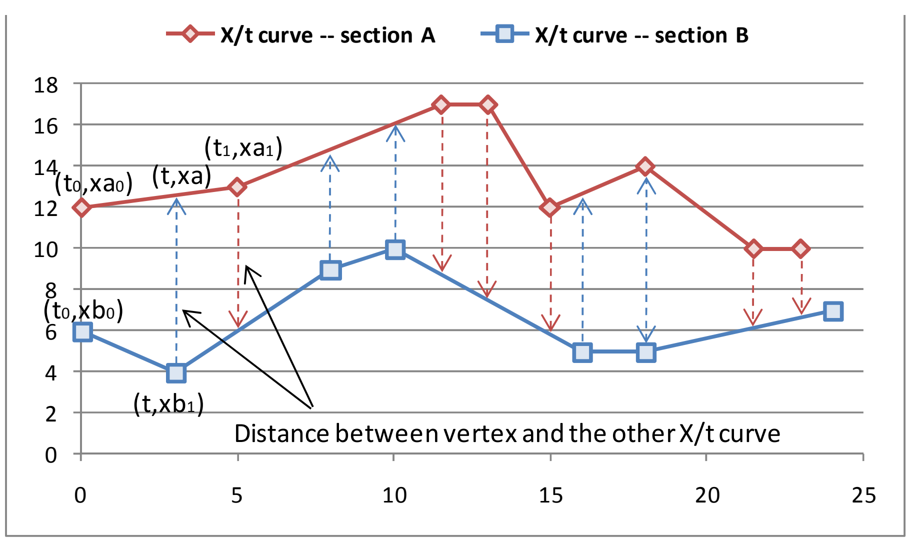


Figure 5 Checking the distance between two x/t curves

2.2. 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; 3) buffer zone path cycling.

2.2.1. 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 Figure 6).

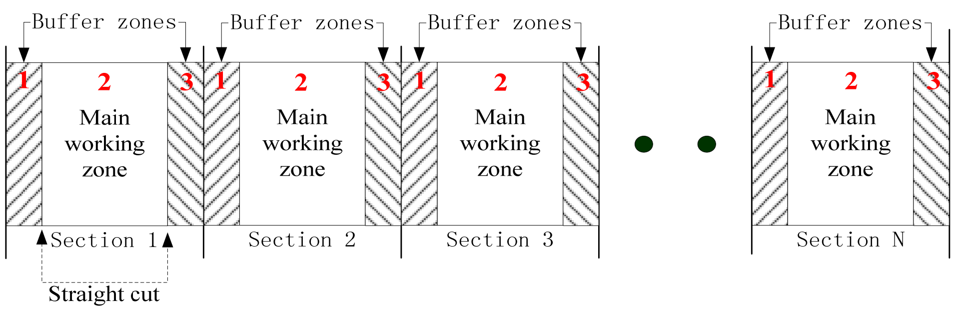


Figure 6 Buffer zone set up

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, 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 Figure 7).

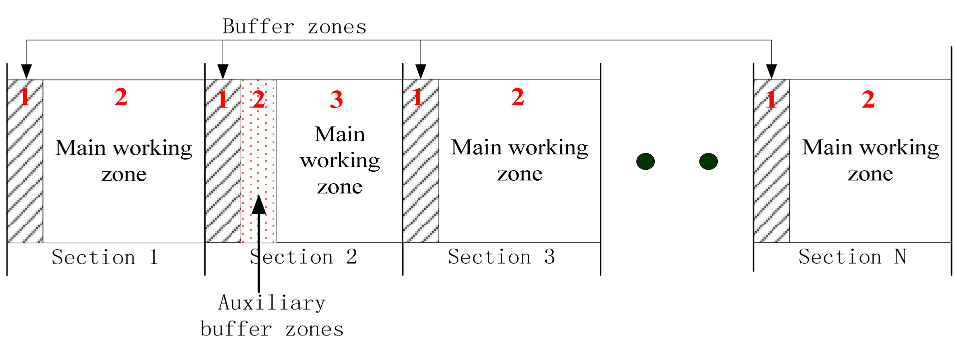


Figure 7 Auxiliary Buffer Zone

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

2.2.2. Path cycling

Path cycling focuses on manipulating the x/t curve of the tool path to avoid collision. As shown in Part I 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 8 illustrates the concept of cycling a tool path (the numbers in the sequences represent the vertex numbers).

