Chapter 1

INTRODUCTION

Rapid change in lifestyle and market scenario is pushing the manufactured goods and services to become increasingly user-friendly and automated. Time-saving and comfortable life is the essence of global industrial growth that supports the concept of forced labour i.e. robot. Gradually, robots have reached almost every part of our society such as educational institutes, hospitals, industries, shopping centres, airport, and transport. Robots possess anthropomorphic characteristic, machine power, and are efficient in performing repetitive tasks due to which they are replacing human operators in industrial and nonindustrial operations (Fu *et al.*, 1987). Several industrial tasks such as pick and place operation, surface painting, welding, and machining are now performed by robots that is promoting industrial automation. While, some of the non-industrial applications includes deep-sea investigation, shopping centers, planetary exploration, surgery assistance and other similar areas where robots are frequently being used (Klafter *et al.*, 2008).

The first industrial robot was installed in 1961 at the General Motor assembly line, New Jersey (Nof, 1999). It was a manipulator arm developed by George Devol in 1954, known as Unimate. Later, in 1962 with Joseph Engleberger, George Devol started a company named Unimation, which started producing industrial robots at mass scale. Manipulator consists of a gripper and hydraulic actuators controlled by programs stored in the magnetic pattern on rotating drum. This robot performs repetitive task e.g. welding of hot casted steel handles to the car doors, which is certainly difficult for human operator.

The first industrial application of robot states that the robots in industries are meant to work in conjugation with several machines to accomplish the given task. The concept of group technology undertakes this purposeful grouping of robots and machines. Furthermore, frequent changes in product design and cheaper selling price demand to minimize industrial input in the production process. Thus, the concept of cellular manufacturing came under the just-in-time (JIT) manufacturing, and the first cellular manufacturing system comes into the picture in 1970s, in Japan which was later adopted by America in 1980s (Hyer and Wemmerlöv, 2002).

The cellular manufacturing use multiple workcells arranged in a planned layout to get the desired product. Workcells are created by combining several objects and processes to produce a product or an assembly. Cellular manufacturing has advantage of reducing the lead-time required, reducing inventory, and preventing breakdown. Cellular manufacturing system is flexible and modify the product design according to the market fluctuations. The cellular concept brings the scattered processes together to form a purposeful arrangement of machines (Harmon and Peterson, 1990).

The evolution of industrial robots had begun in 1980, and their population is increasing day by day. According to International Federation of Robotics, in 2017, a sharp rise in global robot density has noticed and it has increased to 74 units per 10,000 employees (IFR, 2017). Presently, Asia is the leading market in automation, and the number of robot units has increased by 19%. This rise in robot population continued since a decade, and IFR has predicted that by 2019 the number of deployed robots will increase to 2.6 million. The automotive industry is the major consumer, and the metal and machinery fabrication and electronic industry come next.

In India, the automation of conventional processes has enhanced, and robotics industry has bright future. In 2015, the robot sale in India has increased by 27% (IFR, 2016). Industries like Tata Motors, Maruti Udyog, Larsen & Toubro, Bharat Heavy

Electricals Ltd, Bharat Electronics Ltd. are some of the manufacturing firms that have installed robots for their fabrication departments. The medium scale industries such as Electrosteel Castings Ltd., Kanohar Electricals Ltd., were also transforming their traditional fabrication processes into the fast and efficient ones by using automation machines and robots.

Thus, the industrial scenario in India is rapidly transforming towards automatic, efficient, and productive throughput. Moreover, the robotic research and its applications in the country is also expanding to nonconventional areas such as educational institutes, hospitals, entertainment, and construction.

Robotics is a vast conglomeration of various disciplines of engineering and management. The building blocks of robot primarily constitutes of three major attributes: first is the controller and power supply unit which control its motion, second is the mechanical structure which defines its working space and third is its operational unit i.e. end-effector which defines its applicability and task.

