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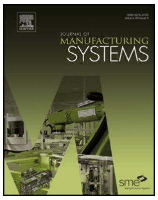

Technical Paper

Fixture layout optimization in multi-station assembly processes using augmented ant colony algorithm

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ABSTRACT

In recent years, ant colony algorithms (ACAs) are used to solve the fixture layout optimization problem for a single workpiece machined in a single manufacturing stage. Assembly processes, however, are normally multi-station manufacturing processes, whose fixture layout optimization problem is much more complex. The purpose of this research is to develop an augmented ACA based on continuous optimization methods to optimize fixture layouts for 2D rigid parts in multi-station assembly processes. The algorithm is augmented by changing the mutation step size in the global search, the limiting step size in the local search, the new pheromone value's expression of the ant, etc. The augmented ACA is used to properly select the coordinates of two locating pins to minimize the sensitivity index. A case about three-station automotive side aperture assembly processes is studied to verify the effectiveness of the augmented ACA. The results show that the augmented ACA can generate more accurate results with a faster rate of convergence and a better stability than the basic ACA. This work could also be applied to fixture layouts optimization problems for 3D rigid parts in multi-station manufacturing processes.

1. Introduction

For a new product development, fixture design is one of the most important design issues during the process design. In automotive industry, assembly processes are representative multi-station panel assembly processes, where fixtures are used widely to determine the locations of parts and/or subassemblies as well as to provide physical support. Fixture design greatly influences the final product quality and dimensional accuracy in multi-station assembly processes. A good fixture layout design can reduce process sensitivities to external variations.

In multi-station panel assembly processes, an n-2-1 fixture layout is generally used, which is represented by $\{P_{4\text{-}way}, P_{2\text{-}way}, NC_i, i=1, 2, \ldots, n\}$, including two locating pins and n net contact (NC) blocks to define the position and orientation of a part (or subassembly). A typical 3-2-1 (i.e., $n=3$) fixture is shown in Fig. 1, where P_3, P_4 and P_5 are NC blocks, P_1 and P_2 are the 4-way pin and 2-way pin, respectively. In X–Z plane, the two locating pins, $P_{4\text{-}way}(P_1)$ and $P_{2\text{-}way}(P_2)$, restrict three degrees of freedom of a part, in which P_1 restrains part motions in both X-direction and Z-direction, and P_2 restrains that in Z-direction. The three NC blocks restrict remaining degrees of freedom of a part in Y-direction. A global motion of a part (or subassembly) is caused by the product dimensional variation from P_1, P_2, while local deformations can be caused by the variation from P_3, P_4, P_5. So the variations from locating pins and NC blocks are generally different. For a 2D model, we only consider the changes induced by the locating pins, and assume that the NC blocks are not the main source of change.

The above-mentioned 3-2-1 fixture is used on every station of a multi-station process to guarantee the product dimensional accuracy. For multi-station assembly processes, the representation of the fixture layout can be found in [2,3]. In Fig. 2, $P_1, P_2, \ldots, P_6$ are called *Principal Locating Points* (PLP). In multi-station processes, a fixture layout can be expressed by these PLPs: $\{\{P_1, P_2\}, \{P_3, P_4\}\}_I \to \{\{P_1, P_4\}, \{P_5, P_6\}\}_{II} \to \{\{P_1, P_6\}\}_{III}$

For multi-station manufacturing processes, there has been much research on the propagation model, dimensional variation, and diagnosis problem, which can be found in [1,4–9].

In recent years, much research is related to optimization algorithm for the manufacturing optimization problems. The research of [10] is the first application of immune algorithm to the

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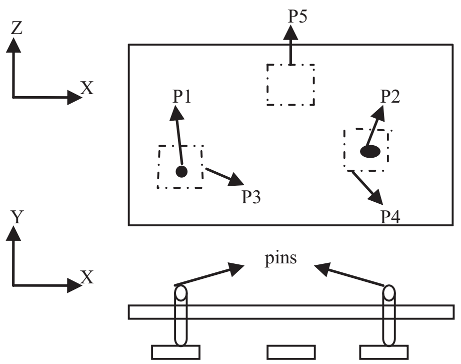
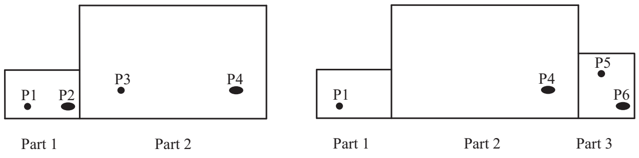
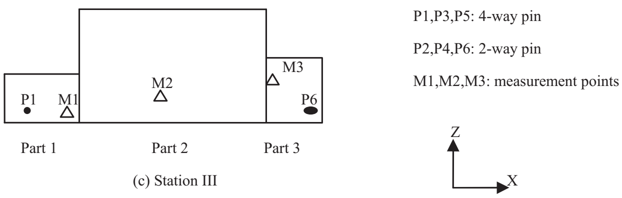


Fig. 1. Top and side views of 3-2-1 fixture layouts.
Adapted from [1].