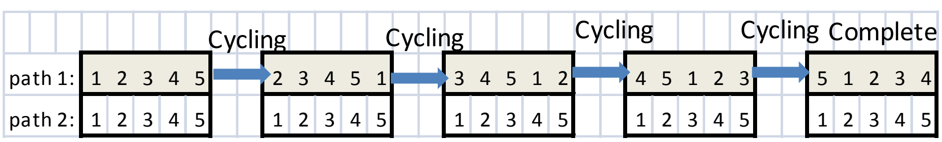


Figure 8 Illustration of cycling a tool path

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 are collision-free and hence the cycling process can be stopped, otherwise the cycling process should be continue 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. Figure 9 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. Figure 10 shows the concept of cycling multiple paths in order to find a set of collision-free tool paths for N machines.

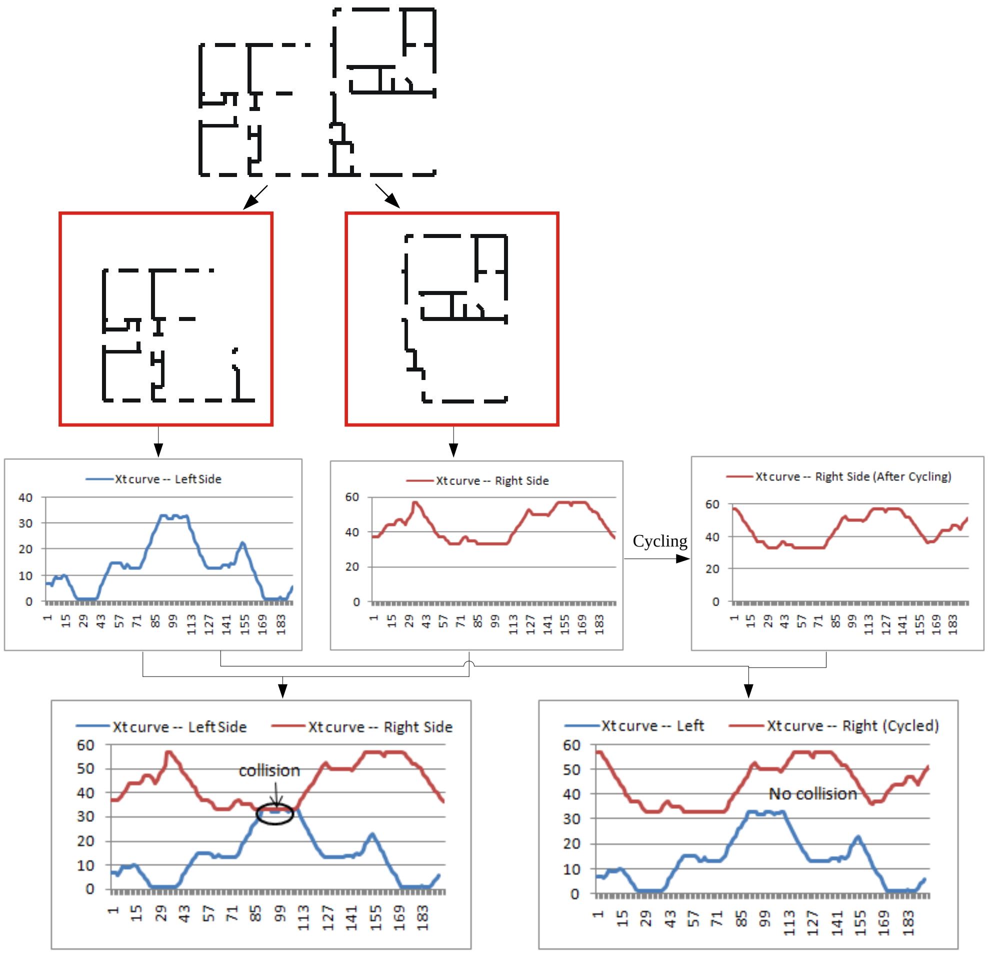


Figure 9 Concept of Path Cycling

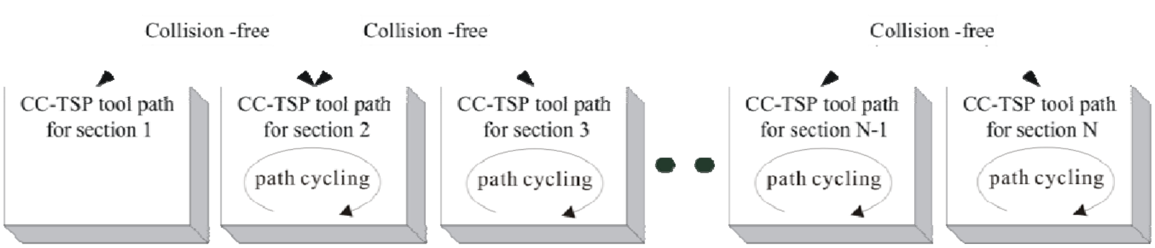


Figure 10 Concept of Applying the appraoch on N machines

2.2.3. 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 11.

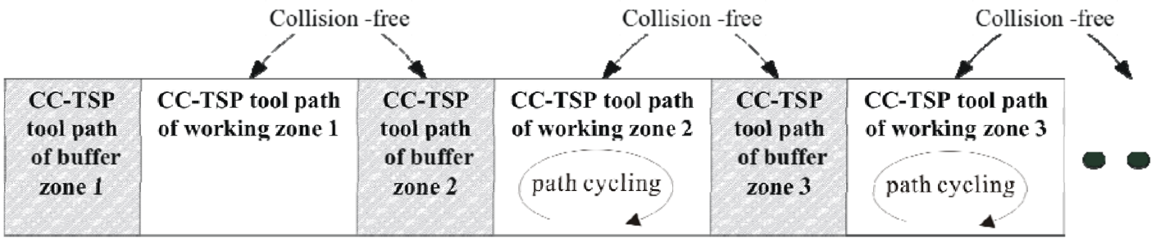


Figure 11 Buffer Zone Path Cycling for N machines system

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 Figure 12). 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 is much greater for finding collision-free tool paths between the main working zone and the buffer zone when cycling the path of the main working zone.