Distinctly, robots are of two types: stationary and mobile. The stationary robot is either an open chain structure of links or a parallel connection of links joining base to the end-effector. The mobile robot can roam around freely in the working environment without need for any physical or electromechanical guidance (Kurfess, 2005). This thesis work presents an analytic study on the open chain kinematic robotic manipulator used for industrial purpose.

1.1. Industrial Robot

According to the International Organization for Standardization ISO 8373, the industrial robot is defined as *'an automatically controlled, reprogrammable, multipurpose* *manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications'* (ISO8373, 1994).

A robot has various electromechanical devices that operate through the programmed controller system. The industrial robot was designed to have flexibility, accuracy, efficiency, and repeatability. Also, for setting up robots in industry, requires managerial and engineering principles. That's why industrial robot is itself a multidisciplinary area and requires a thorough knowledge of electrical, mechanical, computer, electronic, and management.

The robotic parameters are set by a user interface that interacts with the controller through the programming logic. The controller then sends signals to actuators to generate desired motion of joints. The robot joints are connected by rigid links that are combined by the kinematic relationship for connecting base of the robot to the end-effector. The end-effector is either a device to hold a job or a tool to perform specific operation. The base of the industrial robot is fixed to the ground while the end-effector moves from one location to another. The movement of the robot's end-effector is computed through transformations in Cartesian coordinate space.

The sensory devices provide feedback of the motion that facilitate the robot to act intelligently by using computer programming and optimal algorithms. Hence, the industrial robotics has taken a broad research perspective considering the hardware, software, and managerial aspects (Paul, 1972).

Workspace of the robot is a virtual envelope consisting of a set of points in coordinate space that are approachable by its end-effector. The kinematic relationship between links and joints are established by using Denavit-Hartenberg convention (Denavit and Hartenberg, 1955). The forward kinematics evaluates the coordinates positions and orientation of point in the workspace by using angular position of joints as input, and inverse kinematics find the joint parameters by using the position and orientation of a point in the coordinate space. For robotics, the most commonly used kinematic is inverse kinematic as problems are stated in world coordinate system and joint configuration are the independent variable.

In industries, robots are working with machines/equipment in a cell and their loading/unloading location bound to lie in its workspace. The location of the machines around the robot and their sequence is preplanned in a cell. The robotic working producing the desired product is also known as workcell. The design and planning of the workcell is an important research area in the field of robotics. The efficiency of the workcell directly impacts the productivity and the quality of the product manufactured in the lean manufacturing system (Womack *et al.*, 1990).

Therefore, the robotic workcell is a crucial area for industries and much effort is required to design and plan them for efficient production. It also helps in reduction of production cost as the end-to-end process optimization trims the cost invested in the transportation of products and operator movement.

1.2. Robotic Workcell: A Broad Perspective

The concept of workcell originates from the objective of reducing transportation and inventory in the production line that indirectly saves the cost and time involved in producing the final product. The production facility which is generating wide variety of parts and products, the mass production approach is not cost effective. In such case, it is often desirable to build workcells by grouping equipment together that can perform a similar set of operations on the raw material.

The workcell often contains three types of machines that are automatic, semiautomatic and manual (Kreith, 1998). While in present work, the workcell contains a robot with fully automatic machines driven by sensor control data without any human intervention during operation. The robot in such workcell performs monotonous pick and place operation involving massive part with high accuracy and reliability. The performance of such operation by an overhead crane or human operator is a difficult task while the robot is executing such tasks with high precision thereby producing large number of high-quality products in least time. Recognizing various advantages of the robotic workcell motivates its application in the industries and thus promoting research and analysis studies.

Various industrial operations performed in a robotic workcell are machine tending on which forges, machines tools, tanks, and conveyors are loaded and unloaded by robots. For such operation, articulated arm type robots are used with a gripper, which travels through a semi-circular arc type layout of equipment. Packaging is an assembly type operation in which collected objects are inserted in a specific container. A three to six-axis robot can to do such operation with a conveyor belt supplying the objects to be filled in the stationary container. Painting and compound spraying are the major operations in the automotive industry, and both are hazardous for a human operator. The robots used for such operation is specially designed having six *d.o.f.* articulated arm with a paint gun (Fitzgerald, 1998). Several other operations such as welding, finish machining, and palettizing can be performed by articulated robots. All these operations require preplanning of workcell to achieve the desired objective.

