

Optimization of Assembly Sequence

A REPORT SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS

**FOR THE DEGREE OF
BACHELOR OF TECHNOLOGY**

in

MACHANICAL ENGINEERING

by

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**DEPARTMENT OF MACHANICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA – 769 008
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C E R T I F I C A T E

This is to certify that the work in thesis entitled “**Optimization of Assembly Sequence**” submitted by **Mr. Rahul Goyal** in partial fulfillment of the requirements for the award of **Bachelor of Technology degree** in the department of Mechanical Engineering, National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the work reported in this thesis is original and has not been submitted to any other University/Institute for the award of any Degree or Diploma.

He bears a good moral character to the best of my knowledge and belief.

Place: Rourkela
Date:

Prof. (Dr.) Bibhuti Bhusan Biswal
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ACKNOWLEDGMENT

I first express heartiest gratitude to my guide and supervisor *Prof. (Dr.) Bibhuti Bhusan Biswal*, professor of Mechanical Engineering for his valuable and enthusiastic guidance, help and encouragement in the course of the present project work. The successful and timely completion of the research work is due to his constant inspiration and extraordinary vision. It is not possible to acknowledge sufficiently his important contribution of talent and time given unselfishly in proceeding with this work. His overall constructive criticism has helped me to present my work in the present form.

I very much obliged to Prof. (Dr.) *Ranjit Kumar Sahoo*, Professor and Head of Department of Mechanical Engineering for his continues encouragement and support.

Rahul Goyal

ABSTRACT

The assembly sequence is one of the most time consuming and expensive manufacturing activities. Assembly sequence affects many of product development design and production and is relevant to many life cycle issues of the product, so assembly sequence analysis should be part of early product design. The cost of assembly on an average is 10-30% of the manufacturing cost of a commercial product. The ratio between cost and performance of assembly has increased with respect to other types of the manufacturing process and in recent years, this fact has caused a growing interest by industry in this area. Robotic assembly which is comes under the assembly sequence and also comes under the automated assembly system incorporates the use of robots for performing the useful and time taking assembly tasks.

A variety of optimization tools are available for application to problem. It is difficult to model the present as an n-p problem. Finding the best assembly sequence generation involves the conventional methods or soft computing methods by following the procedure of search algorithms. Optimization of a correct and stable assembly sequence is essential for automated, semi-automated or manual assembly systems. Assembly sequence affects flexible and advanced manufacturing system in many aspects such as use of tool, cost, time, layout of area etc.

To solve this kind of problems or time consuming geometric reasoning in assembly sequence, this research proposes a method to determine stable assembly sequence. The objective of the present work is to stable, generate feasible and optimal assembly sequence satisfying the assembly constraint with minimum assembly cost. The present project aims at evolving an approach for generating assembly sequence using the evolutionary technique considering of the instability of assembly motion and/or directions.

To elaborate the effectiveness of the method, one soft computing method is applied to generate the optimized sequence(s).

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Chapter-1

INTRODUCTION

1.1 Overview

Progress and fast growing society depends on the engineering industrial growth. Engineering industries of today are found to use advance manufacturing methods to achieve good quality of products, mass production with competitive cost of manufacturing. Assembly plays a fundamental role in the manufacturing of most products. Parts that have been individually formed or machined to meet designed specifications are assembled into a configuration that achieves the functions of the final product or mechanism. The economic importance of assembly as a manufacturing process has led to extensive efforts to improve the efficiency and cost effectiveness of assembly operations.

Manufacturing and engineering design in industry require specialized knowledge and problem solving techniques. With the help of soft-computing techniques industries can facilitate part design, process planning, scheduling, understanding and diagnosis and effective sequence determination to assemble a product. Products can be any kind of industrial product which covers very broad range. Every product has some specific characteristic in common with other products. The common thing is that, product itself consist of number of parts that must be joined together to form a single assemble finish product. A single assembly tasks involves joining two or more parts or sub-assemblies together.

Firstly, many such orders may not be feasible because of constraints such as movability and stability of assembly and after that some or not good because for that we need some jigs and fixtures, so that not desirable. So, assembly planning can be defined as the process of finding as assembly plan, which defines either, a partial or complete order in which the assembly tasks can be performed.

1.2 Assembly in design and manufacturing

Until recently, assembly has been considered by many to be a low technology process and its costs and importance may have been underestimated. However, with the help of automated assembly, especially programmable, automated assembly- fundamental issues are being rethought ad new methods are being proposed to assist designers and planners. An assembly operation is a type of manufacturing operation, in which two or more parts are joined together to form a new entity or sub-assembly. It means, a product is assembled by repeatedly joining one or several either parts or sub-assemblies to form larger sub-assemblies or a main assembly until a target product is obtained. A product designer must consider a variety of factors like functional goal, design, fabrication and manufacturing, ease of use and future repair of products. A determining factors in manufacturing system in the sequence of assembly, itself a function of product design. Selecting a better assembly sequence has many advantages, including reduced no

of fixture, less workers better testing platform, less risk of part mating because less and easier assembly moves and most important lesser unit assembly cost. In order to fulfill these expanding needs and to survive and grow in the global market, industries use a high level of automation to build product/ assembly. It provides the opportunity to make the production faster and better.

1.3 Evolution of assembly

Research in assembly has gained momentum mainly in the last decades. The reason why it emerged so late as a separate research topic in manufacturing and so active now a days could be explained considering the degree of automation and it is directly associated with the complexity of optimization in assembly and economic considering. Before that, most effort in manufacturing research was directed at primary manufacturing process and it became clear that potential for saving resulting from improvements in this sector was not covering the cost of the effort. It was also identifies that one source to reduce to costs was assembly.

1.4 Stages in assembly

In production system a major role is performed by assembly process. Assembly involves several stages, such as, part handling and accessing, finding the relative position between components, selection of fixture and part placement devices, and assembly sequence determination. Sequence of assembly to get final finished assembly involves the identification, section and sequencing of assembly operations. The sequencing of assembly operations usually leads to the set of all feasible and reliable assembly process. The attentions that need to be made in a feasible assembly process are: the trouble of assembly steps, the needs for holding parts/sub-assemblies, the potential for parts damages during assembly, the ability to do in-process testing, the amount of needs for rework(like repair etc.) the unit cost of assembly etc. These attentions influence the productivity of the system or plant, product quality, and the cost of production. Due to all this reason has caused a growing interest by industry in this area.

1.5 Classification of assembly

Assembly system can be divided in following categories

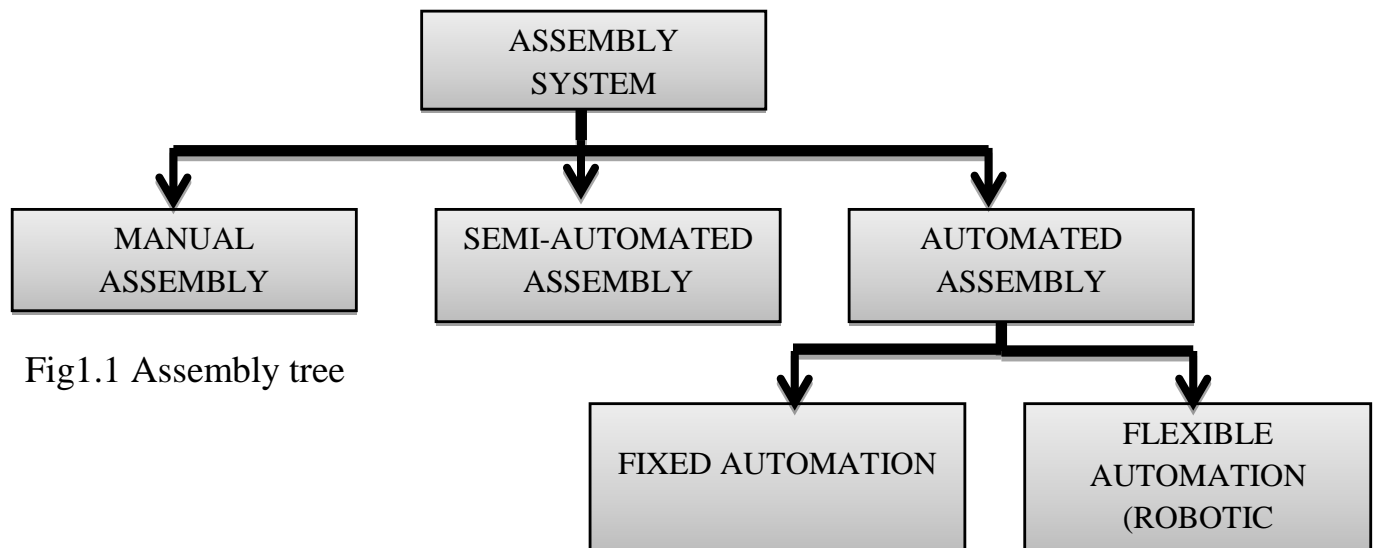


Fig1.1 Assembly tree

1.5.1 Manual Assembly

In this assembly process, parts are transferred to workplaces where workers manually assemble the product or component of assembly product. Generally hand tools or used in this assembly process. Although this is most flexible and adaptable of assembly methods, there is usually an upper limit to production volume, and labor costs are higher. In this process, there is always the possibility of human errors.

