Chapter 5

MULTI-ROBOT WORKCELL LAYOUT DESIGN

Multi-robot workcell consist of more than one robotic manipulator working simultaneously in a coordination to accomplish the assigned task. The multi-robot workcell is considered as an extension of the single robotic workcell resulting in the enhanced production capacity, cost and time saving, and expanding multi-functional capability. Multi-robots are usually installed in-line production systems such as automotive assembly lines, packaging lines, while cellular multirobot systems are often used in the industries.

This chapter presents a novel methodology for the layout design of multirobot workcell by transforming the layout of a single robot workcell using point cloud simulation approach. This chapter demonstrates the second application of the developed approach in the field of robotic cellular manufacturing system explicitly. Point cloud simulation approach has expanded its capability to a new challenging problem. Layout design of the multirobot workcell is far more typical than the single robot workcell and requires more examining of manipulator motion and operation timing at each machine.

As several factors are involved in the multirobot workcell layout design, therefore, section 5.1 presents introduction and highlights of the works done by previous researchers in multirobot design and planning. Section 5.2 presents the problem formulation considering an objective function and various constraints for layout optimization. Section 5.3 presents the proposed multirobot layout design developed by taking data from the parallel single robot workcells. The results obtained by solving the optimization problem are presented in section 5.4 and discussion on some salient points are also presented.

Finally, this chapter is concluded in section 5.5 with some remarks and conclusions of the presented methodology.

5.1. Introduction

Industrial scenario demands workcells to be more automated for coping up the fluctuating requirements and simultaneously optimize its design complexity to save maintenance and operating expenditure. Today, workcells has equipped with advanced robots and AGVs, contributing to its capacitive scalability (Putnik *et al*., 2013). A multi-robot system such as the parallel automotive assembly lines (Michalos *et al*., 2015) having large number of robots while the task specific multi-robot workcell having fewer number of robots are robust, efficient, and efficacious.

The layout design of the multi-robot workcell is more complicated than a single robot workcell. Various problems such as robot workspace limitation, machine reachability, collision-free operation and coordinated task scheduling are more complicated in the multi-robot cellular manufacturing system. Although ample research in the design and planning of the robotic workcell has been done in the past decade, however, available literature in multi-robot workcell layout design lacks promising solutions. In multirobot system, the research areas such as task-oriented workcell planning, coordination between robots and conflict-free path planning have been explored numerously. However, the layout design remains untouched.

Although being the vital part of the manufacturing system, the research in robot workcell layout design has come to saturation. The professional planning packages such as RobotStudio, EASY-ROB, Roboguide, and others are available in the market providing the required solution. The professional planning packages require highly skilled operators for simulation of a manufacturing system involving various sophisticated devices and qualified persons (Dangelmaiera *et al*., 2005). Moreover, the professional packages are non-generic and pose difficulty in their application in the industry which consequently degrades the quality of cellular manufacturing. Thereby decreasing the overall efficiency of the robotic workcell, that reduces their application and impact the industrial automation. Therefore, new design and planning approach for the multi-robotic workcell is undoubtedly needed, which can provide error free implementable solutions.

The task oriented multi-robot positioning in a three-dimensional plane for the construction of large workpiece is an innovative project. Optimal placement of four robots in horizontal and vertical positions for welding an aircraft hull, along with collision checking in the vertical plane has been addressed by Tao and Liu (2011). A multi-functional technique for multi-robot workcell design with collision-free motion planning has been developed, pointing the need to tackle the fluctuating market demand and time taking workcell installation.

The workcell layout design and motion planning of manipulators by collecting together the probabilistic roadmap and the OBB tree method in an offline programming system is most suitable to achieve the desired objective (Pellegrinelli *et al.,* 2014). In offline methods, predetermining the optimal manipulator path and machine position for a task is advantageous for the scalability of the cellular manufacturing system. Rather, most of the investigations in the multi-robot workcell have been focused in the field of motion planning (Chiddarwar and Babu, 2011) and robot coordination (Muralidharan *et al.,* 2008; Parker, 2003).

The CAD-based robotic planning approaches are advantageous for the manipulator trajectory planning and scheduling problems. The CAD data has been integrated with programming languages to solve complex industrial problems such as spray painting (Chen *et al*., 2009), and assembly (Leu *et al*., 2013). The robotic workcell design and planning approach named as IRoSim planning system uses CAD data of machines and robots along with the kinematic data of robots to optimize manipulator motion and generates task-specific workcell design (Baizid *et al*., 2016). For generating CAD data, it is necessary to have a better understanding of CAD drawing tools and its API interface. This interface provides a facility by which the geometric data in the CAD model of an object can be utilized as per the coding performed (Neto and Mendes, 2013).