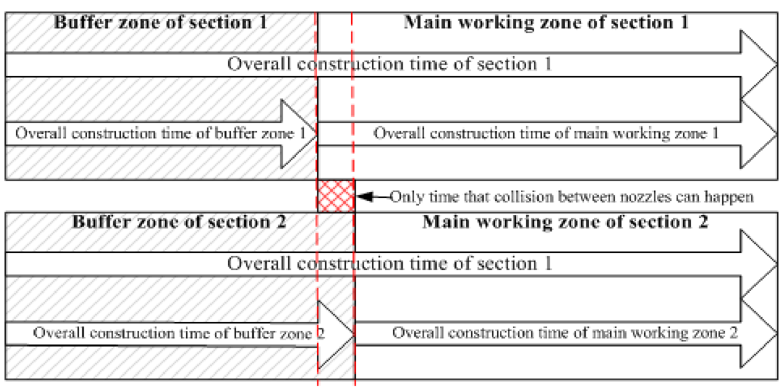


Figure 12 Collisions occurs in the overlap time of construction

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 o*nly 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.

3. ANALYSIS OF MULTI-MACHINE 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 were 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.

3.1. Success rate of different Methods

Different approaches have different success rates of finding collision-free tool paths. Figure 13 shows the success rates of different approaches in two-nozzles (left) and three-nozzles (right) cases.

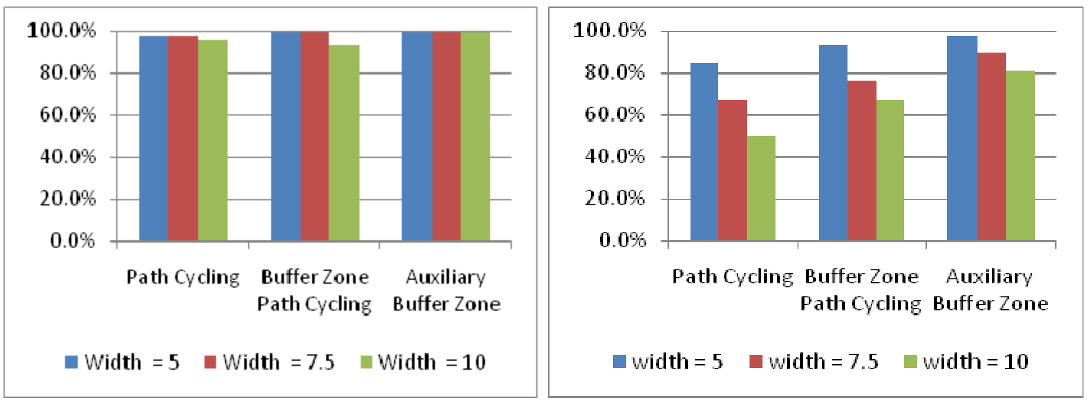


Figure 13 Success rates of different approaches in two-nozzles case (left) and three-nozzles case (right)

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 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).