There are various areas related to robotic workcell which have been numerously explored by researchers in the past few decades (Womack *et al.*, 1990). The first topic is the layout design, in which machines and robot are arranged in a pre-planned layout to conduct desired sequence of operations at least possible expenses. The second is the sequencing and routing, which deals with the movement of raw material inside the workcell. Next is the trajectory planning of the robotic manipulator, for generating the path between machines by avoiding collision with the obstacles. Vision and sensing is the new area that is the main arm for automation and feedback. Human-robot collaboration deals with the coordination between task performed by a robot and human beings together in the workcell to avoid any accident and losses.

The layout design is an initial step for establishing a robotic workcell in an industry. It constitutes several design parameters, which can be optimized to improve the output of the robotic workcell. Layout design of a robotic workcell is part of lean manufacturing and investigated in several ways over the past few decades. Several layout design algorithms and simulation packages are currently available which comprise advanced graphical functions and numerous designing features (Lee & ELMaraghy, 1990; Pires & Sá Da Costa, 2000; Dawande, Geismar, Sethi, & Sriskandarajah, 2007). However, the available packages have high licensing and controlled planning environment, and therefore they were least used for research and analysis purpose. Thus, the workcell design and planning require generic, accurate and adaptive simulation package, which can open new paradigms in the field of robotics cellular manufacturing.

The conventional approaches were commonly used for layout designing of robotic workcell (Tay and Ngoi, 1996). The conventional approaches were straightforward application of mathematical models and advanced simulation packages, and skilled operators were not required in it. Another such approach for layout planning has been presented by Mata and Tubaileh, which uses the ball and line modeling technique to design the layout more functionality (Mata and Tubaileh, 1998).

These approaches are inexpensive and readily applicable, but the mathematical complexity involved in modeling of machines and robots is inherited with several assumptions. Problems occurring due to conventional approaches were now solved by using commercial planning packages, which provides the graphical design of the final layout and correctly simulates the workcell conditions.

In general, the robotic workcell consists of single robot and multi-machines, and this format solves various industrial purposes. However, for complex operations such as assembly and palletizing, where multiple tasks are performed simultaneously, the multirobot workcell can be the better option. The multirobot workcell contains two to three robots working in a coordinated manner, avoiding collision between themselves and machines. The multirobots are used in assembly lines, while the cellular manufacturing has the least application of them. The multirobot cells have high productivity and saves floor space by minimizing the requirement of machines for performing similar tasks by single robot workcells. However, the layout design of multirobot workcell is more complicated than a single robot workcell.

Various problems such as robot workspace limitation, floor area limits, robot-machine reachability, collision-free operation and coordinated task scheduling are relatively more complicated in the multi-robot workcell. Although, much work has already been reported in various areas of the multi-robotic workcell design, so far, the available literature lacks promising solutions. Moreover, interest in multi-robot layout design has grown considerably because of the need to increase productivity and meet market demands. Multirobot system thus helps to install new and efficient automated manufacturing techniques in the industries.

Most of the robotic workcells handle repetitive task, thus, the trajectory of the robot is the crucial factor in optimizing the cost and the time involved in producing the desired product. The offline trajectory planning methods often utilize informal ways to simulate trajectory and for checking collision between manipulator and machine (Zha and Du, 2001; Chettibi *et al.*, 2004). The problem formulation also lacks constraints considering the machine and robot geometry, which generate impractical solutions. These solutions increase the calibration time and thus required several manipulations while starting an operation in a workcell.

The geometric modeling and simulation of the robot has been performed by using virtual simulation system that was a remarkable development for realistic collision simulation (Fawaz *et al.*, 2009). This simulation system provides continuous feedback of the error produced during operation. Further, the adaptive learning algorithms, sophisticated obstacle avoidance, and augmented reality approach are advantageous for complex trajectory planning problems (Wang *et al.*, 2010; Phung *et al.*, 2011; Nee *et al.*, 2012). These approaches work in dynamic environment with motion modulation using potential field approach and can work under close spatial tolerance with obstacles and machines. However, these approaches require auxiliary devices to simulate realistic working environment.