The motivation for using CAD-based workcell planning method lies in the fact that it reduces the complexity involved in the rigorous mathematical modeling for checking the collision and indexing the machines on the workcell floor. The spherical design methodology has been used by Mata and Tubaileh (1998) to model workcell machines and the line diagram to model robot. The collision detection by this method was inaccurate, and the mathematical formulation was complicated. Easing the problem formulation in the multi-robot workcell design helps in efficient solutions and reduces the computational power required.

For solving a layout design problem, algorithms such as simulated annealing, genetic algorithm, and sequential quadratic programming are being used to solve the nonlinear objective functions. Variants of above approaches such as the modified simulated annealing approach were also developed to solve a more complicated case of workcell design with 3D models of the machines and robot (Barral *et al.*, 2001).

The present chapter proposes the multi-robot layout design methodology using the point cloud simulation approach. In this method, the CAD data is directly utilized through indigenously developed algorithms and excludes API programming requirement. This work studies the benefits of the multi-robot workcell against the parallel single robotic workcells performing the similar task. The point cloud simulation approach based single robot workcell layout designing has already been developed, and in this work, the layout optimization for multirobot workcell has been addressed.

5.2. Problem Formulation

The final step of the proposed method is to find the optimal configuration of the multi-robot workcell. Considering N number of machines and M number of robots in the workcell. Each machine is associated with two location variables (x, y) and one orientation variable along the z-axis. During the iteration process, the position of the machine is referred by its job point while the robot position is referred by its base. Considering the two-dimensional movement of the robot along its base and fixing the machines with the ground (restricting motion in the z ordinate) simplify the problem formulation and reduce the computational load without losing the applicability of the solutions.

The orientation of the machines is defined as the rotation of the object along the z-axis and measured as the angle between the x-axis of the coordinate frame and the x-axis of the job point of the corresponding job point of the machine. The orientation of the robot is equivalent to the rotation of the robot base, calculated along z-axis. Assuming no tilt and twist in machine and robots, thereby avoiding the orientation along x-axis and y-axis. Therefore, the total number of variables to be optimized are $3N+2M$. Thus, the final formulated problem for a multi-robot workcell is to find the optimal location and orientation of job points of all machines and the position of each robot.

Considering that each robot has similar degree-of-freedom and pass through a sequence of N machines, located by N job points, denoted by $x^j \in R^d$, where d is the dimension of the Cartesian coordinate frame, $j = 1$ *to* N and α^j denotes the orientation of machines. The end-effector of each robot reaches different locations of the jth machine during iteration by using the inverse kinematics of robot-joint coordinates vectors q(j), which corresponds to the *j*th robot configuration. The objective function is formulated on the minimization of the total joint angular distance travelled by all robots in a cycle.

The optimization algorithm deals with large point cloud data matrices of machines and robots. It checks the collision and avoids overlap between any two objects in the workcell by measuring the Euclidean distance between each point of their point cloud matrices. The above process of collision checking is most accurate, but it is computationally expensive. Thus, a faster 3D collision detection method has been adopted known as Axis Align Bounding Box method (Ericson, 2004). By this approach, the collision between two objects has been checked by calculating the intercepts between their minimum bounding boxes on each coordinate axis. The minimum bounding box of an object is a rectangular parallelepiped-shaped volume enclosing object's point cloud.

Objective function:

$$\text{Min}\left\{\sum_{\boldsymbol{i=1}}^{\boldsymbol{N-1}}\sum_{\boldsymbol{j=i+1}}^{\boldsymbol{N}} c_{ij}\,.\,f_{ij}.\ (\boldsymbol{q^i}-\boldsymbol{q^j})^4\right\} \quad \ldots (5.1)$$

Subject to:

$$\vec{\boldsymbol{q}}^{\boldsymbol{j}} = \mathbb{IK}(\mathrm{R}, \mathrm{HT}(\vec{\boldsymbol{X}}^{\boldsymbol{j}})),\ j = 1, \ldots\ldots, N \quad \ldots (5.2)$$

$$\begin{aligned}\boldsymbol{N_{jj+1}} = [\ &\{ ({}^{j}_{x}M_{min} \leq {}^{j+1}_{x}M_{max}) \oplus ({}^{j}_{x}M_{max} \geq {}^{j+1}_{x}M_{min}) \} \ldots \\ &\vee \{ ({}^{j}_{y}M_{min} \leq {}^{j+1}_{y}M_{max}) \oplus ({}^{j}_{y}M_{max} \geq {}^{j+1}_{y}M_{min}) \} \ldots \\ &\vee \{ ({}^{j}_{z}M_{min} \leq {}^{j+1}_{z}M_{max}) \oplus ({}^{j}_{z}M_{max} \geq {}^{j+1}_{z}M_{min}) \}]\ j = 1, \ldots, N-1 \quad \ldots (5.3)\end{aligned}$$