3.2. Construction time in different methods

Figure 14 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* save 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%).

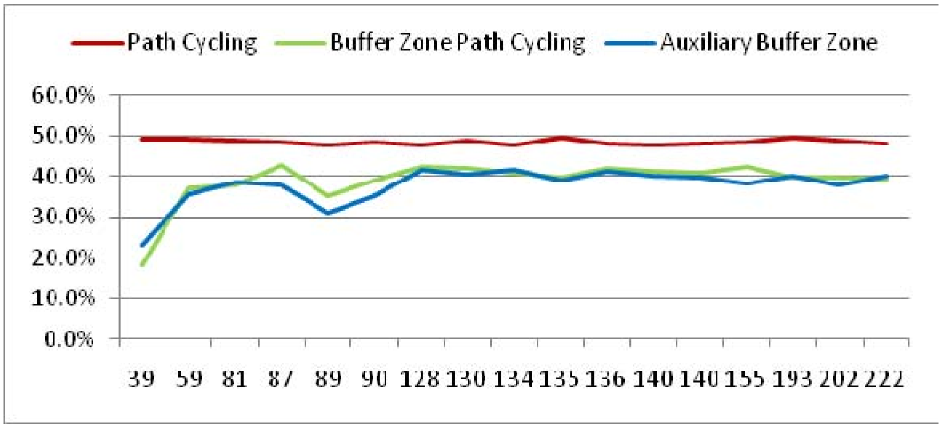


Figure 14 Percentage of construction time saved with four approaches in two nozzle cases

The performance differences in the three-nozzle case are similar to the differences in the two-nozzle case. Figure 15 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.

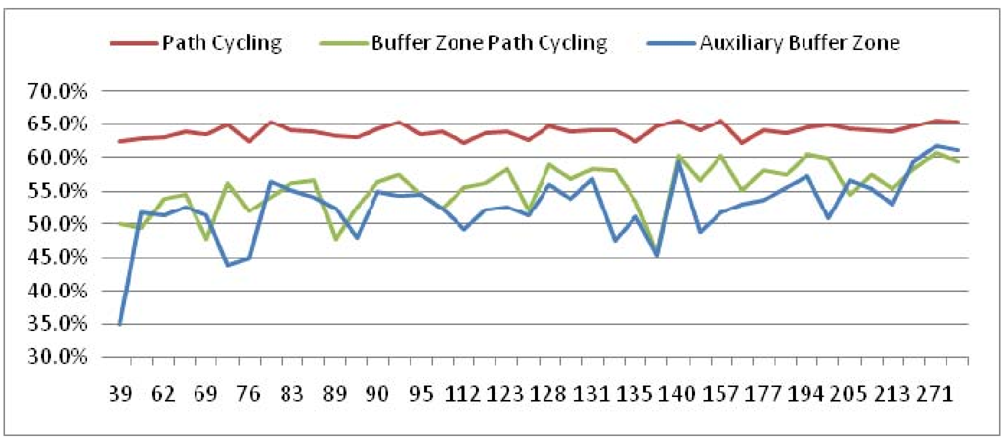


Figure 15 Percentage of construction time saved the three approaches in the three-nozzle case (Path Cycling: top curve; Buffer Zone Cycling: middle curve; Auxiliary Buffer Zone: lower curve)

3.3. Total construction time for different number of nozzles

According to the earlier discussion regarding 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 Figures 16 and 17 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-nozzles system, respectively; and the lower curve represents the construction time by using *Path Cycling* and *Buffer Zone Path Cycling* for the three nozzles system, respectively.