1.5.2 Semi-automatic Assembly

Fixed or hard automation is characterized by custom-built machinery that assembles one and only one specific product. Obviously, this type of assembly requires a large capital investment. As production volume increases, the fraction of the capital investment compared to the total manufacturing cost decreases. Sometimes, this kind of assembly is called “Detroit-type” assembly.

1.5.3 Automated Assembly

Automated assembly is an optional capital investment on the part of management. Many areas of manufacturing require the purchase of fabricating machines such as presses, molding machines etc.

Automatic assembly is a high-production tool. Robotic assembly system which comes under the automated assembly system incorporates the use of robots for performing the necessary assembly tasks. Robotic assembly system are programmable and have the flexibility to handle a wide range of style and products, to assemble the same products in different ways, and to recover from errors or other unexpected events that causes the execution of the assembly to deviate from the preplanned course of action. Even with flexibility of the mechanical hardware, current robotic assembly systems are limited due to inadequate data structure for representation of tasks plans.

1.6 Comparison of Assembly method

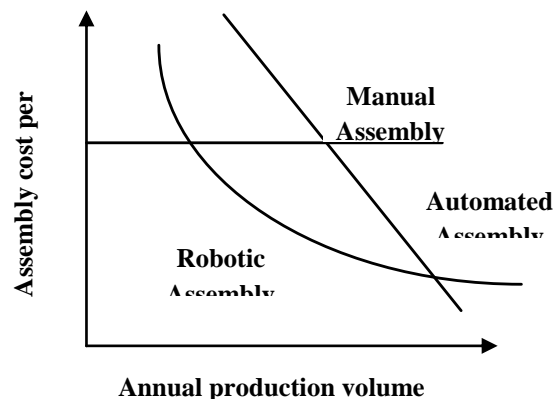


Fig: 1.2 Relative costs of different assembly methods by type and volume

Graphically, the cost of different assembly methods can be displayed as in Figure 1.2. The non-linear cost for robotic assembly reflects the non-linear costs of robots.

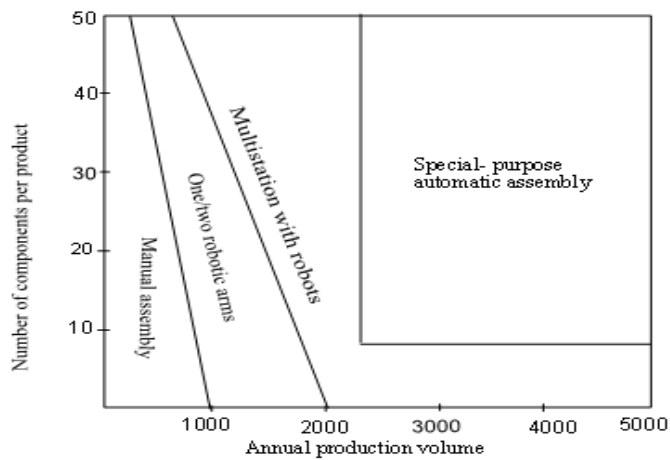


Fig: 1.3 the appropriate ranges for each type of assembly method

The appropriate ranges for each type of assembly method are shown (approximately) in Figure 1.3. Assembly methods should be chosen to inhibit bottlenecks in the process, as well as minimum costs.

1.7 The Benefits of robotic assembly

The manual assembly process is likely to want much time and min. qualitative assembly as compared to the automated one. In automated assembly, robotic assembly forms a major role and it has advantage of max process capability and measurability. It is faster, more efficient and accurate than any other conventional methods. It is characterized by no fatigue, more output, better performance, and flexibility.

The following points are discussed on the benefits of robotic assembly;

1. Non-stable product design: If the products design changes, the robot can be reprogrammed accordingly. However, this does not usually apply to the peripheral items in the system that contact the parts such as feeders, grippers etc.
2. Production volume: A robot system can operate economically at much longer station cycle times than '5S' system of standardize cleanup.
3. Style variations: A robot can more readily be arranged to accommodate styles of the same product.
4. Fluctuation in demand: A truly programmable assemble system could be switched to different products according to demand.
5. Part defects: The robot can be programmed to sense problems that may occur and re-attempt the insertion procedure.

6. Part size: The part can be presented in patterns or arrays on pallets or part trays. In this case the severe restriction on part size is high-speed automation do not apply.

1.8 Rules to Simplify the Design and the Assembly Process

- a) Minimize no. of parts: for reducing no of assembly, no of parts should be reduced. Hence, in most cases, the reduction in assembly cycle time. This is to be applied during conceptual and detail design stage.
- b) Design for simplicity of handling: This is determined during the design phase and it depends on the specific part property (ies).
- c) Design for simplicity of insertion: good insertion can be designed into components in the detail design stage by having suitable tolerances and chamfers on the mating parts.

1.9 Reason for automated assembly

- ❖ Cost reduction
- ❖ Direct labor cost reduction
- ❖ Marketing considerations
- ❖ Lower cost limit
- ❖ Improved deliveries
- ❖ Uniform quality
- ❖ Reduced warranty expenses

1.10 Objective of research work

Under this context the objectives of the present research work are:

- i) To make an all-compassing study of robotic assembly systems
- ii) To develop a methodology for determining sequences of assembly for robotic assembly cells in a systematic manner.
- iii) To develop a methodology for planning the tasks involved in the robotic assembly cells.
- iv) To develop convenient and appropriate techniques and tools for the purpose of integrated assembly sequence generation and task planning for robotic assembly cells.

1.11 Summary

Assembly is an important process to consider for two reasons: its ubiquity and its role as system integrator. All most all products are assembled, so improving the assembly process has benefits to all industries. And since assembly is typically the final manufacturing process it can bring to light problems that arise at earlier stages in the manufacturing system, such as quality problems in piece –part production or scheduling problems in part delivery. Recognition of the benefits of concentrating on assembly as a key process is long standing. For the same reasons that assembly is a key process in the manufacturing process:

Chapter-2

LITERATURE SURVEY

2.1 Overview

Many researches in last decade describe efforts to find more efficient methods for assembly sequence generation. This is due to fact, earlier described process are time consuming and non-optimizing due to the problem of trapping in local optima.

There have been many research work and experimental inference for the generation of suitable and correct assembly sequence which is reflected through the last no of literatures and books.