$$\begin{aligned}\boldsymbol{T_{jk}} = [\ &\{ ({}^{j}_{x}M_{min} \leq {}^{k}_{x}R_{max}) \oplus ({}^{j}_{x}M_{max} \geq {}^{k}_{x}R_{min}) \} \ldots \\ &\vee \{ ({}^{j}_{y}M_{min} \leq {}^{k}_{y}R_{max}) \oplus ({}^{j}_{y}M_{max} \geq {}^{k}_{y}R_{min}) \} \ldots\end{aligned}$$

$$\vee \{ ({}^{j}_{z}M_{min} \leq {}^{k}_{z}R_{max}) \oplus ({}^{j}_{z}M_{max} \geq {}^{k}_{z}R_{min}) \}] \; j = 1,..,N \;\; k = 1,..,M \quad \ldots (5.4)$$

$$\boldsymbol{B_{jk}} = [\{ ({}^{k}_{x}R_{min} \leq {}^{k+1}_{x}R_{max}) \oplus ({}^{k}_{x}R_{max} \geq {}^{k+1}_{x}R_{min}) \} \ldots$$

$$\vee \{ ({}^{k}_{y}R_{min} \leq {}^{k+1}_{y}R_{max}) \oplus ({}^{k}_{y}R_{max} \geq {}^{k+1}_{y}R_{min}) \} \ldots$$

$$\vee \{ ({}^{k}_{z}R_{min} \leq {}^{k+1}_{z}R_{max}) \oplus ({}^{k}_{z}R_{max} \geq {}^{k+1}_{z}R_{min}) \}] \;\; k = 1,..,M \quad \ldots (5.5)$$

Where f_{ij} and c_{ij} correspond to material flow and transportation cost, $\boldsymbol{q^i}$ and $\boldsymbol{q^j}$ are the joint angle values of the *i*th and *j*th object in the workcell, respectively. IK is the inverse kinematics of the given robot model evaluated by using the RVC toolbox. HT is the homogeneous transformation of the *j*th machine's job point $\overrightarrow{\boldsymbol{X}}_{\boldsymbol{j}}$. ${}^{j}_{x}M_{min}$ and ${}^{j}_{x}M_{max}$ are the minimum and the maximum value of *j*th object minimum bounding box edge along the x-axis, respectively. ${}^{k}_{x}R_{min}$ and ${}^{k}_{x}R_{max}$ are the minimum and maximum value of the minimum bounding box along the x-axis of *kth* link of robot *R*, respectively. $\boldsymbol{N_{jj+1}}$ and $\boldsymbol{T_{jk}}$ are the intercepts produced due to collision between point clouds machine and robot, and $\boldsymbol{B_{jk}}$ is the intercepts produced due to collision between point clouds of two robots. Similarly, other values along y and z-axis for *j*th, *j+1*th object and robot links can be obtained. $\oplus$ is the logical symbol for the *XOR* gate and $\vee$ is the logical symbol for *OR* gate.

The equation 5.2 checks whether the allocated job point lies within the robot configuration space or not. It limits the optimal location of machines within the configuration space of the robot. The equation 5.3 shows the mathematical formulae for checking overlapping between two machines; similarly, equation 5.4 represents the collision detection between the robot and machines.

The equations 5.3 & 5.4 state that for the collision to occur between a machine and the robot or a machine, then simultaneously on each coordinate axis the minimum value of *j*th machine minimum bounding box should be lesser than the maximum value of *j+1*th machine or robot *k*th link minimum bounding box. Along with above, the maximum value of jth machine minimum bounding box should be greater than the minimum value of $j+1$th machine or robot kth link minimum bounding box on the same coordinate axis. Equation 5.5, checks the collision between links of two robots for a given sequence of tasks. The nonlinear minimization problem formulated has been subjected to bounded constraints, which requires an exhaustive search technique such as genetic algorithm, simulated annealing, and SQP algorithm, to get the global minimum solution.

The multi-robot workcell design by the proposed method is open to any algorithm mentioned above, whereas the simulated annealing algorithm has proved to be efficient in obtaining the global optimum solution (Cagan *et al.,* 2002). Also, the *simulannealbnd* function of the Global Optimisation Toolbox in Matlab is based on simulated annealing algorithm and used to get the optimal solution of the formulated problem. An initial feasible input required for running the simulated annealing algorithm is an operating condition of the workcell in which each robot can reach each machine without collision. By constructing the point cloud map of the multi-robotic workcell in Matlab, the initial feasible values of all the variables to be optimized has been generated.

5.3. Proposed Multirobot Layout Design

The multirobot layout design by the point cloud simulation approach presents a new process by which an innovative idea of transforming two identical single robotic workcells into a multirobot workcell of same capacity has been proposed. Generally, the multirobot workcell have complex working and architecture, which disfavor their application and therefore, several single robot workcells are installed to increase the production capacity. However, multirobot workcells are robust, consumes lesser investment, have high dexterity, and requires lesser area. Thus, to utilize the benefits of the multirobot system, this chapter presents a novel methodology for the transformation of a robotic workcell system in industries.