Various trajectory planning problems utilizes CAD-based graphical simulation system that has substantially improved the results produced (Neto and Mendes, 2013; Baizid *et al.*, 2016). The drafting software transfer geometric data of the machine model through the programmed formats, which can be further utilized for the pre-assigned purpose. The aforementioned areas are crucial for successful and efficient working of robotic workcell. However, the present thesis work undertakes the two essential areas: layout design and trajectory planning. Further, this research work concentrates on developing rapid and advance simulation approach for providing the promising solution to various problems in the field of robotic workcell design and planning.

1.3. Present Research Problem: *Motivation and Objectives*

The present global scenario sees the rapid advancement in technology and the competitive environment among every branch of industry. In such environment, the manufacturing firms are adopting better solutions to the problems arising due to fluctuating demands, frequent change in product designs, low cost, and high quality of finished goods. Such problems are demanding industries to develop robot based automated cellular manufacturing systems that can trim their manufacturing costs and simultaneously produce high quality goods in minimum time.

Robotic workcells have different aspects which directly or indirectly affect the overall performance. The workcell design and planning have several issues. However, the two fundamental aspects of workcell, i.e., its layout design that takes the problem of locating robot and machines optimally and the trajectory that takes the movement of end-effector between machines have been considered in present work. Though, ample amount of work has already been reported on the above topics. This research work shows that still better approach can be developed to solve the forthcoming problems in the manufacturing industry.

The objective of the present work is to develop a new design and planning approach, which can produce an optimal layout of the robotic workcell. Also, to generate the optimal trajectory of the robot for given operating condition. The present approach aims to fulfill the above objective by considering the realistic simulation and modeling ideas. Further, the present approach has also been expanded to multirobot workcell design problem and presents a novelty in this stagnant area.

1.3.1. Research Motivation

The following are the important research possibilities that have motivated to undertake the present work in the field of robotics:

- ⇒ The modeling and simulation of various components of the workcell has been performed, so as to conduct the study in the realistic environment and be able to provide implementable solutions which may reduce the calibration time and effort required to start an operation in the workcell.
- ⇒ The layout design of robotic workcell should be independent of changes in product design, task performed, change in the machines and equipment and also change in the robot. The layout should be flexible and adaptable.
- ⇒ The trajectory planning for the robotic manipulator in the predefined layout of a workcell is a crucial area. The trajectory planning lacks realistic simulation due to which the unknown obstacles during operation compels to manipulate the obtained solutions. The trajectory of the robot also affects the expenditure invested to run the workcell, and the efficient trajectory planning reduces the maintenance and saves production time.
- ⇒ Modeling and design of multi-robot workcell under realistic constraints from working environment can saves the floor space area and can increases the productivity. The multirobot workcell design lacks efficient and flexible designing methods, and its complex design reduces its implementation in the industry.

Thus, it is expected that the present research work based on the motivation mentioned above, will add new chapters to the existing knowledge in the field of robotic workcell in cellular manufacturing systems.

1.3.2. Research Objectives

As discussed above, the present work is motivated to develop a layout design and trajectory planning approach for robotic workcell. This work takes forward the following broad objectives:

- ⇒ To develop a modeling and simulation approach to conduct the layout and trajectory analysis for the robotic workcell in a real world constrained situations. The errors and computational complexity should be minimum, and the approach should also give practical solutions. The approach should consider the actual geometry and dimensions of the machines and robots to simulate the realistic operating condition.
- ⇒ To design the layout of the robotic workcell by optimizing the location of the machines for a robot centered arc type layout design.
- ⇒ To plan trajectory of the robot using the developed simulation approach taking the actual geometry and dimensions of robots, machines, and obstacles during simulation.
- ⇒ To develop a multirobot workcell layout by transforming the single robotic workcell layout using the developed approach and optimizing the layout to save floor space and maintain the productivity.