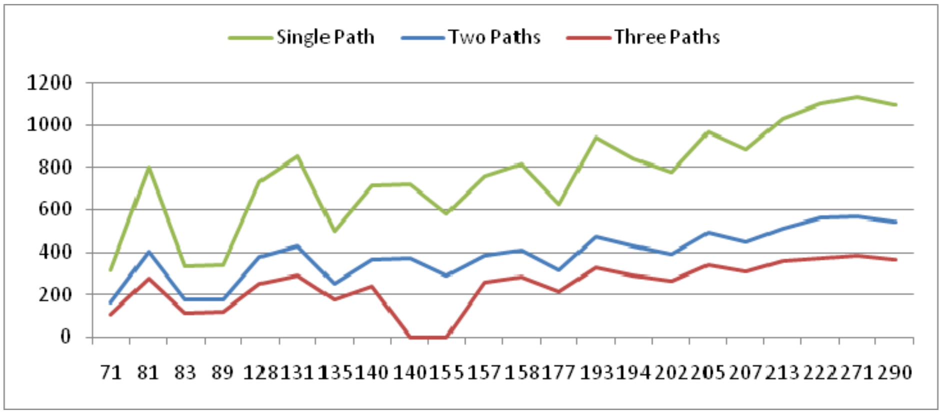


Figure 16 Construction time difference among single-nozzle, two-nozzle and three-nozzle cases (Path Cycling)

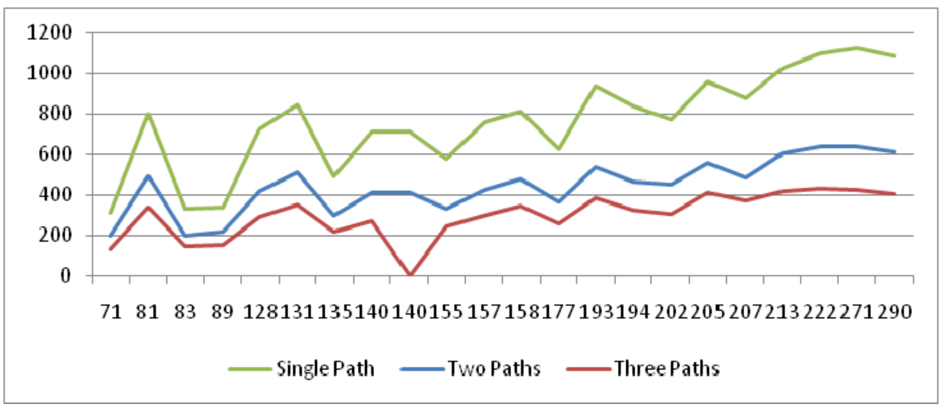


Figure 17 Construction time difference among single-nozzle, two-nozzle and three-nozzle cases (Buffer Zone Path Cycling)

There are spots in Figures 16 and 17 where the value of the lower curve reaches zero, which means that solutions are not found for particular structures when a three-nozzles 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-nozzles cases.

3.4. Conclusions about algorithms for the multiple nozzle system

Base on the foregoing discussions about the analysis of the performance results of the algorithms we can conclude that *Path Cycling* could save more construction time than *Buffer Zone Path Cycling*. *Buffer Zone Path Cycling* always performs better than *Auxiliary Buffer Zone*, although the success rate of these two methods are almost similar. However, the *Buffer Zone Path Cycling* method has a higher success rate in finding solutions than does *Path Cycling*. Also, the larger the number of wall segments in the structure, the easier it will be to find a solution for the multi-machine systems. Compared to the single-nozzle case the percentage of construction time saved in building larger structures using the multi-machine system is significantly higher. Furthermore, it should be pointed out that the width of the structure layout is a critical factor for the success rate.

4. CRITICAL PARAMETERS FOR THE OVERHEAD PLATFORM SYSTEM

The discussion so far applies to the Multi-Gantry configuration and in a certain condition to the Overhead Platform configuration. The movements of the nozzles of the Overhead Platform system are restricted by the overhead platform that carries them and unless the entire large gantry moves the nozzles cannot reach all areas of the structure being constructed, if the dimension of the structure along the machine rails is larger than the machine width (i.e., the width of the overhead platform). In such a case the suggested strategy for using the Overhead Platform system is to separate the original layout into different sections with each section being as wide as the overhead platform and then perform the tool path optimization for each section (see Figure 18*)*.

