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Optimization of machining fixture layout for tolerance requirements under the influence of locating errors

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Abstract

Dimensional accuracy of workpart under machining is strongly influenced by the layout of the fixturing elements like locators and clamps. Setup or geometrical errors in locators result in overall machining error of the feature under consideration. Therefore it is necessary to ensure that the layout is optimized for the desired machining tolerance for a given deviation in the set up or geometry of the locator. Also, the locator layout should be capable of holding the workpart in a unique position during machining thus providing deterministic location. This paper proposes a Genetic Algorithm (GA) based optimization method to arrive at a layout of error containing locators for minimum machining error satisfying the tolerance requirements and providing deterministic location. A three dimensional workpiece under the 3-2-1 locating scheme is studied. Results indicate that by optimally placing the error containing locators the geometric error component of the machining error can be substantially reduced thus enabling compliance to overall dimensional requirements.

Keywords: Machining error, optimal layout, locator error, genetic algorithm

1. Introduction

Fixtures form an integral part of the manufacturing process and are required to hold the workpiece in the desired position. The fixture design should aim at restraining unwanted movement of the workpiece under the action of cutting forces throughout machining. Dimensional accuracy of the machined part thus depends on the design of the locators and the layout and can contribute up to 20-60% of the overall machining error of the workpiece (Qin, 2008). The fixture should be capable of holding the workpiece in a unique position for machining. This condition is called deterministic location. Asada and Andry (1985) used the kinematic model and concluded that a full rank Jacobian matrix is the necessary condition for deterministic positioning of the workpiece. They also derived the condition for attachability and detachability of the workpiece within a fixture.

Cai *et al*. (1997) used a variational method for achieving robust fixture configuration. A non linear programming method was used with an objective of minimizing the positional error of the workpiece resulting from source errors at the locators. This work considered the requirement for deterministic location but did not present a model for the analysis of machining error on a required feature. Choudhuri and De Meter (1999) presented a model to relate datum establishment errors to locator geometric variability. The work studied the effect of given locator errors on the variation of machining feature under a particular locating scheme. Again, deterministic location was not addressed and the effect of locator positions on the resultant machining error was not discussed.

Rong *et al*. (2001) used three different approaches of locating and analyzed the positional variation of locating points resulting from the error of the locators and the locating features. The work however did not address the issue of deterministic location. Song and Rong (2005) discussed the criteria for the locating completeness. Some researchers optimized the clamping force (Li and Melkote,2001 a) or clamping sequence (Raghu and Melkote, 2004) to minimize the workpiece positional error. (Li and Melkote, 2001 b) optimized the fixture layout to minimize the workpiece error.

Since the workpiece is evaluated by its compliance to the specified tolerance, influence of locator errors on the required machining tolerance received much attention in recent years. For example Wang (2002) studied the effect of fixel errors on the tolerance of critical dimensions. This work suggested employing a D optimality model to obtain an optimal layout. Marin and

Ferreira (2003) discussed the effect of deterministic locator errors on profile tolerance of machined parts. Qin *et al*. (2006) discussed an optimization methodology to minimize the workpiece positional variation. However machining error is not discussed. The same authors (2007) presented a method for locating design based on the degrees of freedom constrained by the layout. Cases of complete, partial over and under over locations were discussed. Wang *et al*. (2007) analyzed the different error components of the workpiece surface. However this study did not discuss the effect of locator layout on machining error . Evolutionary techniques for solving optimization problems have been found to have a higher probability in finding the global optimum values compared to traditional techniques. GA is one such technique that finds increased use in solving optimization of locator layout problems. The task is to arrive at a particular layout of fixture elements that provides the minimum error on the workpiece (Kaya, 2005; Krishnakumar and Melkote, 2000; Padmanaban and Prabaharan, 2008). Simple two dimensional cases are studied in these three works. The way of correlating the layout optimization procedure to the tolerance on critical machining features on the workpiece is not discussed. Chen *et al*. (2007) optimized the locator layout to control the deformation of a workpiece. But geometric errors of locators were not considered.

While the above mentioned studies have provided important and extensive concepts of fixture design they have one or more limitations such as not addressing the effect of locator geometric errors on overall machining error, condition for deterministic location and correlation of layout optimization with the critical machining feature. Most of the above works employed traditional optimization methods that may not yield the global optimum results.