It is expected that the results of the present research work will be helpful in solving the problems related to robotic workcell design and planning realistically and thus producing productive workcell which can increase the automation of the small and medium scale industrial organizations.

1.4. The Thesis Work Organization

The present research work is outlined in the following seven chapters:

Chapter 1: Introduction

This chapter presents the fundamental aspects of the robots in the industrial and non-industrial applications. The brief background of the robotic workcell layout design and trajectory planning problems has been presented. This chapter also give brief introduction of various modeling and simulation approaches. The research motivation and objectives of present thesis have been introduced in this chapter. At last, the outline of the thesis work has been defined.

Chapter 2: Literature Review

This chapter presents the summary of the previous work conducted by various researchers related to layout design of robotic workcell and trajectory planning of the robotic manipulator. Various layout design methods, the programming packages and the approaches used to validate the simulation methods have been discussed in detail. The layout design methods of multirobot workcell have also been discussed. Different algorithms to plan the trajectory of the robotic manipulator have been explored. The kinematic and dynamic characteristics of the robotic manipulator has presented in detail. Various interpolation profiles used to generate trajectory points, the case studies and approaches taken to validate the developed trajectories have been presented. The techniques used for collision avoidance and the development of point clouds have been summarized in this chapter.

Chapter 3: Point Cloud Simulation Approach

This chapter describes the proposed technique for design and planning of robotic workcell. The detailed procedure to generate the point cloud model of machines and robots have been discussed. The working point cloud model of the robot has been kinematically tested. The algorithms for generating the point clouds and their transformation from one location to another have presented. The algorithm to optimize the layout design of machines and trajectory of the robot has been critically discussed. Finally, the industrial case study conducted to validate the proposed approach has been discussed in this chapter.

Chapter 4: Layout Design of Robotic Workcell

The point cloud simulation approach is used to design the layout of the industrial robotic workcell having four machines and a robot at the centre of an arc type layout. The point clouds of machines and robot are prepared by collecting the data from the robotic workcell installed in a steel industry. Further, the problem is formulated to search the optimal location of the machines in the workcell according to the optimization criteria taken. The final solution is then plotted as the point cloud maps which shows their isometric and top view, hence provides the visual images of the developed solutions. This chapter finally concludes the layout design procedure followed.

Chapter 5: Multi-Robot Workcell Layout Design

This chapter presents the layout design of multirobot workcell using the data from the single robot workcell. The advantage of developing the point cloud-based simulation approach has been approved by this study. Two industrial robotic workcells, working parallelly has transformed into a multi-robot workcell having same productivity. The idle time in a cycle is utilized to adjust the sequence of operation performed by two robots in the workcell. The reachability of the robotic manipulator is a significant problem in multi-robot workcell which is tackle by adjusting the angular position of the machines in the cell. Finally, some concluding remarks regarding the study has been presented.

Chapter 6: Trajectory Planning of a Robotic Manipulator

The application of point cloud simulation approach to the trajectory planning of a robotic manipulator has been demonstrated in this chapter. The trajectory planning is conducted under realistic environment, which comprises of actual dimensions of machines, robot, tool, and workpiece grasp by the robot during trajectory. The task is to find the alternate path to avoid the collision with machines and simultaneously optimizing the time taken and jerk produced during motion. Three different predefined mathematical interpolation profiles have been analyzed for the current trajectory planning problem. Finally, this chapter concludes the best trajectory profile for the formulated problem.

Chapter 7: Conclusions and Scope for Future Work

This chapter presents the relevant conclusions drawn from the research work presented in above chapters. The detailed study of the application of point cloud simulation approach to solve the layout design and trajectory planning problem in the robotic workcell has been discussed critically. At last, the possible scope for future research on the present topic has also been presented.

In the end, it is expected that the findings in this thesis work will prove to be useful and helpful for other researchers to get motivated and in turn search for new objectives, to extend this work further.