Table 2.1 some important literature related to the present work

Sl	Author(s)	Year	Topic
1.	A Bourjault	1984	Showed that a set of logical expressions could be used to encode the directed graph of assembly states.
2.	T. De. Fazio and D. Whitney	1987	Develops a graphical method for generation of liaison sequence from the precedence relationship assembly sequence.
3.	L.S.Homem de Mello and A.C. Sanderson	1989-91	Develop another graphical method to reduce the query and answer method for the generation of all mechanical assembly sequence.
4.	Masclé and J.figour	1990	Generates a constraint method which orderly disassembled the least constraint part at each step and obtains the assembly in its reverse.
5.	Y. Huang and C. Lee	1989 1990	Develops a classified method and gives the precedence knowledge in mating operation assembly planning.
6.	S. H. Lee	1990	In disassembly method, this reduces the $n!$ sol. to some extent.
7.	Cho and H. Cho	1993	Works on topological modeling and graphical inference which gives knowledge about part contact level graph and indication about the feasible assembly sequence.
8.	D. S. Hong and H. S. Cho	1993 1994	A computational scheme has been developed for generation of optimized assembly sequence based on neural network.
9.	M. Dorigo	1997	Use the ant colony in travelling salesman problem.
10.	J. F. Wang, J. H. Liu, and Y. F. Zhong	2005	The solution is based on assembly by using ant colony algorithm.
11.	L.N De Castro and J. T. Timmis	2002	Develops a new computational intelligence approach by using artificial immune system.

2.2 Assembly Sequences Generation and disassembly

De Fazio and Whitney used a logical method through a set of questions (the no of questions to be asked is $2L$) that resulted in the desired precedence relationship among the parts. The precedence relationships are used for the generation of assembly sequences. The techniques do not lead to failure if an unclear liaison is omitted or if conservatively too many are included. Still, the method may be very reasonably applied to assemblies with parts counts in the teens or even tens.

Ko and Lee developed a method to automatically generate an assembly procedure for parts/assemblies. The assembly generation procedure is based on two steps: i) any component in an assembly is located at a different/specific vertex of a hierarchical tree; and ii) then the assembly process is generated from the hierarchical tree with the help of interference checking.

Chen has given the problem of automatically finding all the feasible/stable assembly sequences for a set of n parts. The method proposed is feasible and practical in generating all the feasible assembly sequences when the number of parts is greatly increased. This approach results in only 1 questions to be answered. The proposed method shows feasibility and economy for the assembly of a large number of parts.

Baldwin, Abell et al. described an integrated computer aid that generates all feasible and stable assembly sequences. Generation of all possible assembly sequences is done using the cut-set method to find and represent all geometric and mechanical assembly constraints as precedence relations. Still, the work presented may further extend editing capabilities and may connect the programs to geometric database and knowledge bases that may provide some of the information about fixturing, orientation, interference and assembly difficulty that the user put in manually in the proposed method.

L. Laperrière and H. A. ElMaraghy this paper describes a programming system capable of automatically generating robotic assembly sequences. It is a generative robotic assembly process planner. A geometric model of the product to be assembled is defined interactively in the feature-based product database. Assembly relationships between components are modeled interactively in the graphical relation diagrams. An initial and a final relation diagram are used to describe the initial and final states of the assembly, respectively.

De Mello and Sanderson developed an algorithm for correct and complete generation of mechanical assembly. In their approach the complete assembly is decomposed into distinct sub problems following a set of rules for validity and feasibility of the decomposed items, which are tested, on the relational model of the assembly. The methodology results in a valid and feasible disassembly sequence from which the target assembly sequence(s) is/are obtained. Since the process is tested for decomposition, the algorithm is claimed to be correct and complete. However, for completeness of methodology from robotic assembly viewpoint, the relational model should contain more relevant information and accordingly the decomposition algorithm will be influenced.

Yang and Chen stated that the connections between product parts are divided into the fixed connection and contact connection based on the study of the assembly structure. According to the properties of subassemblies, subassemblies are classified into two types: I-subassembly and II-subassembly. The directed graph representation of assembly is established and expressed as the adjacent matrix and interference matrix. A method for generating subassemblies is presented. The method is based on the matrix representation of assembly information, so it can be easily implemented with computer. In assembly sequence planning, subassemblies can be successfully generated using the method presented in the paper, so that the combinatorial explosion can be overcome and the generation of assembly can be simplified.

Subramani and Dewhurst carried out work on generation of disassembly sequences for identified services or repair items. The method for the generation of disassembly sequences is based on construction of disassembling diagram (DAD) from the relational model of the product. However, the suggested method does not claim to produce the optimal disassembly sequence.

2.3 Summary

The problem of sequencing has a primary role in the development of computer –aided assembling planning systems. In these last two decades, this stimulating subject has been debated very frequently in the scientific world, and this fact is demonstrated by the very wide literature concerning this topic in the presented chapter. Several kinds of algorithms have been developed and tested to generate feasible sequences. Nevertheless, some issues still exist and currently prevent a fully automated solution to this problem. These issues mainly concern: integration with CAD, feasibility check of sequences, selection of the best assembly sequence.

Chapter-3

GENERATION OF ASSEMBLY SEQUENCE

3.1 Overview

The problem of sequencing has a primary role in the industry development of automated assembly. Many algorithms and programs have been developed and tested to get required sequence. In some other methods, the researchers need to draw the graph of connections corresponding to assembly and then answer a set of question to every connection. These precedence relationships between the connections are then used to generate the assembly sequences. One common thread that seems in most of the works is the strategy of “assembly by disassembly” in which assembly sequence is generated by starting with the complete assembly product and working reverse through disassembly steps. It is less complex than the forward procedure. It is assumed that exactly two parts or sub-assemblies are joined at one time and after those parts is put together to form a final product. The correctness of algorithms and methods is based on the assumption that it is always possible to decide to correctly whether two sub-assemblies can be joined, based on physical and geometrical area.

The methodology used here operates on a relational model of assembly. The relational model (liaison) used in this work provides an efficient data structure that maintains contact geometry and connection information at the first level of representation and complete part geometry at a next level. In this research, a product is considered to be suitable for robotic assembly when the following conditions are satisfied.

- i. All the individual components should be rigid.
- ii. Assembly operations can be performed in all mutually perpendicular directions in space excepting +Z direction; and
- iii. Each part can be assembled by simple insertion or screwing.

3.2 Product modeling for assembly sequence generation

The product modeling is a procedure to explain the assembled state in terms of connective relations between the component parts of given assembly. The connective relations are described in terms of the connective directions and the mating method.

Considering the product consisting n parts, the representation of the end product can be made in the following manner.

The product consisting n parts is represented in the format

$$A = (P, L),$$

Where A is a product having parts $P = \{p_\alpha | \alpha=1, 2, \dots, n\}$, and interconnected by the liaisons $L = \{l_{\alpha\beta} | \alpha, \beta = 1, 2, \dots, r, \alpha \neq \beta\}$ (Cho and Cho).

Here n represents the number of parts of a product and r is the relationship between the connected parts and $(n-1) \leq r \leq n$ $(n-1)/2$. The liaison $l_{\alpha\beta}$ represents the connective relationship between a pair of parts p_α and p_β . The connective relations can be divided into a contact-type and a fit-type connection. The representation of liaison $l_{\alpha\beta}$ is given by

$$l_{\alpha\beta} = \text{liaison} (p_\alpha, C_{\alpha\beta}, f_{\alpha\beta}, p_\beta),$$

Where the $C_{\alpha\beta}$ is the contact-type connection matrix and the $f_{\alpha\beta}$ is fit-type connection matrix.

The dimension of each matrix is 2×3 elements, and represented by

$$C_{\alpha\beta} = \begin{pmatrix} Cx & Cy & Cz \\ C\bar{x} & C\bar{y} & C\bar{z} \end{pmatrix}, \text{ and } f_{\alpha\beta} = \begin{pmatrix} fx & fy & fz \\ f\bar{x} & f\bar{y} & f\bar{z} \end{pmatrix}$$

The assembly directions for robotic assembly are taken to be $d \in \{x, y, \bar{x}, \bar{y}, \bar{z}\}$.