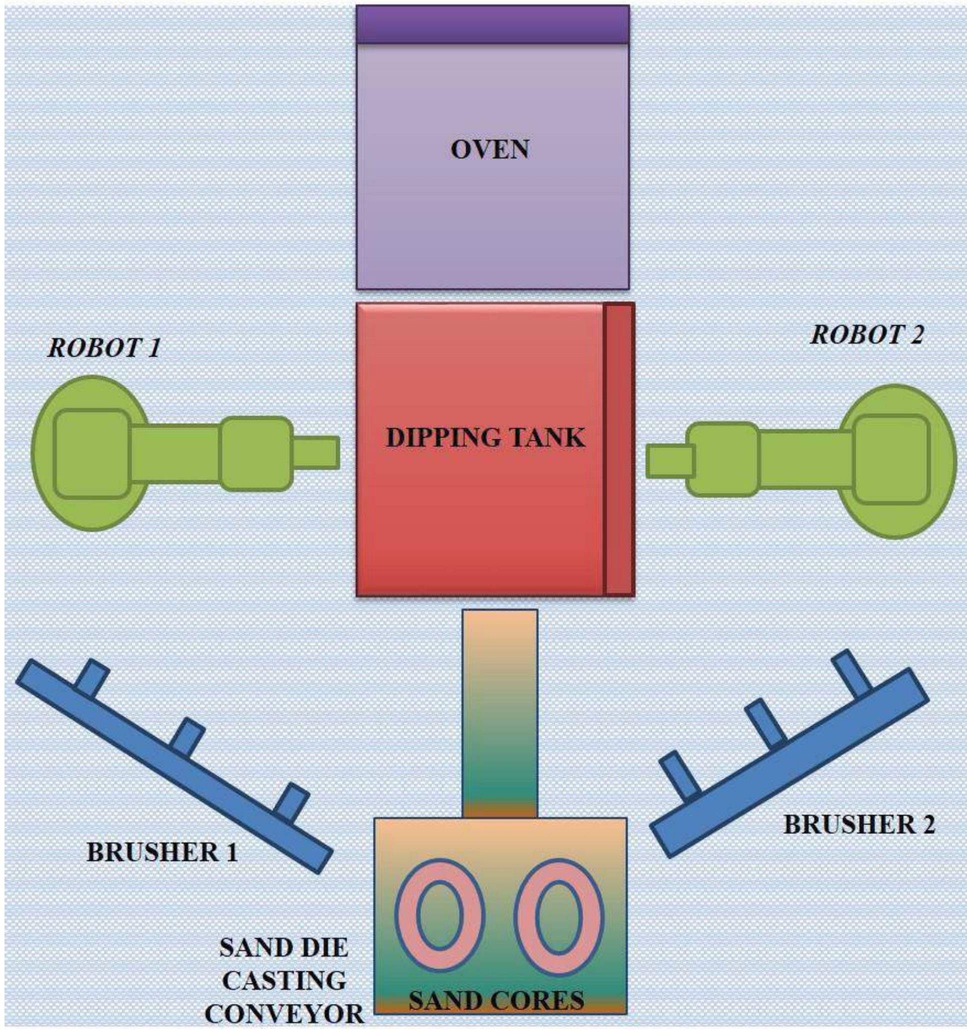

Figure 5.1. Proposed multirobot workcell layout design

The proposed design of the multirobot workcell is presented in Fig. 5.1. It shows five machines arranged in assembly line type layout system. In this system, all machines are arranged in the middle and the robots are placed opposite to each other. This is the initial feasible configuration of the multirobot workcell obtained by hit and trial method checking the reachability of each robot to the respective machine considering limitation from the task sequence, collision avoidance and the operation time. This layout design is obtained by transforming the layout plan of two single robotic workcells working together in a foundry whose depicted layout has been shown in Fig. 5.2.