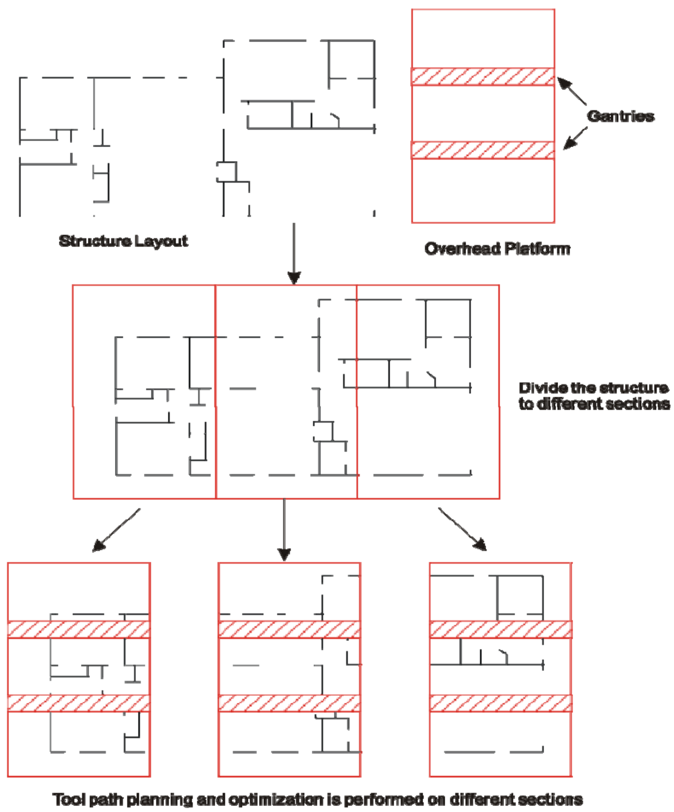


Figure 18 Tool path planning and optimization process for the Overhead Platform system

Several characteristics of the overhead platform can affect the efficiency of the system. In addition, these characteristics have different impacts on constructing structures with different dimensions and layouts. Features of the overhead system can be predefined in order to increase the system performance when the system is used to build numerous structures with similar dimensions and topologies such as community or colony houses. Once the relationship between design parameters and efficiency of the system is found, the optimal values of critical features of the overhead platform can be determined to design the machine.

In order to relate the design parameters and efficiency of the system for constructing specific sets of structures a procedure can be followed which involves factor identification and factor range determination, and statistical simulation.

Factor identification: Construction efficiency in terms of construction time and energy usage as well as construction quality is the performance metrics of the system. Various machine features can be considered as performance factors. These features include the speed of the gantry and nozzle, the number of nozzles, the width and length of the overhead platform, the width of the smaller gantries carrying the nozzles, the orientation of the operation, etc. Figure 19 shows some alternative configuration that may be used. Besides the machine features, the features related to the geometry and topology of the structure, such as dimensions and complexity in terms of the number of vertical or horizontal wall segments, also need to be considered. In general, all factors can be identified according to the system and structure characteristics. The range of performance factors can be determined based on the system mechanical restrictions, and design requirements. The range for each factor should be determined before performing the simulation.

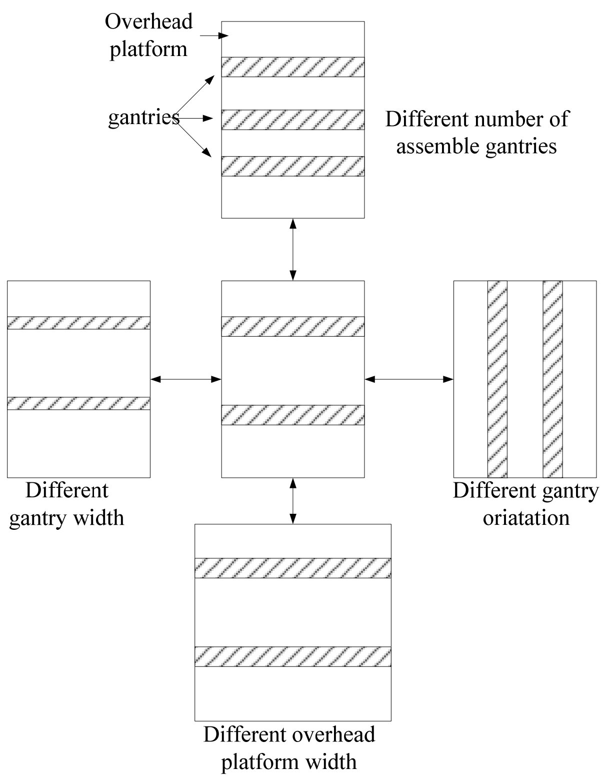


Figure 19 Different overhead platform configurations

Statistical simulation: Once the factors and their ranges are known, the step increment for performing the simulation scenarios can also be defined. Algorithms presented in the Part I of the paper can be used to find the overall construction times with different factors within different ranges. Statistical analysis can then be used to find the behavior of the factors and their impact on the system efficiency.