The representation of the elements of contact-type and fit-type are:

$$C_d = \begin{cases} 0: \text{no contact in the } d \text{ dir}^n \text{ bet}^n p_\alpha \& p_\beta \\ rc: \text{real contact in the } d \text{ dir}^n \text{ bet}^n p_\alpha \& p_\beta \\ vc: \text{virtual contact in the } d \text{ dir}^n \text{ bet}^n p_\alpha \& p_\beta \end{cases}$$

And

$$f_d = \begin{cases} 0: \text{no fit in the } d \text{ dir}^n \text{ bet}^n p_\alpha \& p_\beta \\ sw: \text{screwing in the } d \text{ dir}^n \text{ bet}^n p_\alpha \& p_\beta \\ rf: \text{round peg in hole fit in the } d \text{ dir}^n \text{ bet}^n p_\alpha \& p_\beta \\ mp: \text{multipleround peg in hole fit in the } d \text{ dir}^n \text{ bet}^n \\ p_\alpha \text{ and } p_\beta \end{cases}$$

Each element of f_d can also be represented as round-peg fit (rf), a polygon fit (pf), a tight fit (tf), a caulking (ca), a riveting (ri), a multi-peg-fit (mp), a virtual fit (vf) or no fit (0).

The connection matrix is represented in the format following.

$$l_{\alpha\beta} = \text{liaison} \left(p_\alpha, \begin{pmatrix} 0 & rc & rc \\ rc & rc & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & rf \\ 0 & 0 & 0 \end{pmatrix}, p_\beta \right)$$

Now, for a grinder assembly as shown in Fig-3.1(a) is considered as an example problem for optimizing the assembly sequence and validating the proposed method.

Fig-3.1(b) shows the direction for assembly, and fig-3.1(c) shows the liaison diagram of the individual component of the product and the table 3.1 shows the part description of the assembly product.

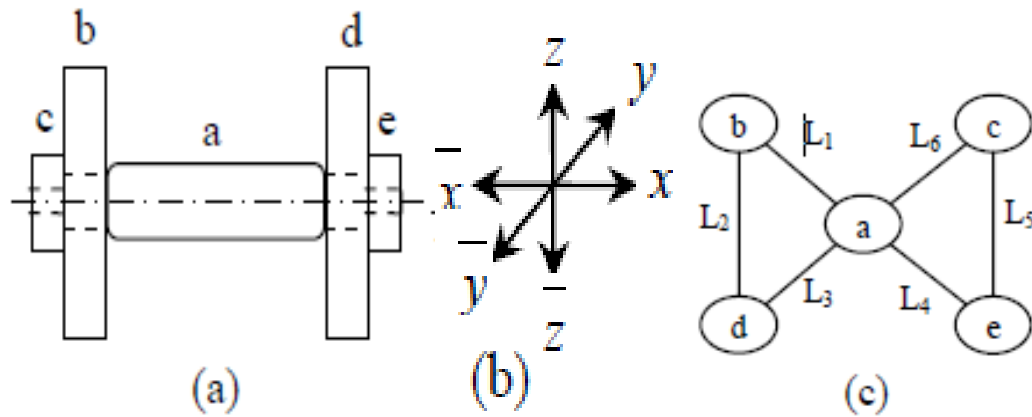


Fig 3.1 (a) A simple example of a product (Grinder assembly), Fig 3.1(b) Directions for assembly, Fig 3.1 (c) Liaison graph model of grinder.

Table3.1: Part description of grinder assembly

Part Symbol	Part Name
a	Shaft
b	Blade
c	Nut
d	Blade
e	Nut

As per the codes of the model/parts, the liaisons of the assembly components are shows as follows:

$$l_{ab} = liaison \left(a, \begin{pmatrix} o & rc & rc \\ rc & rc & rc \end{pmatrix}, \begin{pmatrix} o & o & o \\ rf & o & o \end{pmatrix}, b \right)$$

$$l_{ac} = liaison \left(a, \begin{pmatrix} o & o & o \\ vc & o & o \end{pmatrix}, \begin{pmatrix} o & o & o \\ sw & o & o \end{pmatrix}, c \right)$$

$$l_{ad} = liaison \left(a, \begin{pmatrix} rc & rc & rc \\ o & rc & rc \end{pmatrix}, \begin{pmatrix} rf & o & o \\ o & o & o \end{pmatrix}, d \right)$$

$$l_{ae} = liaison \left(a, \begin{pmatrix} vc & o & o \\ o & o & o \end{pmatrix}, \begin{pmatrix} sw & o & o \\ o & o & o \end{pmatrix}, e \right)$$

$$l_{bc} = liaison \left(b, \begin{pmatrix} o & o & o \\ rc & o & o \end{pmatrix}, \begin{pmatrix} o & o & o \\ o & o & o \end{pmatrix}, c \right)$$

$$l_{de} = liaison \left(d, \begin{pmatrix} rc & o & o \\ o & o & o \end{pmatrix}, \begin{pmatrix} o & o & o \\ o & o & o \end{pmatrix}, e \right)$$

3.3 Assembly Constraints

The assembly constraints are divided into two categories: precedence constraints and connectivity constraints. A precedence constraint of a liaison $l_{\alpha\beta}$ is represented by a set of n_p parts that must be connected before two parts p_α and p_β are interconnected. The precedence constraint $PC(l_{\alpha\beta})$ of a liaison $l_{\alpha\beta}$ is expressed by

$$PC(l_{\alpha\beta}) = \{ p_\gamma \mid \gamma = \gamma_1, \gamma_2, \dots, \gamma_{n_p} \}$$

And the precedence constraint $PC(p_f)$ of the part p_f is expressed by,

$$PC(p_f) = \bigcup_{l=l_1}^{l_q} P(l_{\alpha\beta})$$

Where $P(l_{\alpha\beta})$ is a precedence constraint of a liaison $l_{\alpha\beta}$ and is directly inferred from the part contact level graph.

While taking into consideration the overall structure of a product assembly, an assembly task can hardly be performed successfully because a last assembled part p_j often prevents a part being assembled. In such a case p_k should be assembled before p_j . Such a p_k is called a **precedence constraint** to assembly of p_j .

In this study the precedence constraints of the liaisons are:

$$PC(l_{ab}) = \{ \Phi \}, PC(l_{ac}) = \{ b \}, PC(l_{ad}) = \{ \Phi \}, PC(l_{ae}) = \{ d \},$$

$$PC(l_{bc}) = \{ \Phi \}, PC(l_{de}) = \{ \Phi \}$$

Accordingly, the precedence constraint of the parts can be listed as;

$$PC(P_a) = \{ b, d \}, PC(P_b) = \{ \Phi \}, PC(P_c) = \{ b \},$$

$$PC(P_d) = \{ \Phi \}, PC(P_e) = \{ d \}.$$

3.4 Part contact level graph

The part contact level graph represents the overall structure of product assembly. In the graph, each node is denoted by a part, while each line represents directional connection between two parts. The assembly direction can be shown $\mathbf{d} \in \{x, y, z\}$ frame or in opposite frame. The part contact level represents a precedence level with which a part can be assembled along a given direction while taking into consideration the contact type connections in that particular directions.

3.5 Feasible assembly sequence using Part Contact level graph

It is a sequence of assembling parts on a base assembly, part by part. The feasible base part is defined as a part whose assembly precedence constraint is satisfied. At first, feasible base part (fbp) for a product must be chosen among n parts. A feasible base part relates to the part whose precedence constraint $PC(\text{fbp})$, does not exist i.e. $FBP = \{\text{fbp}_i \mid PC(\text{fbp}_i) = \{\phi\}\}$.

3.6 Part instability

The part stability is considered by evaluating the instability conditions. More is the instability, more is the weighted factor or vice versa. The part instability, $S(p_k)$ of a part (p_k) is defined as the half-degrees of freedom (hdof) of both translational and rotational motions. This is represented as 2×6 matrix, which consists of a 2×3 matrix, $T(p_k)$ representing hdof of translational motion and a 2×3 matrix, $R(p_k)$ expressing hdof of rotational motion as explained as follows. Fig-3.2 shows the direction of possible motions of the parts in 12 half degrees of freedoms.