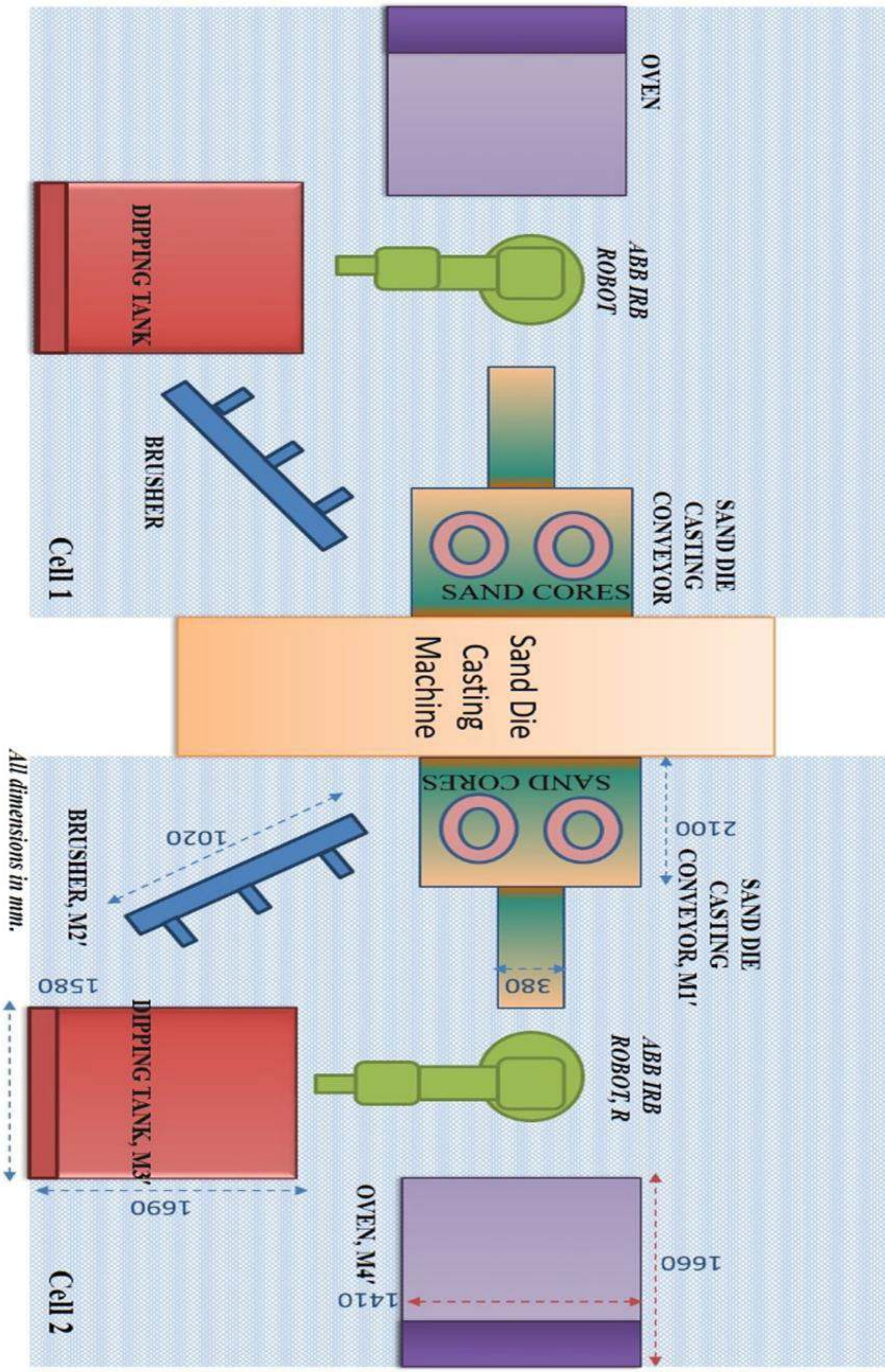

Figure 5.2. Depicted diagram of two single robotic workcells operating simultaneously

Fig. 5.2 shows two robotic workcells, Cell 1 and Cell 2, which contains similar quantity of machines and robot producing same product in fixed quantity. These workcells are operating in a foundry of pipe industry and producing two sand cores each in a cycle. These sand cores are then used by the centrifugal casting machine to produce C.I. pipes. Both single robotic workcells produce four sand cores thus the proposed multirobot workcell should produce same amount of sand cores to establish it as an alternative solution. Table 5.1 shows the initial feasible configuration of multirobot workcell determined by hit and trial method. It also shows the location and orientation of machines in a single robot workcell as plotted in Fig. 5.2.

Table 5.1. Initial feasible configuration of the multirobot and single robot workcell

Multi-Robot Workcell			***Single Robot Workcell***		
Machine	***Position (m)***	***Orientation (degree)***	***Machine***	***Position (m)***	***Orientation (degree)***
M1	(1.50, -2.00)	90	**M1´**	(-0.25, -2.08)	90
M2	(-0.30, -1.50)	-45	**M1´**	(1.19, -2.06)	216
M3	(1.50, 0.00)	90	**M1´**	(1.19, -0.29)	180
M4	(1.50, 1.50)	-90	**M1´**	(0.00, 1.33)	-90
M5	(3.30, -1.50)	45	**R**	(0, 0)	180
R1	(0, 0)	0	--	--	--
R2	(3, 0)	180	--	--	--

The advantage of the proposed multirobot layout is that it requires lesser number of machines to produce the same quantity of products as produced by two cells together. It saves initial expenditure, workcell floor area, transportation and inventory cost and several other indirect factors such as robot effort, robot life, machine utilization, and operation time are also influenced by such layout transformation. In this chapter, the effect of layout change on the manipulator effort which is also proportional to the power consumed by joint actuator has been analyzed keeping the time and productivity similar to the two parent workcells.

