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Development of locating system design module for freeform workpieces in computer-aided fixture design platform☆

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ABSTRACT

Development of an efficient computer-aided platform for fixture design requires intelligent algorithms to be developed as decision making tools for different designing functions. Locating system design is among the representative fixture design functions which are in need of such intelligent algorithms to implement their complicated roles. This rather unmet need has already hampered the development of automated computer-aided fixture design systems. The authors have proposed an analytical and algorithmic locating system design procedure as a part of their continuous effort to establish a PythonOCC-based platform, which is the subject of the present paper. In order to surmount the geometrical restrictions, workpieces with freeform geometries of NURBS types have been taken into consideration for locating system design. Constraining workpiece's degrees of freedom, capacity of locating surfaces in bearing the machining loads, and ease of workpiece loading and unloading into and from the fixture together with some other checking rules constitute the characteristic criteria of the proposed analytic procedure. The proposed procedure has been employed for several workpieces with freeform geometries to evaluate its efficacy.

1. Introduction

Fixture design is accomplished in four stages of setup planning, fixture planning, unit design and verification [1]. Among these stages, fixture planning is defined as the collection of activities implemented for determination of fixture general requirements at each setup such as design of locating, clamping and supporting systems for the workpiece regardless of its geometry (polyhedral or freeform) [2]. It means that the fixture design principles may be applied to the freeform workpieces similarly to the polyhedral ones. Fixture planning for workpieces with freeform geometry requires more complicated treatment due to the inconsistent surface normal vectors at different points on the workpiece. Pin-array configuration has been widely employed in fixture design of freeform workpieces by considering pins conformability with the workpiece surfaces [3].

Computer aided design of fixtures requires efficient mathematical tools especially for the freeform workpieces. The screw theory has been extended by Roth and Ohwovoriole [4] to fixture design activities. They used the concept of contrariety, reciprocity and repelling conditions between the screws in fixture design. These screws may be employed for theoretically modeling of locators, clamps and supports. Chou et al. [5] and also Marin and Ferreira [6] used the screw theory for automatic determination of the locating and clamping points for polyhedral workpieces. In the study carried out by Martin and Ferreira, the disturbance twists were applied to the workpiece and projected on the locating surfaces assumed to be pre-known. By dividing the locating surfaces into the repelling and contrary regions, the poses of the best locators were chosen by considering contrary condition to the maximum number of disturbance twists. The suggested model in [6] was implemented in [7] for benchmarking of the CAFD platform. In the present study, the use of screw theory for locating system design is extended to workpieces with freeform surfaces.

Different optimization techniques have also been used in fixture design at different stages, including in the present study. Wang et al. [8] optimized the poses of locators with objective function as the maximum positioning accuracy, workpiece positioning repeatability and keeping workpiece stability in the designed fixture. Clamping poses were also optimized by minimizing the clamping force intensities at the clamping points. A 2D-section of an airfoil surface of turbine blade was employed as case study to evaluate the capabilities of the suggested method. Pelinescu and Wang [9] suggested a methodology for calculation of the locating and clamping positions with the objective of maximum positioning accuracy, total restraint and minimum force intensity at the contact points between workpiece and fixture elements. Kulankara et al. [10] used simultaneous optimization of locating layout and

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Nomenclature

Symbol	Description
A_{tri}	Area of triangle constructed by the base locators
BI_i	Machining load bearing index of locator i
$(EL_{max})_i$	Maximum edge length of the projected ith candidate surface
$\mathbf{EV_i}$	Characteristic vector of ith locating surface
$\mathbf{F_M}$	Resultant machining force
f_n, f_{t_1}, f_{t_2}	The components of reaction force at the locators along the normal direction, and along the first and the second tangential directions
$\mathbf{G_w}$	Workpiece center of geometry
$\overline{\mathbf{G}}_\mathbf{w}$	Projected workpiece's center of geometry on the base locating surface
$\mathbf{g}$	Gravity vector
$(IV_4)_{WLD}, (IV_5)_{WLD}$	Degree of interference between $\overline{\mathbf{WLD}}$ and side locators
$(IV_{st})_{WLD}$	Degree of interference between $\overline{\mathbf{WLD}}$ and stop locator
k	Distance of M_t to $\overline{G}_w$
$\mathbf{L}_i$	ith locating vector
LRM	Locator's relationship matrix
M_1	Projected edge length control factor
$\mathbf{M}_t$	Center of virtual area created by three base locating points
$\mathbf{N_i}$	Surface normal vector at ith locating point
$\mathbf{N_{ij}}$	The ith surface's normal vector at jth locating point
$\mathbf{N_b}$	Normal vector of the virtual triangular base surface at M_t
$\mathbf{N_s}$	Average normal vector of side locating surface
$\mathbf{N_{st}}$	Normal vector of the candidate surface at the potential stop locating point
n	Quantity of the surface mesh nodes
P_1	The first coefficient in the priority analysis
P_2	The second coefficient in the priority analysis
P_3	The third coefficient in the priority analysis
S_1	Score of the side locating candidate surfaces for the first basic rule
S_2	Score of the side locating candidate surfaces for the second basic rule
S_3	Third score of the candidate side locating surfaces
S_4	Score of the stop locating candidate surfaces for the first basic rule
S_5	Score of the stop locating candidate surfaces for the second basic rule
S_6	Score of the stop locating candidate surfaces for the third basic rule
$\overline{\mathbf{WLD}}$	Workpiece loading direction
(x_A, y_A, z_A)	Coordinates of the first base locator
(x_B, y_B, z_B)	Coordinates of the second base locator
(x_C, y_C, z_C)	Coordinates of the third base locator
$\mathbf{X}_M$	Resultant machining load axis vector