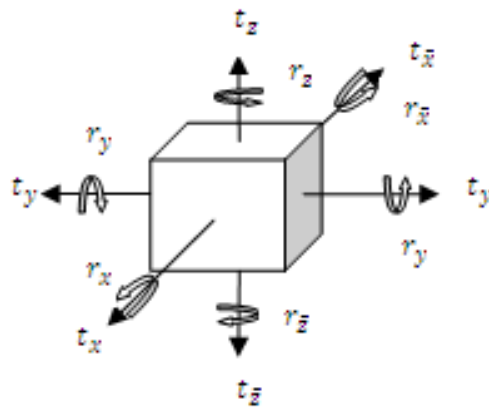


Fig-3.2: Motion of a part in free space

3.7 Summary

A systematic method of generating feasible assembly sequence has been proposed. The method is based upon the evaluation of base assembly motion instability along with part contact level graphs that infers the precedence constraints. To formulate a scheme for generating such a stable sequence, instability of base assembly movement has been defined utilizing the instability of each individual part motion. This gives the stable sequences. With the help of these, anyone can find the most desirable sequence which yields the min no of direction changes in base assembly movement.

Chapter-4

SOFT COMPUTING METHOD AND ASSEMBLY SEQUENCE

4.1 Overview

Many types of optimization tools are available for application to the problem, like Simulated Annealing, Evolutionary Computation, Tabu Search, Ant Colony Optimization, and Artificial Immune System but their suitability and/or effectiveness are also under scanner. Searching the best sequence generation involves the conventional or soft computing methods by following the procedures of search algorithms. Intensification is an expression commonly used for the concentration of search process on areas in search space with good quality solutions. Diversification denotes the action of leaving already explored areas and moving the search process to unexplored areas. Metaheuristic is set of algorithms concepts that can be used to define heuristic methods applicable to a wide set of different problems.

Metaheuristics are very advantageous for large search space problems. Study of various optimization methods tells that Ant Colony Optimization (ACO) & Artificial Immune System (AIS) method can be advantageously used to solve such problem. The concept of ACO is the foraging behaviors of the real ant which enables them to find shortest path between a food source and nest. It is best suitable for combinatorial optimization problem. AIS can be defines computational system inspired by theoretical immunology, observed immune function, principle and mechanism in order to solve problem.

4.2 Ant Colony Technique

The main concept of ACO is to imitate the cooperative manner of an ant colony to solve combinatorial type's optimization problems within a reasonable amount of time. At the time of their oath from nest to food source, ants can deposit and sniff a chemical substance known as pheromone, which gives them with the ability to communicate with each other. An ant lays some pheromone on the ground to mark the path it follows by trail of this substance. Ant move at random, but when they encounter a pheromone trail, they decide whether or not to follow it. The probability that an ant choose one path over others is determined by the amount of pheromone on the potential path of interest. With the continuous action of the colony, the shorter path are more frequently visited and become more attractive for subsequent ants. The main characteristics of an ant algorithm are positive feedback, distributed computation, and the use of a constructive greedy heuristic search.

The generic ant algorithms have four main steps as follows:

1. Initialization: Set initial population of the colony and the pheromone trail. Place starting nodes for all ants randomly.

2. Solution construction: Taking into account the problem-dependent heuristic info & the trail intensity of the path, each ant choose the next that has been visited to move by probability. Repeat the step till a completed solution is constructed.
3. Trail update: Evaluate the solution and deposit pheromone on the solution paths according to the quality of solution to know about solution whether it is better or not.
4. Pheromone evaporation: The pheromone trail of all paths is decreased by some constant factor at the end of an iteration of building completed solutions.

ACO algorithms have been applied successfully in a variety of optimization problem like Travelling salesman problem, just-in-time sequencing, and job-shop scheduling.

4.3 Artificial Immune Concept:

Like a Genetic Algorithm (GA), Artificial Immune System (AIS) is also population based and the optimal solution is obtained by the evolution of the population. In AIS, the problems to be solved are regarded as antigens. In general, 3 types of measurements are used to evaluate the antibodies, namely, fitness for the quality, affinity for similarity between antibodies, & concentration for population variety. AIS is computational intelligence paradigm inspired by the biological immune system, which has found application in pattern recognition, scheduling, control, machine-learning, and information system security. To implement the optimization ideas addressed previously, immune operations including immune selection, clonal selection and inoculation are introduced. AIS are realized by the following steps: (1) recognition of antigens; (2) generation of initial antibodies; (3) evaluation of antibodies; (4) proliferation and suppression of antibodies; (5) generation of new antibodies; (6) improvement of antibodies. Steps 3-6 will be iterated until convergence criteria are satisfied.

4.4 Objective function of assembly sequence generation (ASG)

Energy function, E_{seq} , is associated with assembly sequence, and it is represented as:

$$E_{seq} = E_J + E_P + E_C$$

where,

E_{seq} = Energy function associated with ASG

E_J = Energy related to Assembly cost

E_P = Energy related to Precedence Constraints

E_C = Energy related to Connectivity Constraints

where, C_J is an energy constant related to assembly sequence cost J .

The value of J can be decided as;

$$J = \begin{cases} 1: \text{if an assembly sequence violates} \\ \text{assembly constraints, or it is unstable} \\ \rho_s C_{as} + \rho_t C_{nt} : \text{otherwise} \end{cases}$$

The energy associated with precedence constraints is $E_p = C_p \sum_{i=1}^n \mu_i$, where, C_p is a positive constant and μ_i is the precedence index which is assigned to 0, if it satisfies the precedence constraints, otherwise 1.

The energy associated with connectivity is $E_c = C_c \sum_{i=1}^n \lambda_i$ in a similar manner connectivity index λ_i is inferred on the basis of liaison relationships.

The objective of the present work is to generate feasible, stable and optimal robotic assembly sequence with minimum assembly cost, which is linked with affinity values of artificial immune algorithm. The objective function for the assembly is Minimize $E_{seq} = C_j J + \sum_{i=1}^n (C_p \mu_i + C_c \lambda_i)$

4.5 Degree of motion instability and the number of assembly direction changes

The possible assembly direction sets DS^k_{cbade} ($k=c, b, a, d, e$) for each part of a sequence are expressed by

$$p_c : DS^c_{cbade} = \{d_j^c \in D \mid j = 1, 2, \dots\}$$

$$p_b : DS^b_{cbade} = \{d_j^b \in D \mid j = 1, 2, \dots\}$$

$$p_a : DS^a_{cbade} = \{d_j^a \in D \mid j = 1, 2, \dots\}$$

$$p_d : DS^d_{cbade} = \{d_j^d \in D \mid j = 1, 2, \dots\}$$

$$p_e : DS^e_{cbade} = \{d_j^e \in D \mid j = 1, 2, \dots\}$$

The ordered lists DL_i^{cbade} ($i=1, 2, \dots, m$) of possible assembly directions corresponding to the assembly sequence can be expressed by:

$$\begin{aligned}
DL_1^{cbade} &= \{d_1^c, d_1^b, d_1^a, d_1^d, d_1^e\} \\
DL_2^{cbade} &= \{d_2^c, d_2^b, d_2^a, d_2^d, d_2^e\} \\
&\dots \\
&\dots \\
DL_m^{cbade} &= \{d_m^c, d_m^b, d_m^a, d_m^d, d_m^e\}
\end{aligned}$$

The hierarchical tree of the sequence assembly directions may be represented in the format given in the Fig-4.2 (a)

Based upon the above equation, the normalized degree of motion instability and the normalized number of assembly direction changes are calculated. The formula for normalized motion instability C_{as} is:

$$C_{as} = \frac{1}{m} \sum_{i=1}^m \left\{ \frac{1}{12 \times i} \sum_{j=1}^i (S\{BA_j\})_i \right\}$$

where DS_j ($j=1,2,3,4,5$) is the in-subassembly formed at the j^{th} assembly step, and $S\{BA_j\}$ means the degree of motion instability of the j^{th} subassembly. A zero degree of motion instability means the parts belonging to the subassembly are completely fixed to each other, whereas twelve degrees means the parts are free to move in any direction. Similarly, the normalized number of assembly direction changes C_{nt} can be expressed as:

$$C_{nt} = \frac{1}{m} \sum_{i=1}^m \left\{ \frac{1}{i} \sum_{j=1}^i (NT_j)_i \right\}$$

where (NT_j) is assigned to 1 if direction change of BA_j occurs for a DL_i^{cbade} , otherwise it is 0. If the sequence is unstable for all $(DS_j)_i$ ($j=1,2,3,4,5$) are assigned to 1. So the number for all C_{as} , and C_{nt} s lie between 0 to 1. The zero means, the sequence completely satisfies the constraints, and one means, unstable relationship. For a study, a possible sequence $seq = \{c - b - a - d - e\}$ is considered. In this study each set of possible assembly directions are represented in the format DS^k_{cdabe} ($k=c, b, a, d, e$) and these are:

$$DS^c_{cbade} = \{\phi\}, DS^b_{cbade} = \{\bar{x}\}, DS^a_{cbade} = \{\bar{x}, z, \bar{z}\}, DS^d_{cbade} = \{\bar{x}, z, \bar{z}\}, DS^e_{cbade} = \{\bar{x}, z, \bar{z}\}$$