Since the final machining accuracy of the workpiece depends on the correctness of the locators it is essential that the locators are machined to the required accuracy and set up without any errors. However it is possible that errors are present in the form of dimension or set up of the locators which will be transferred to the workpiece thus causing deviation from the required dimension. Effect of locator error is comparable to the workpiece elastic deformation in case of low elasticity work parts. In the case of a rigid, bulky workpiece the locator error is much more predominant. Hence the locator layout is to be designed optimally so as to minimize the effect of the locator errors on the final machining accuracy of the workpiece.

In this paper, a GA based optimization of locator layout is attempted considering the geometric errors of locators satisfying the conditions of tolerance requirements on the critical machining feature while ensuring deterministic location.

Rest of the paper is organized as follows. The source errors are reviewed in Section 2. Section 3 gives a brief account of deterministic location and its requirements. Concepts of GA and its application to the present work are discussed in Section 4. Section 5 presents the numerical illustration of the case studied. Results are discussed in Section 6. Major conclusions drawn in the study are presented in Section 7 of the paper.

2. Source errors and resultant errors

2.1 Workpiece positional error

Fixture elements (locators and clamps) are required to hold the workpiece in the desired position throughout the machining process. It goes without saying that any deviation in these elements will translate into a faulty positioning of workpiece thus resulting in machining error. Locators may deviate from the ideal condition in two ways. First is in the form of the dimension or shape of the locator which is known as geometrical error. The second is due to the wrong set up. In this case the locator is correct in shape or dimension but its placement is incorrect within the layout. Apart from these, the workpiece locating surface can also have deviations. These errors are part of the 'source errors' and are illustrated in Figure 1.

Consider a fixture workpiece system as shown in Figure 2. We define three co ordinates systems. The global co ordinate (GCS) system is fixed to the machine table, the workpiece coordinate system (WCS) is fixed to the workpiece and LCS is the locator coordinate system. At each contact point the normal vector is denoted as $\mathbf{n_i}$ (n_{ix}, n_{iy}, n_{iz}) and the source error in all the locators is collectively written as a vector $\boldsymbol{\delta}\mathbf{s}$. Note that this $\boldsymbol{\delta}\mathbf{s}$ denotes change in vector $\mathbf{r}_c$. As a result of these source errors the workpiece position and orientation change, denoted by ΔX and ΔΘ. Now the workpiece positional error in GCS is written as

$$\boldsymbol{\delta}\mathbf{p} = [\Delta X \;\; \Delta\Theta] = [\delta x, \delta y, \delta\gamma]^T \qquad \text{for 2 D}$$

$$\boldsymbol{\delta}\mathbf{p} = [\Delta X \;\; \Delta\Theta] = [\delta x, \delta y, \delta z, \delta\alpha, \delta\beta, \delta\gamma]^T \qquad \text{for 3 D} \tag{1}$$

Now the Jacobian matrix is defined as (Qin, 2008)

$$\mathbf{J} = \left[\mathbf{J}_1^T \;\; \mathbf{J}_2^T \ldots \mathbf{J}_m^T\right]^T \tag{2}$$

$i = 1 \ldots m$ denote the number of locators

with

$$\mathbf{J}_i = \left\lfloor -n_{ix}, -n_{iy}, n_{iy}\, x_i - n_{ix}\, y_i \right\rfloor \qquad \text{for 2D}$$

$$\mathbf{J}_i = \left\lfloor -n_{ix}, -n_{iy}, -n_{iz}, n_{iz}\, y_i - n_{iy}\, x_i, n_{ix}\, z_i - n_{iz}\, x_i, n_{iy}\, x_i - n_{ix}\, y_i \right\rfloor \qquad \text{for 3 D} \tag{3}$$

The normal vectors $\mathbf{n}_i..\mathbf{n}_m$ are collectively written in the form of a normal vector matrix as

N=diag ($\mathbf{n}_1\ \mathbf{n}_2 \ldots\ \mathbf{n}_m$)

Now the following relation can be written between source error and workpiece positional error

$$\delta\mathbf{p} = -\mathbf{J}^{+}\, \mathbf{N}^{T}\, \delta\mathbf{s} \tag{4}$$

where $\mathbf{J}^{+}$ is a Moore Penrose inverse matrix of $\mathbf{J}$.