clamping force intensity on the basis of a repetitive method using genetic algorithm. Vallapuzha et al. [11] compared the applicability of different pseudo-gradient and GA-based optimization methods on fixture layout design from viewpoints of functionality, efficiency and result quality. An optimization method was suggested by Kong and Ceglarek [12] for reconfiguring the designed assembly fixture for the new workpieces with similar geometry. Jiang et al. [13] suggested an algorithm for determination of positioning accuracy in checking fixtures. A multi-objective optimization method was developed based on 3-2-1 locating principle with objective functions of positioning accuracy, workpiece stability and deterministic locating conditions. A model was developed by Xiong et al. [14] for optimization of locating positions in flexible aerospace workpieces aimed at minimization of the total and partial workpiece elastic deformation near the active machining regions. The GA optimization method was combined with FEA to calculate the workpiece elastic deformations.

The volume of calculations in the design of locating and clamping systems increases by switching from polyhedral to freeform workpieces. Nategh [15] reported several heuristic and innovative fixture design methods for freeform workpieces, such as pin-array configuration, using smart alloys in fixture structure, swivel jaws, string or wires for workpiece gripping, etc. In research reported by Afzeri [16], hybrid GA and PSO based optimization technique was suggested for determination of the best points at which the pins may be applied to the workpiece surfaces. The initial configuration of pins was obtained from GA method with objectives of the minimum workpiece deformation and sliding on the pins. In a comprehensive study, pin array method was incorporated in fixturing of workpiece with freeform geometry with the objective of maximum conformation between the workpiece and locators [17]. The quantity, position and dimension of pins beside the clamping force intensity were optimized by assuming the workpiece surfaces as Bezier patches. Yeung and Chen [18] optimized the positions of locators on the freeform workpiece using genetic algorithm and generalized locating matrix as fitness function. The results were verified for achieving the deterministic locating conditions. A feature-based method was suggested by Zhou et al. [19] to design fixture for the freeform workpieces. Nategh and Parvaz [20] reported an algorithmic procedure for design of clamping system for workpieces with freeform geometry. The method was developed on the basis of three criteria including the positive reaction force on the locators with certain intensity, minimum quantity of clamps and stability of the workpiece under its weight and application of the clamping forces. In [21], research has been conducted for optimizing the N-2-1 locating system for non-ideal flexible sheet metal part by considering the variations of workpieces in the production batch. In an attempt to virtually mounting of flexible workpieces in the inspection fixture, Abenhaim et al. [22] suggested a virtual fixture without the main drawbacks of the previous researches. In this regard, the workpiece point cloud was mapped to the nominal CAD model through embedding the information extracted from finite element analysis to the constrained boundary displacement optimization model with the objective functions of minimizing the distances between the points at unconstrained regions, keeping the distance between the constrained regions and limiting the reaction forces in specific intervals. Yang et al. [23] proposed an efficient locating layout optimization concept which produced sample set from few FE calls and by inter-relating this sample data set to the workpiece deformation through kriging surrogate model, the optimum fixture layout was calculated based on the N-2-1 schema by application of cuckoo search algorithm. Li et al. [24] proposed a flexible fixture based on the controlled motor-driven modular elements for flexible workpieces with introducing the follow-up support strategy which was similar to concept of the moving locator introduced in [14]. Several researches have been recently reported for optimization of the fixture layout for flexible workpieces through different optimization techniques such as [25] and [26]. More recently, Calabrese et al. [27] suggested an optimization-based model for maximization of the fixture performance in machining of thin-walled workpieces which manipulates the topology of fixture into the solid lattice structure. The objective function was defined as maximization of fixture stiffness during