(a) Station I

(b) Station II



(c) Station III

Fig. 2. Assembly processes.
Adapted from [15].

optimization of machining parameters. Then Yildiz [11] extended the work of [10], combined it with a hill climbing local search algorithm, and firstly applied it to the shape design optimization problems. On the basis of immune algorithm, Yildiz [12] introduced a new hybrid optimization approach by combining it with simulated annealing algorithm to optimize the solution of engineering problems. Durgun [13] and Yildiz [14] respectively used the Cuckoo Search Algorithm (CS) to solve the structural design optimization problems of vehicle components and select optimal machining parameters in milling operation, and compared the results with those obtained by hybrid immune algorithm and hybrid particle swarm algorithm.

Because of the inter-station complex connection of variation propagations, it is a challenge to develop a valid algorithm for fixture layout optimization in multi-station manufacturing processes. For 2D rigid parts, Kim and Ding [2] were the first to solve this issue considering lap joints. They used the augmented basic Exchange Algorithm (EA) as the optimization method to determine the PLPs' distribution. Li et al. [3] integrated layout design and tolerance allocation for a multi-station sheet metal assembly, where the gradient-based optimization algorithm was applied to solve the problem of tolerance allocations and the neighborhood cultivation genetic algorithm (NCGA) was applied to generate the Pareto set. The extension of [2] in designing fixture layouts for a product family can be found in [15]. Izquierdo et al. [15] presented a methodology for a product family to achieve robustness of the fixture layout design via an optimal distribution of the locators in a multi-station assembly system. Tian et al. [16] presented the genetic algorithm (GA) to design a robust fixture layout for multi-station assembly processes. Chaipradabgiat et al. [17] developed a methodology for adjusting fixture locators to minimize the cost of total productions in multi-station assembly systems. Huang et al. [18] used Sequential Space Filling Methods (SSFM) to design the fixture layout's robustness for multi-station assembly processes. A sequential subspace searching technique was developed based on space filling methods, comparing with direct space filling and GA.

For single stage fixture layout optimization, Krishnakumar and Melkote [19] presented a fixture layout optimization approach, using GA to obtain the optimal fixture layout which can minimize the machined surface's deformation of the workpieces. Li and Melkote [20] presented an optimal synthesis approach in which clamping force and fixture layouts are connected, and the sequential quadratic programming optimization method was applied. Prabhaharan et al. [21] and Padmanaban et al. [22] used an ant colony algorithm (ACA) to obtain the optimal fixture layout, then minimized the elastic deformation of machined surfaces, and compared it with GA. Padmanaban et al. [23] applied ACA based on continuous optimization methods to optimize the machined fixture layout, making the deformation of the part being minimized, and compared it with ACA based on discrete optimization methods of [22].

Through the aforementioned research, we can conclude that:

1. GA and ACA have a wide range of applications for the fixture layouts optimization problems;
2. ACA based on optimization methods achieves better solutions at a faster convergence rate than the GA solutions;
3. The ACA based on the continuous fixture layout optimization method obtains better solutions than the ACA based on the discrete optimization method.

But how to use ACA to solve the problem of the fixture layout optimization for multi-station assembly processes, has not yet been found. In this research, the objective is to develop an effective and fast algorithm for fixture layout optimization in multi-station manufacturing processes.

We propose an augmented ACA based on a continuous optimization method to solve the fixture layout optimization problem of 2D rigid parts in multi-station assembly processes. Firstly, three assumptions are given, which are showed as follows:

(i) A generic 3-2-1 fixture layout is used;
(ii) 2D rigid parts are selected;
(iii) Lap joint is considered.

Secondly, three aspects of work will be finished:

(i) A state space model of multi-station assembly processes is used;
(ii) A sensitivity index, which connects fixture layout design with the dimensional accuracy of final products, is derived;
(iii) An augmented ACA is developed to select the location of PLPs to minimize the sensitivity index.

In this paper, four aspects are changed to augment the ACA based on continuous optimization methods of [23]:

1. In each iteration, arranging all the fixture layouts on the basis of the ascending order of the corresponding objective function value $S_{\max}$ before the global search.
2. Changing the mutation step size Δ in the global search.
3. In the next iteration, changing the expression of the new pheromone value of the ant for each fixture layout.
4. Changing the limiting step size $L_s = K_1 - A \times K_2$ in the local search by changing K_1 and K_2 from a fixed value to a variable value with certain regularity.