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Optimal design of fixture layout in a multi-station assembly using highly optimized tolerance inspired heuristic

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ABSTRACT

The multi-station assembly (MSA) process requires auxiliary devices such as fixtures and clamps to accurately locate and firmly hold the workpiece in a desired position. Improper positioning of these fixtures and clamps affects the dimensional integrity of final product. This study determines the optimal design of fixture layout that minimizes the product dimensional variations caused by the manhandling and aging of auxiliaries. In order to model variation propagation from one assembly station to another in the MSA, a state space model is employed. Further, an E-optimality based sensitivity criterion is proposed to mathematically formulate and measure the quality of the fixture layout design. In order to solve the mathematical formulation, a highly optimized tolerance inspired heuristic is proposed. The proposed approach takes its governing traits from local incremental algorithm (LIA) which was initially exploited to maximize the design parameter (yield) in the percolation model. LIA analogous to the evolution by natural selection schema, assists in suitably exploring the search space of the underlying problem. The assembly of Sports Utility Vehicle side frame has been used to illustrate the concepts and test the performance the proposed solution methodology. Further, robustness of the proposed heuristic is demonstrated by comparing its results with that of obtained from Basic Exchange Algorithm used in the literature.

1. Introduction

Among automotive industries, dimensional integrity an indicator of a high quality product, is a crucial factor in winning the market amid the acute competition. This fact has driven the organizations to design their assembly systems with higher precision to manufacture products with greater dimensional integrity. Fixture failures are recognized as the major contributor (approximately 72%) among all root causes of dimensional variation in an assembled product [1–3]. In the multi-station assembly (MSA) process, operations involve unification of two or more than two panels/sub-assemblies at more than one workstation. To provide physical support to a panel/subassembly, a 3-2-1 principle fixture layout design is generally employed. As illustrated in Fig. 1, 3-2-1 layout comprises of two locating pins and three net contact (NC) blocks. Locating pins are of two types: 4-ways pin (pin-hole locator, $P_{4\text{-ways}}$) to restrict motion of a panel in X-Z plane and 2-ways

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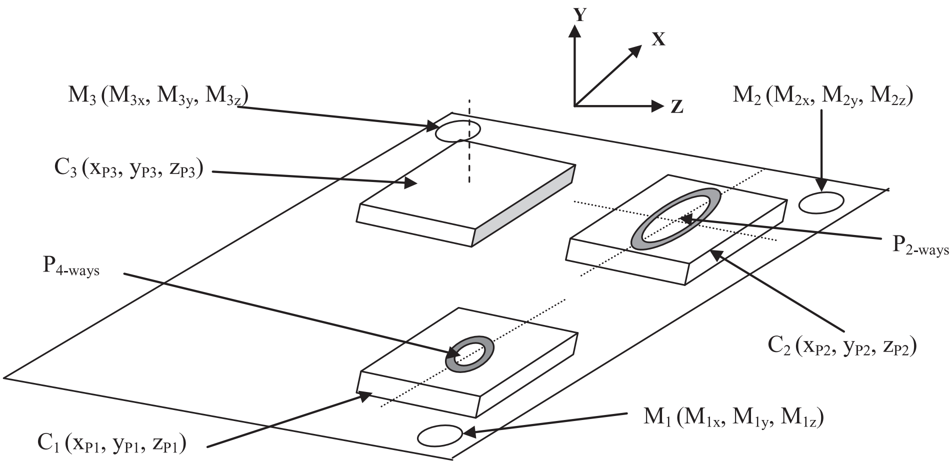

Fig. 1. Generic 3-2-1 fixture layout design for rigid parts.

pin (pin-slot locator, $P_{2\text{-ways}}$) to prevent movement in *Z*-direction. Synchronization of these two pins restrains the rotation and translation motion of the panel in *X-Z* direction during assembly process. In addition, two principal locating points (PLPs) on each panel/sub-assembly restrict its movements in *X* and *Z* directions. Three NC blocks are used to constrain deformation in *Y*-direction. The current paper mainly deals with assembly process of rigid bodies in 2-D and deformation in *Y*-direction is a topic for future research.