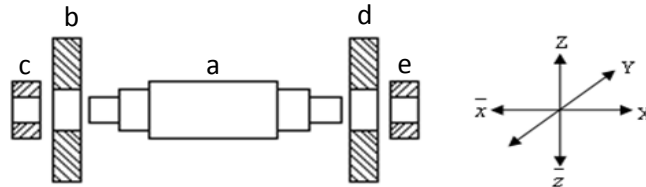


Fig-4.1: Parts of grinder

The order list of possible assembly directions corresponding to the assembly sequence “c – b – a – d – e” can be obtained.

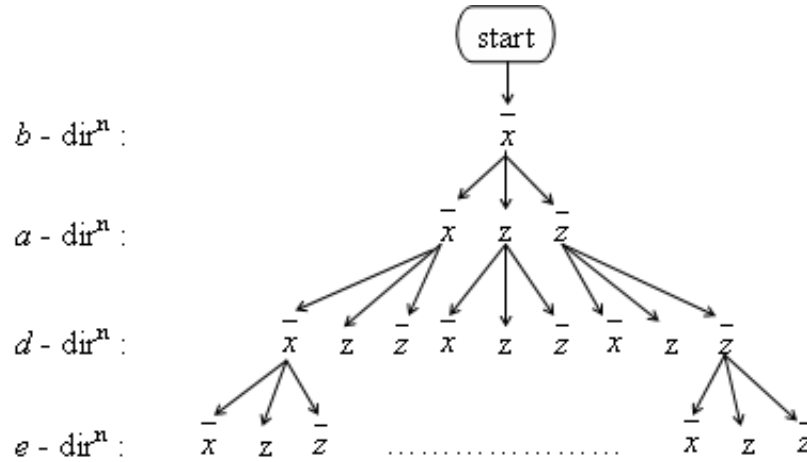


Fig-4.2 (a)

$$DL_1^{cbade} = \{\bar{x}, \bar{x}, \bar{x}, \bar{x}\}, DL_2^{cdade} = \{\bar{x}, \bar{x}, \bar{x}, \bar{z}\}, \dots, DL_m^{cbade} = \{\bar{x}, \bar{z}, \bar{z}, \bar{z}\}$$

Fig-4.3 (b)

Fig-4.2(a) Hierarchical tree structure of possible assembly direction, Fig-4.2 (b) Ordered list of possible assembly direction.

The ordered lists DL_i^{cbade} ($i = 1, 2, \dots, m$), given by the equation

$$DL_1^{cbade} = \{d_1^c, d_1^b, d_1^a, d_1^d, d_1^e\}$$

$$DL_2^{cbade} = \{d_2^c, d_2^b, d_2^a, d_2^d, d_2^e\}$$

...

...

$$DL_m^{cbade} = \{d_m^c, d_m^b, d_m^a, d_m^d, d_m^e\}$$

The energy matrix is having the dimension of $5n \times 5n$ matrix. Each cell represent as the energy between two elements. In this study, each energy cell has been calculated and applied in ACO method.

4.6 Applying ACO TO ASG

According to Marco Dorigo the basic concept of an ant colony algorithm is to solve combinatorial problems within a reasonable amount of time. In this study, disassembly sequence is represented as disassembly operations (DO). The sequence considered the no of parts presented and the direction in which it is to be disassembled i.e. $DO = (n, d)$, where ‘n’ is the

number of components and 'd' is the direction of disassembly. In this paper, each component is having five possible DOs, i.e. (n, +x), (n, +y), (n, +z), (n, -x) and (n, -y). If the assembly consists of 'n' number of parts, then the disassembly operation is having '5n' number of nodes.

The disassembly operation is assigned to '1' if there is interference in that direction, otherwise '0'. That means if DO=1, it cannot be disassembled from the product. In the modified ACO algorithms, a pheromone ' τ_{ij} ' is used as the share memory of all ants and simultaneously it considers the energy matrix which is to be minimized. The pheromone ' τ_{ij} ' is updated during the processing. Like the shortage path in TSP, this algorithm also gives the minimum energy path which is to be follow during disassembly. In this study the pheromone is expressed as 5n X 5n matrix as because one of the Z directions is restricted for robotic assembly.

Interference matrix in (+)ve X, Y, Z directions:-

$$DM = \begin{matrix} & e_1 & e_2 & & e_n \\ \begin{matrix} e_1 \\ e_2 \\ \dots \\ e_n \end{matrix} & \begin{bmatrix} I_{11x}I_{11y}I_{11z} & I_{12x}I_{12y}I_{12z} & \dots & I_{1nx}I_{11y}I_{11z} \\ I_{21x}I_{21y}I_{21z} & I_{22x}I_{22y}I_{22z} & \dots & I_{2nx}I_{2ny}I_{2nz} \\ \dots & \dots & \dots & \dots \\ I_{n1x}I_{n1y}I_{n1z} & I_{n2x}I_{n2y}I_{n2z} & \dots & I_{nnx}I_{nny}I_{nnz} \end{bmatrix} \end{matrix}$$

where I_{ijd} is equal to 1 if component e_i interferes with the component e_j during the move along direction +d-axis; otherwise I_{ijd} is equal to 0. The initial disassembly matrix is calculated as:

$$DM = \begin{matrix} & \begin{matrix} a & b & c & d & e \end{matrix} \\ \begin{matrix} a \\ b \\ c \\ d \\ e \end{matrix} & \begin{matrix} \begin{matrix} x & y & z & \bar{x} & \bar{y} & x & y & z & \bar{x} & \bar{y} & x & y & z & \bar{x} & \bar{y} & x & y & z & \bar{x} & \bar{y} \end{matrix} \\ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix} \end{matrix}$$

$$DO_{i,(+d)} = \bigcup_{j=1}^n I_{ijd} \quad \text{And} \quad DO_{i,(-d)} = \bigcup_{j=1}^n I_{jid}$$

$$\begin{bmatrix} DO_{a,x} = 1 & DO_{a,y} = 1 & DO_{a,z} = 1 & DO_{a,\bar{x}} = 1 & DO_{a,\bar{y}} = 1 \\ DO_{b,x} = 1 & DO_{b,y} = 1 & DO_{b,z} = 1 & DO_{b,\bar{x}} = 1 & DO_{b,\bar{y}} = 1 \\ DO_{c,x} = 1 & DO_{c,y} = 1 & DO_{c,z} = 1 & DO_{c,\bar{x}} = 0 & DO_{c,\bar{y}} = 1 \\ DO_{d,x} = 1 & DO_{d,y} = 1 & DO_{d,z} = 1 & DO_{d,\bar{x}} = 1 & DO_{d,\bar{y}} = 1 \\ DO_{e,x} = 0 & DO_{e,y} = 1 & DO_{e,z} = 1 & DO_{e,\bar{x}} = 1 & DO_{e,\bar{y}} = 1 \end{bmatrix}$$

Where U is the Boolean operator OR. The result will be equal to 0 if all the elements involving in the operation are 0. This means the element can be disassembled in that direction. If the DO is equal to 1, the element cannot be disassembled. In this study, the initial feasible disassembly operations are (c, -x) and (e, +x).