According to the analysis of the results from Part I of the paper, the three algorithms (*Path Cycling, Buffer Zone Path Cycling and Auxiliary Buffer Zone*) progressively have higher chances of converging towards a feasible solution. However, the extent of optimality of solutions progressively declines. Therefore, *Path Cycling* would be first preferred, followed by *Buffer Zone Path Cycling*. If neither of these methods can find the solution the method with a higher success rate, *Auxiliary Buffer Zone* may be attempted.

5. SAMPLE OPTIMAL FEATURES FOR THE OVERHEAD GANTRY SYSTEM

An average construction layout shown in Figure 20 is chosen to demonstrate the process of analyzing the optimization result in order to determine the critical parameters for the Overhead Platform system. In this case the orientation of the operation (rails being along the length or width of the structure), the number of the nozzles (2 or 3), the width of the overhead platform (40 feet or 60 feet) and the nozzle-carrying gantry widths (2.5feet, 5 feet or 7.5 feet) are selected as the performance factor. Construction time as the measure of system efficiency, total machine time as the measure of energy consumption and total number of vertices number as the measure of structure complexity are the three criteria for estimating the overall system performance.

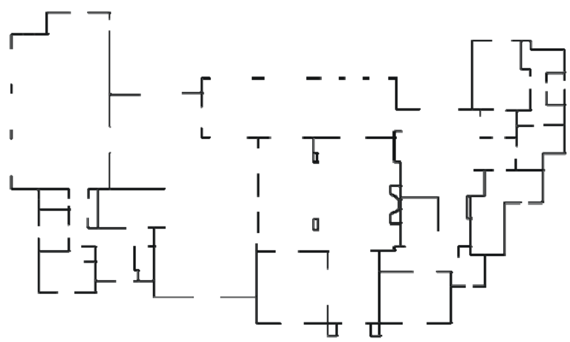


Figure 20 Structure layout (113 feet in length, 66 feet in width, and containing 194 wall segments)

Table 1 shows solution results using the three methods for different overhead sections based on the aforementioned priority sequence for using the solution techniques.

Table 1 Solution results for the three solution techniques

	Overhead Platform Width = 60				Overhead Platform Width = 40					
	Gantry Orientation is Vertical		Gantry Orientation is Horizontal		Gantry Orientation is Vertical			Gantry Orientation is Horizontal		
	Part 1	Part 2	Part 1v	Part 2v	Part 1	Part 2	Part 3	Part 1v	Part 2v	Part 3v
2 nozzles W = 2.5	A	A	A	A	A	A	A	A	A	A
2 nozzles W = 5	A	A	A	A	A	A	A	A	A	A
2 nozzles W = 7.5	A	A	A	A	B	A	B	A	A	A
2 nozzles W = 10	A	A	A	A	C	A	C	A	A	A
3 nozzles W = 2.5	A	A	A	A	A	A	A	A	A	A
3 nozzles W = 5	A	A	B	A	B	A	A	A	A	A
3 nozzles W = 7.5	B	A	B	A	C	B	B	A	A	A
3 nozzles W = 10	C	B	C	B	_	_	_	C	B	C

A Path Cycling   B Buffer Zone Path Cycling   C Auxiliary Buffer Zone

W = Width of the gantries

The table shows that in most cases *Path Cycling* can find the tool paths for different sections of the layout, but other methods still need to be applied in a few cases. Even though *Auxiliary Buffer Zone* has a high success rate to find the solution, some physical limitations (e.g., width of the divided sections being too small compared to the gantry width) lead to some no-solution cases. Table 2 shows the simulation results for all three criteria.