5.4. Results & Discussion

The multi-robot workcell design has been optimized by using point cloud simulation approach as stated in chapter 3. Based on the problem formulated in section 5.2 using minimum joint displacement as the objective function, the solutions are obtained on a personal computer and the results and discussion has been presented further.

In the optimization process, it is assumed that the position of one robot is fixed to the origin of the coordinate frame while other robots and five machines are variables. There are six location variables and five orientation variables. The orientation of robots is neglected for simplification as it is insignificant in this case robot is fixed to floor, perpendicular to the machine line, opposite to each other. The result obtained from optimization of the proposed multirobot layout is shown in Table 5.2.

Table 5.2. Optimal location and orientation of the multirobot workcell

Object	***Multi-Robot Workcell***	
	Position	Orientation
M1	(1.67, -2.02)	90
M2	(-0.25, -1.45)	46.98
M3	(1.40, 0.03)	90
M4	(1.65, -1.46)	-90
M5	(3.31, -1.46)	-44.12
R1	(0, 0)	--
R2	(2.76, -0.18)	--

Table 5.2 shows the optimal solution generated for the multirobot layout design problem. In this table, the coordinate position and orientation of five machines and location of two robots are enlisted. The point cloud simulation approach minimizes the total effort invested by both robots while traversing from one machine to another. In this approach, the difference of the angular movement of the joint actuators between two consecutive machines has been calculated. The results found the 33.64% reduction in the net joint effort invested by the robots in comparison to the effort required in the proposed multirobot workcell layout. The optimal layout is the improved version of the proposed layout. The important point regarding the improvement is that this is calculated with similar productivity per cycle as of two single robot workcells together. Fig. 5.3 shows the point cloud map of the optimal layout of the multi-robot workcell which is quite similar to the proposed multirobot layout in Fig. 5.1.

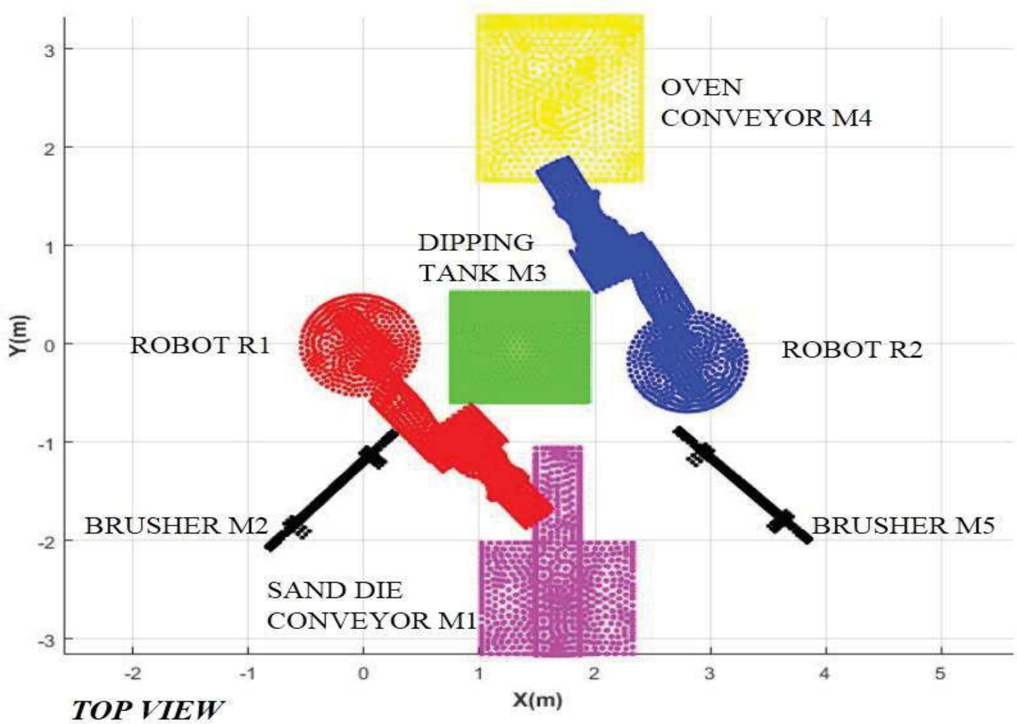

Figure 5.3. Point cloud map of the optimal multirobot workcell layout

The change in the location of machines and robot can be observed, and significant change has been noticed in machine M4. This change is due to the free space available around it, while the space near machine M1 is congested due to machines M2 and M5. This congestion is due to the fixed task sequence followed by the robots to produce sand cores. Each robot moves from in a sequence which starts from Sand die conveyor which is common to both robots, then moves to Brusher on respective side, then on the Dipping tank and finally on the Oven conveyor. The point cloud map of the single robot workcell is also presented for comparison in Fig. 5.4.