4.7 Solution Method

Robotic assembly is a case of combinatorial optimization problem. The problem is similar to Traveling salesman problem i.e. to give the shortest path with minimum cost. Combinatorial optimization problem is a triple (S, f, Ω) , where S is the set of candidate solutions, f is the objective function which assigns an objective function value $f(s)$ to each candidate solution $s \in S$, and Ω is a set of constraints. The solutions belonging to the set of solutions S that satisfies the constraints Ω are called *feasible solutions*. The stable solutions $\tilde{\Omega} \subseteq \Omega$ belong to the feasible solutions. One of the major advantages is that, the optimal solution satisfies all the assembly constraints, objective function and also it is a part of stable solutions $\tilde{\Omega}$.

In ant system, m ants simultaneously build a solution of the ASG. Initially ants are put in first feasible DO. At each construction step, ant k applies a probabilistic state transition rule, called *random proportional rule*, to decide which node visit next.

$$P_d^{(i,j)} = \begin{cases} \frac{[\tau(i,j)]^\alpha [\eta(i,j)]^\beta}{\sum_{u \in C_d(i)} [\tau(i,u)]^\alpha [\eta(i,u)]^\beta}, & \text{if } j \in C_d(i) \\ 0, & \text{otherwise} \end{cases}$$

The heuristic value selected in this study is $\eta(i,j) = \frac{1}{E_{seq}}$.

After all the ants have constructed their tours, the pheromone trails are updated. The pheromone evaporation is giving by $\tau(i,j) \leftarrow (1-\rho)\tau(i,j)$, where $0 \leq \rho \leq 1$ is the pheromone evaporation rate. After evaporation, all ants deposit pheromone on the arcs they have crossed in their tour:

$$\tau(i,j) \leftarrow (1-\rho)\tau(i,j) + \sum_{k=1}^m \Delta\tau_k(i,j)$$

Where m is the number of ants that find the iteration-best sequences and $\Delta\tau^k(i,j)$ is the amount of pheromone ant k deposits on the arcs it has visited. It is given an equation:

$$\Delta\tau^k(i, j) = \begin{cases} \frac{1}{E_{seq}^k(i, j)}, & \text{if } (i, j) \in \text{sequence of ant } k \\ 0, & \text{otherwise} \end{cases}$$

Where, $E_{seq}^k(i, j)$ is the tour energy the k^{th} ant belonging to that tour? During the construction of sequences, local pheromone updating encourages exploration of alternative solutions, while global pheromone updating encourages exploitation of the most promising solutions.

4.8 ACO Algorithm

1. Generate the initial feasible Dos and compute their quantity
2. Set the cycle counter $NC = 1$
3. While $NC < NC_{\max}$
 - a. Place ants on the initial feasible nodes of the DCG
 - b. While each ant has not completed its tour
 - i. Put current DO into sequence of the ant
 - ii. Generate candidate list of the ant and calculate the energy
 - iii. Calculate $p_k(i, j)$ of each candidate
 - iv. Choose next DO j based on energy matrix
 - v. Move the ant to DO j
 - vi. Add the component number of DO j to the tabu list of the ant
 - vii. Locally update PM
 - c. Evaluate all solutions taking into account their reorientations
 - d. Globally update PM using iteration-best solutions
 - e. Update the best sequence of each ant if its iteration sequence is the best one found so far
 - f. Empty the sequence, candidate list, and tabu list of each ant
 - g. Set $NC = NC + 1$
4. Output the reversed best sequence of each ant

The reverse of the output is the optimal assembly sequence generation with inverse directions. The solution may be optimal or near optimal.

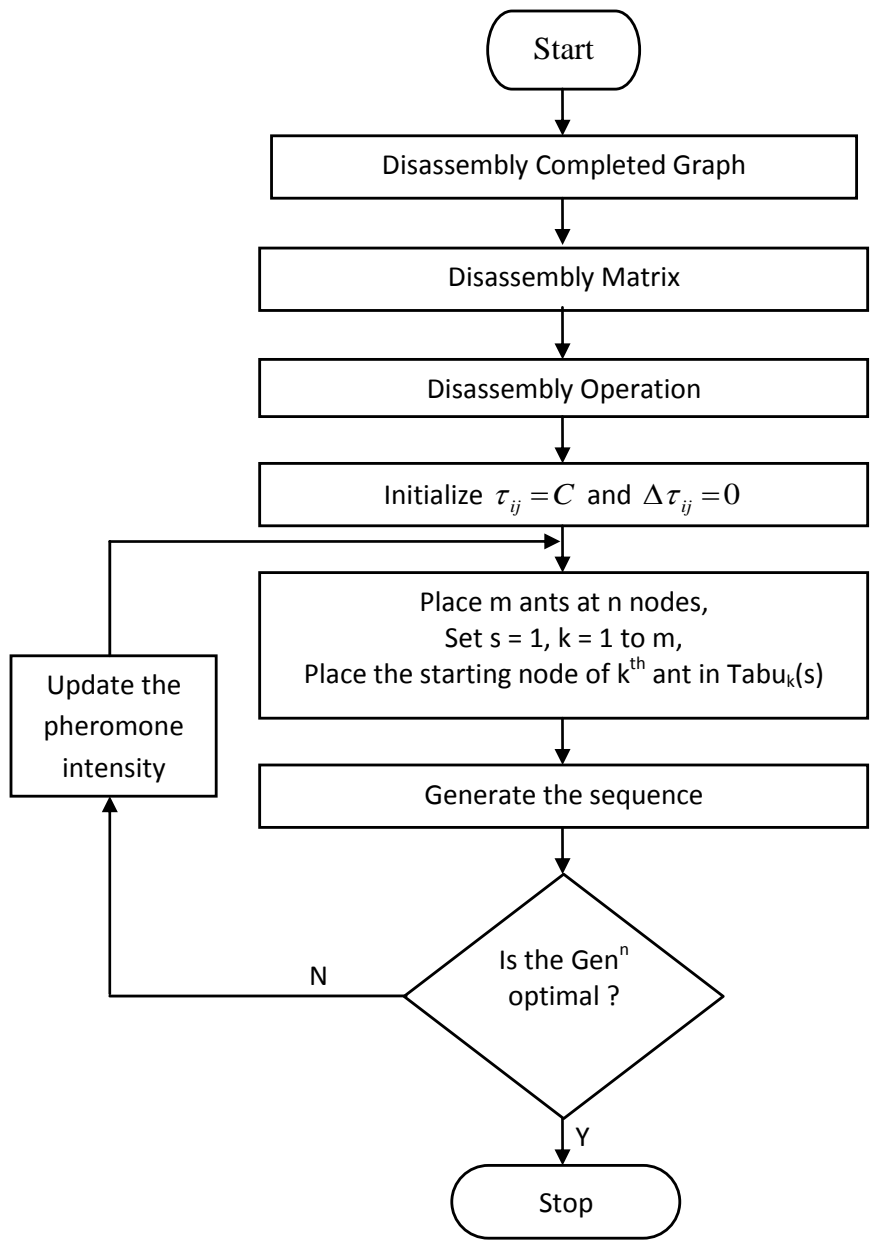


Fig 4.4- Flow diagram of the ACO procedure

4.9 Applying AIS to ASG

The artificial immune system was built on the two principles.

- a) Clonal selection principle
- b) Affinity maturation principle

Each assembly (antibody) has an energy value that refers to the affinity value of that antibody. Affinity value of each antibody is calculated as

$$\text{Affinity } (p) = \frac{1}{E_{Seq}}$$

Where, E_{Seq} is the energy value of an individual assembly. For stable sequence the energy factor is low and for unstable, it is high. The sequence constraint consists of precedence, connectivity relationships. Lower the energy factor higher is the affinity value. The cloning of antibodies is done directly proportional to the affinity function. More clones are generated on higher affinity values or lower energy values.

The affinity maturation principle is defined by two methods;

- Mutation and
- Receptor editing.

In this study two phase mutation has been taken;

- inverse mutation and
- Pairwise interchange mutation.

In the first one, randomly two positions were selected and then inverted. After inverting if the mutated sequence affinity is greater than the original one, then the mutated one is stored. Otherwise, it will go to the pairwise mutation. Here randomly two positions were interchanged. If the affinity value is more than the original one, then it stores the new one. Otherwise, it stores the original one.