Table 2 Comparison of different overhead platform set ups

Number of Nozzles	Orientation of the Gantry	Width of Overhead Platform (feet)	Width of Gantry (feet)	Total Construction Time (min)	Total Machine Time (min)	Total no of Vertexes
2	Horizontal	60	2.5	440.0	873.0	388
2	Horizontal	60	5.0	440.0	873.0	388
2	Horizontal	60	7.5	440.0	873.0	388
2	Horizontal	60	10.0	440.0	873.0	388
2	Vertical	60	2.5	433.3	862.5	388
2	Vertical	60	5.0	433.3	862.5	388
2	Vertical	60	7.5	433.3	862.5	388
2	Vertical	60	10.5	433.3	862.5	388
2	Horizontal	40	2.5	451.7	894.1	388
2	Horizontal	40	5.0	451.7	894.1	388
2	Horizontal	40	7.5	451.7	894.1	388
2	Horizontal	40	10.0	451.7	894.1	388
2	Vertical	40	2.5	476.3	937.5	388
2	Vertical	40	5.0	476.3	937.5	388
2	Vertical	40	7.5	579.1	1145.7	398
2	Vertical	40	10.0	609.1	1205.7	406
3	Horizontal	60	2.5	319.6	930.4	388
3	Horizontal	60	5.0	344.5	984.7	388
3	Horizontal	60	7.5	350.7	989.1	388
3	Horizontal	60	10.0	394.3	1131.1	432
3	Vertical	60	2.5	322.3	937.0	388
3	Vertical	60	5.0	340.2	942.4	422
3	Vertical	60	7.5	406.8	1106.5	456
3	Vertical	60	10.0	424.6	1218.1	424
3	Horizontal	40	2.5	321.3	938.6	388
3	Horizontal	40	5.0	321.3	938.6	388
3	Horizontal	40	7.5	325.2	934.3	392
3	Horizontal	40	10.0	436.7	1204.9	424
3	Vertical	40	2.5	352.0	1007.0	388
3	Vertical	40	5.0	406.0	1098.9	404
3	Vertical	40	7.5	552.6	1480.9	476
3	Vertical	40	10.0	0.0	0.0	0

The results show that the three-nozzle system use more overall machine time and consumes more energy. Since the construction layout we chose in this specific case is not for a large scale structure, the two-nozzle machine case is appropriate to utilize. Regardless of the manufacturing cost, the 60 foot Overhead Gantry system could be chosen to yield the best performance. Otherwise, the 40 foot overhead machine would yield a reasonable performance and should be used in most cases. The horizontally oriented gantries should pair up with the 40 foot overhead platform for better performance. Therefore, we conclude that the two-nozzle, 40 foot horizontal overhead system better suits the construction of the given structure.

Note that the time estimates are based on true fabrication speed of the CC nozzle. These simulation results demonstrate the impressive speed of the Contour Crafting technology when multiple nozzles work concurrently.

6. CONCLUSION

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 as many sections as the number of nozzles involved in the construction. The workloads contained in each section should be similar so that the waiting time of moving to the next layer is minimized for each individual nozzle. 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 safety area to prevent pairs of adjacent nozzles from getting too close to each other. The path cycling concept simply manipulates the construction sequence without compromising the construction efficiency. This two-step procedure is then followed by three candidate solution approaches: *Path Cycling*, *Buffer Zone Path Cycling* and *Auxiliary Buffer Zone*. These approaches progressively have higher chances of converging to a feasible solution. However, the extent of optimality 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.

50 structure layouts with different levels of complexity have been used to compare the results of different approaches. The results indicate that *Individual Path Cycling* and *Buffer Zone Cycling* are methods with higher success rates and reasonable solution quality with respect to the extent of optimality. With a gantry width of 5 feet, 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 about 37% (ranging from 18% to 43%). The average percentage saved in *Auxiliary Buffer Zone* is about 36% (ranging from 22% to 42%).

There are two kinds of multi-machine Contour Crafting systems. The Multi-Gantry system consists of different individual gantries, and the Overhead Platform system has an overhead platform that carries several gantries. Critical design parameters significantly contribute to the construction efficiency of the overhead platform system. The number of assembled gantries, orientation of the gantries, width of the overhead platform and width of the gantry are the most important machine design factors to consider. For a given structure, the optimal design parameters for Overhead Platform, which is the more complex machine type, may be determined using the optimization results generated by the three proposed algorithms.

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