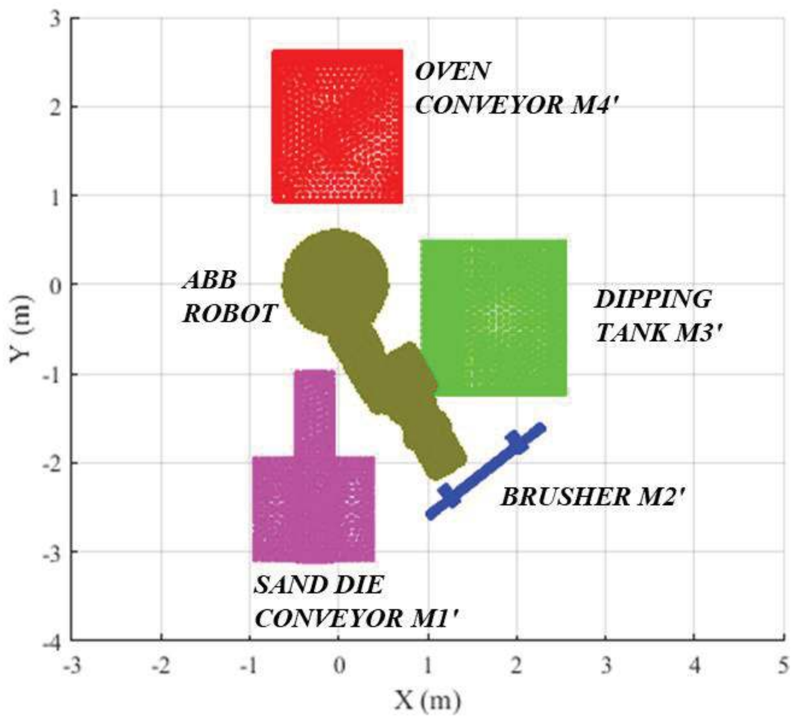

Figure 5.4. Point cloud map of the single robot workcell layout

From Figs. 5.3 & 5.4, it is understood that though multi-robot workcell occupies more area compared to one single robot workcell, but the net occupied shop floor area has been reduced by 49.2%. This is a substantial saving for an industry, which can be utilized for useful purposes. Table 5.3 shows the floor space area occupied by machines in each workcell. Two single robot workcells possesses eight machines while the multirobot workcell have total five machines. In this calculation, the empty space is neglected and comparative analysis with respect to machines' base area has been presented in the table. The parts of machine which are outside the boundary of the workcell such as in the current studying industrial cell there are Oven, Sand die casting chamber as shown in Fig. 5.2, which are outside the boundary and are not considered in this study because they are outside the reach of the robot and the workpiece, i.e. sand cores are in processing stage.

Table 5.3. Area occupied by machines in the workcells

S. No.	***Machine***	***Multi-Robot Workcell***		***Single Robot Workcell***	
		Quantity	Cross section area (cm^2)	Quantity	Cross section area (cm^2)
M1	Sand die conveyor	1	18,489	2	18,489
M2	Brusher	2	1,020	2	1,020
M3	Dipping Tank	1	26,702	2	26,702
M4	Oven conveyor	1	23,406	2	23,406
Total	--	5	70,637	8	139,234

In an industry, the purpose of installing parallel single robot workcells is to increase the production capacity and promote distributed manufacturing. This step, in turn, increase the initial expenditure and running cost which also enhances the risk involved. Therefore, in this thesis work, we propose a methodology which has successfully transformed two single robot workcells into a multi-robot workcell with same productivity level by using point cloud simulation approach. However, this transformation is only possible when there is synchronization between the moving speed of both robots and each machine operating speed. The idle time at each machine should be utilized to distribute task among the robots.

Table 5.4. Operation time and robot idle time at each machine

Object	*Description*	*Robot idle time (sec)*	*Total time required to complete an operation (sec)*
M1	Die casting machine with conveyor	0	7.40
M2	Core brushing machine for finishing	0	3.82
M3	Core dipping tank	14	27.09
M4	Furnace with conveyor	0	13.75

Table 5.4 shows the time required to perform an operation on each machine and the idle time for a robot during an operation. The idle time is the time span when the robot is at rest at some machine, waiting for the processing on the workpiece. From the table, we can observe that at machine M3 only there is an idle time of 14 s, while other machines have no robot idle time. This idle time is utilized by the second robot to perform rest operations on other machines. Also, the speed of the Sand die conveyor, and the oven conveyor is double as in the single robotic workcell because the input and output capacity of the workcell has now increased.