In receptor editing, worst percentage of antibodies were eliminated and randomly created antibodies were replaced with them. This mechanism corresponds to new search regions in the total search space.

4.10 AIS algorithm

1. Generate a population of p antibodies (assembly sequence).

For each iteration

- a. Select the sequence in the antibody population
- b. Find out the affinity of each antibody based on energy factor
- c. Cloning process

2. Steps in mutation process

For each clone

- a. Find inverse mutation (generate a new sequence)
- b. Select the new sequence obtained from the inverse mutation
- c. Find the energy factor of the new sequence
- d. If the energy factor(new sequence) < energy factor(clone) then
Clone = New Sequence
Else, do pairwise interchange mutation (generate a new sequence)
 - I. Select the new sequence
 - II. Find the energy factor of the new sequence
 - III. If energy (new sequence) < energy (clone) then
Clone = new sequence
Else, clone = clone, antibody = clone

3. Eliminate worst no of antibodies in the population

- a. Create new antibodies at the same no,
- b. Change the eliminated ones with the new created ones while stopping criteria = false

4.11 Summary

The soft computing technique itself generate the stable assembly sequence in application with number of constraints and optimize the stable sequence to give out the best possible result as needed in assembly sequence.

Chapter-5

RESULT AND DISCUSSIONS

5.1 Overview

The results obtained by using various methods for the products under consideration are presented in the following sections. Three different kinds of approaches conventional technique using PCLG and part instability methods along with directional precedence constraints those are suitable and convenient for assembly sequence generation. 2nd uses anyone of the metaheuristic optimization tool, viz. ACO, to solve the assembly sequence generation. 3rd uses AIS which is computational system inspired by the theoretical immunology.

5.2 Convectional assembly sequence generation

The grinder assembly is considered example to study for inference of the feasible assembly sequence by using the procedure of PCLG and part instability. After applying the PCLG and part instability criteria, the following result are found out. After PCLG no of sequence found is 13, and after putting part instability criteria it reduced to 3.

Seq No.	Sequence Order				
1	a	b	c	d	e
2	b	a	c	d	e
3	d	a	e	b	c

We take the example of grinder assembly to strengthen the methodology. The simulation results of selecting the parameter are taken a value between the domains of 5 to 75.

5.3 Simulation of C_j , C_p C_c

Let the product is composed to n parts and having $5n$ different nodes as disassembly considered in 5 directions except the restricted motion of robot in $-z$ direction. That means, for each part there are 5 different assembly directions.

According that concept, the objective matrix now becomes a size of $5n \times 5n$ nodes. Each node is having a weighted value in connection with other nodes. If the preceding of assembly is approaching towards instability, the value of weighted factor is rising on and vice versa. This means that the lowest selected through iteration means the more is the stable assembly. The assembly constraints C_j , C_p and C_c mentioned in equation are assigned random values from 5 to 75 with the increment of +5. So,

The simulation results are listed in table 5.1

Energy Constants			Cost Constants	
C_J	C_P	C_C	ρ_t	ρ_t
55	45	55	0.5	0.5

The simulation condition for ant parameter on table 5.2

Influencing parameter of pheromone trail		Pheromone Evaporation rate	Base part	Assembly directions	Disassembly directions
α	β	ρ			
1	2	0.25	a	$\frac{x}{y}, \frac{y}{z}, \frac{\bar{x}}{\bar{z}}$	$\frac{x}{x}, \frac{y}{y}, \frac{z}{z}$

5.4 Sample calculation

➤ Select the partial sequence, suppose $(d, (\bar{x})) - (a, (\bar{x}))$.

Step 1: Find-out the precedence constraints of each part. Here it is

$$PC(a) = \{b, d\}, \quad PC(b) = \{\Phi\}, \quad PC(c) = \{b\}, \quad PC(d) = \{\Phi\}, \quad PC(e) = \{d\}$$

Step 2: Precedence index are $\mu_1 = 0, \mu_2 = 1$

$$\text{Step 3: } E_p = C_p \sum_{i=1}^2 (\mu_1 + \mu_2), \quad E_p = 45 \times 1 = 45$$

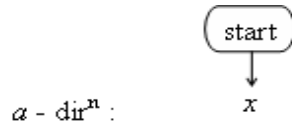
$$\text{Step 4: } l_{da} = \left(d, \begin{pmatrix} o & rc & rc \\ rc & rc & rc \end{pmatrix}, \begin{pmatrix} o & o & o \\ rf & o & o \end{pmatrix}, a \right)$$

Step 5: λ_1 is for the C_d matrix and λ_2 is for the fit-type connection, here $\lambda_1 = 0, \lambda_2 = 0$

$$\text{Step 6: } E_c = C_c \sum_{i=1}^n (\lambda_1 + \lambda_2), \quad E_c = 55 \times 0 = 0$$

Step 7: $DS_{da}^a = \{\Phi\}, DS_{da}^a = \{x\}, BA_1 = \{a\}, S\{BA_1\} = 1 + 2 = 3$

Step 8: Order list :-



$$DL_1^{22} = (x)$$

$m = 1$

Step 9: $C_{as} = \frac{1}{1} \sum_{i=1}^1 \left\{ \frac{1}{12 \times 1} \sum_{j=1}^1 (3) \right\} = 0.25$

Step 10: $NT_1 = 0, C_{nt} = \frac{1}{1} \sum_{i=1}^1 \sum_{j=1}^1 (0) = 0$

Step 11: $C_J = 55$

$J = \rho_s C_{as} + \rho_t C_{nt}$ if it stable or assembly exist , otherwise '1'

$$J = \rho_s C_{as} + \rho_t C_{nt}$$

$$J = (0.5 \times 0.25) + (0.5 \times 0) = 0.125$$

$$E_J = C_J \times J = 55 \times 0.125 = 6.875$$

Step 12: $E_{seq} = E_P + E_C + E_J = 45 + 0 + 6.825 = 51.875$

➤ **Now, Partial sequence is (b,(z)) – (c,(y))**

Step 1: $PC(a) = \{b, d\}, PC(b) = \{\Phi\}, PC(c) = \{b\},$

$$PC(d) = \{\Phi\}, \quad PC(e) = \{d\}$$

Step 2: $\mu_1 = 0, \mu_2 = 0, E_P = C_P \sum_{i=1}^2 (\mu_1 + \mu_2),$

$$E_P = 45 \times 0 = 0$$

Step 3:
$$l_{bc} = \left(b, \begin{pmatrix} o & o & o \\ rc & o & o \end{pmatrix}, \begin{pmatrix} o & o & o \\ o & o & o \end{pmatrix}, c \right)$$

Step 4: $\lambda_1 = 1$ for $C_d, \lambda_2 = 1$ for $f_d,$

$$E_C = C_C \sum_{i=1}^n (\lambda_1 + \lambda_2), \quad E_C = 55 \times 2 = 110$$

Step 5: $C_J = 55$

$J = 1$, if the assembly is unstable, otherwise

$$J = \rho_s C_{as} + \rho_t C_{nt}$$

But here (b,(z)) – (c,(y)) relationship is unstable, so $J = 1$

$$E_J = C_J \times J = 55 \times 1 = 55$$

Step 6: $E_{seq} = E_P + E_C + E_J = 0 + 110 + 55 = 165$

5.5 Result of AIS for assembly sequence

The energy values are calculated from the objective function. The inverse of these are the affinity. The values for grinder assembly are

Sequence Order					Energy	Affinity
a	b	c	d	e	54.375	0.0183908
b	a	c	d	e	165	0.00606061
d	a	e	b	c	51.875	0.01927711

After doing 750 iterations, we'll get an optimal solution of assembly sequence. One which has min energy of sequence is optimal assembly sequence. A lot of constraints are applying for the generating optimal stable assembly sequences. The choices of generating optimal solutions are drastically reduced.

5.6 Discussion:

The approach is able to produce result or better than those generated by other algorithms that are representative of state-of-art in evolutionary objective optimization. The present approach uses an affinity measure to control the amount of mutation be applied to the antibodies. Affinity here is defined as non-dominance and feasibility. The result shows that the evolved method could be effectively utilized to generate stable assembly sequences.

Chapter-6

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