The complexity of fixture layout design problem is illustrated by considering Sports Utility Vehicle (SUV) side frame, which comprises of four panels viz. A-pillar, B-pillar, rail roof side panel and rear quarter panel (see Fig. 2). It is assumed that only two workpiece (panels or subassembly) can be assembled at each station. First two panels are assembled at station 1. Then, sub-assembly is passed on to the second station where it is assembled with the third panel. Fourth panel is assembled with the incoming sub-assembly (from station 2) on third station. Subsequently, assembled product is transferred to the fourth station where variations of product measurement points $[M_1–M_{10}]$ are collected. Stepwise assembly of four panels at various stations can be represented in terms of PLPs as illustrated in Fig. 2. Fixture layout in Fig. 2 generically refers to an arrangement of 8 locators (2 locators on each panel). Assembly process can also be represented in terms of processing sequence as follows:

$$\{(P_1, P_2)^p, (P_3, P_4)^p\}^1 \Rightarrow \{(P_1, P_4)^s, (P_5, P_6)^p\}^2 \Rightarrow \{(P_1, P_6)^s, (P_7, P_8)^p\}^3 \Rightarrow \{(P_1, P_8)^s\}^4,$$

where superscripts (1, 2, 3, and 4) indicate station number and $P_1, P_2 \ldots .P_8$ stand for pair of locators employed. For example at station 3, the sub-assembly "A pillar + B pillar + rail-roof side panel" is restrained by locator pair P_1 and P_6 while new panel "rear quarter" is located by locator pair P_7 and P_8. Superscript '*p*' and '*s*' are used to indicate that locator pair is used to restrain the movement of a panel or a subassembly respectively.

Locators may be broken, worn, loose, or bent due to daily operations, which may result in depreciated product dimensional integrity during MSA. Moreover, variation generated at one station propagates to downstream stations in assembly line. In discrete part manufacturing, optimal design of fixture layout involves searching for position of PLPs such that the effect of these fixture variations on final product quality can be minimized. There can be infinite choices (candidate locations) to place locators in the continuous search space within each panel. In order to eliminate infinite possibilities, search space is reduced by discretizing each panel. In the current study, discretization distance is equal to the diameter of locator (10 mm). Based on the dimensions of each panel, the number of candidate locations to put one locator are $N_1 = 697$, $N_2 = 1038$, $N_3 = 429$, $N_4 = 6189$ [4]. It is evident that even small number of panels can generate a large number of alternatives for fixture layout design. Therefore, efficient method is needed to identify the optimal fixture layout for MSA.

Introduced by Carlson and Doyle [5], Highly Optimized Tolerance (HOT) is inspired by the behavior of biological organism and advanced engineering technologies. Tradeoffs between yield and resource cost lead to the unpredictable event sizes in systems which are optimized by engineering design based frameworks. HOT is applied to study the behavior of complex systems in an uncertain environment. The characteristics associated with systems at HOT state are *power laws* and robustness against uncertainties, design flaws and rare perturbations. A HOT inspired heuristic is introduced in this paper to identify the optimal fixture layout design in MSA. In proposed heuristic, power law is applied in estimating the dynamic probability of placing locators on each panel. Furthermore, probability of placing a locator at the gravitational center (GC) is assumed zero and correspondingly candidate locations within each panel have assigned probabilities according to their Euclidean distance from GC. The assembly of a side frame has been used to illustrate the concepts. Further, robustness of heuristic is demonstrated by comparing its results with that of obtained from Basic Exchange Algorithm used in the literature.

The rest of the paper is organized as follows, relevant literature pertaining to fixture layout is detailed in the Section 2. State space model for modeling the variation propagation is discussed in Section 3. Background of HOT and