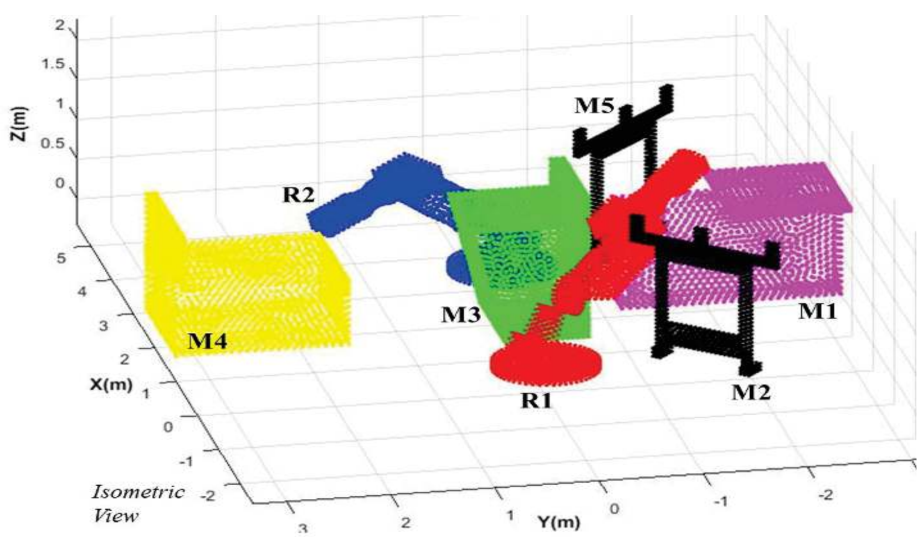

Figure 5.5. Point cloud map of the optimal multirobot layout in isometric view

Fig. 5.5 shows the isometric view of the multirobot workcell in which the position of two robots, location and orientation of each machine has been shown. From Fig. 5.5 the sequence of motion of two robots can be understood in which both robots R1 and R2 are working on each machine alternatively avoiding clashes while traversing from one machine to another. The motion sequence of two robots is explained as follows.

The sequencing of two robots R1 and R2 in the multi-robot workcell is synchronized to get approximately the same operating time as taken by a single robot workcell. This sequencing has been obtained by installing an extra machine tool, a Brusher, next to the Sand die casting conveyor. The second robot, R2 of the multi-robot workcell travel through the added Brusher and rest of the operation remains same as that of the first robot R1. A Brusher is a non-electrical brush stand and cost less in comparison to other machines such as oven and dipping tank. Also, the total time required during the dipping operation on machine M3 is nearly equal to the time required to complete an operation on other machines in a cycle as calculated from Table 5.4. While robot, R1 performs its task at dipping tank, in the meantime, the robot R2 can perform an operation on other machines and get ready to load the dipping tank again. The total distance traveled by both robots in multirobot workcell is equivalent to the combined distance traveled by each robot in the single robot workcells.

Thus, the proposed methodology successfully designs a new multirobot workcell which can serve as an alternative to the parallel single robot workcells in an industry, with minimum robot effort and floor area.

5.5. Concluding Remark

The point cloud simulation based optimization is a favorable technique for designing the typical architecture of a multi-robot cellular manufacturing system. The work presented in this chapter presented a methodology to design and optimize the layout a multi-robot workcell. The proposed method works by integrating the point cloud modeling with the efficient optimization algorithm. This work reduces the overall programming effort and directly utilize the point cloud data of an object for optimization. The visual feedback helps to verify the results more clearly, and any error and aesthetic problems can be checked by the user immediately. The point to point collision detection ensures more accurate and realistic collision checking and overlap between machines and robots.

Also, any change in the cell design can be adjusted only by adding or removing CAD drawing of the machine or robot in the algorithm. Further, the industrial case study by the proposed approach shows the relative improvement of 33.64% in the robot joint effort in the multirobot workcell. The results affirm the accuracy of the point cloud collision detection due to which close tolerance in the solutions can be possible and saves the considerable amount of workcell area. This work shows the designing and verifying the multi-robot workcell in one package which could further expand to path planning of the manipulators and task scheduling for the multi-robotic workcell.

The multirobot workcell are least used in industries as they have complex planning and typical layout design. The point cloud simulation approach not only successfully develop the layout but also transform the single robot workcells into a multi-robot workcell. The developed methodology has one limitation, regarding the computational power required as there are large number of variables in the optimization problem.

In next chapter, the trajectory planning of the robotic manipulator has been discussed, and the point cloud simulation approach has been able to develop a methodology to solve the third issue in the field of robotic cellular manufacturing.