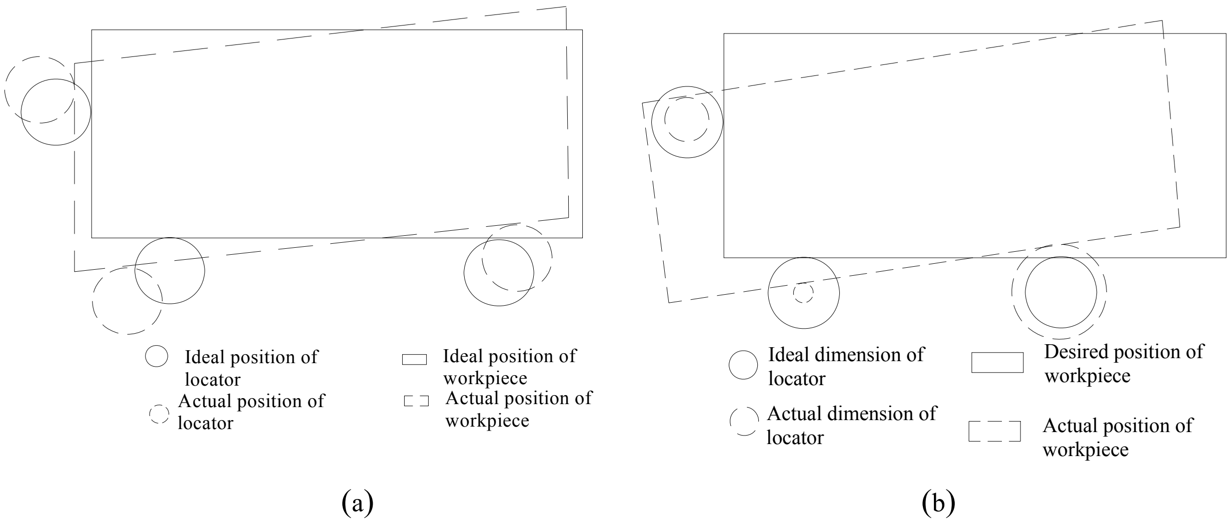

Figure 1. Source errors in locating (a) Set up errors (b) Dimensional errors

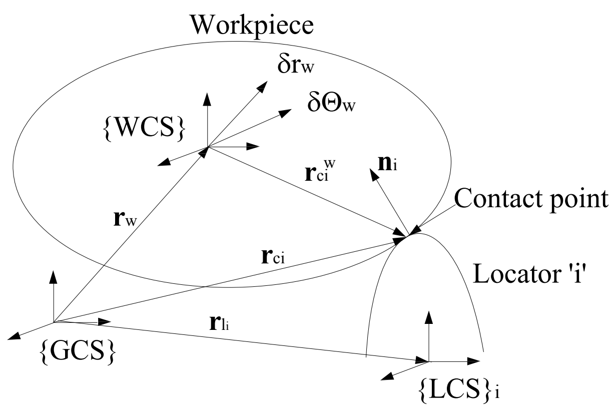

Figure 2. Coordinate systems and positional error

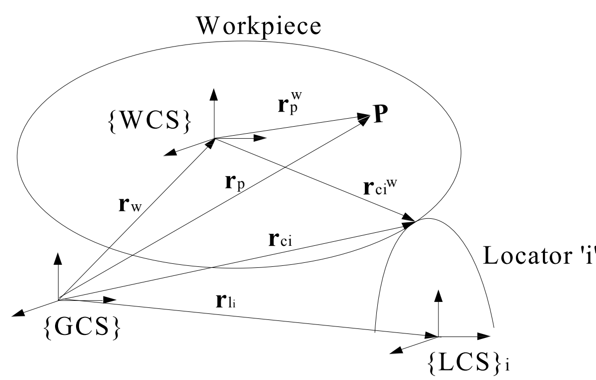

Figure 3. Machining error

2.2 Machining error

Effect of the source errors $\delta \mathbf{s}$ results in the workpiece positional error $\boldsymbol{\delta}\mathbf{p}$ as discussed earlier. If the processing datum and the locating datum do not coincide, it is called datum error ($\boldsymbol{\delta}\mathbf{dt}$). This error, combined with the workpiece positional error result in what is called the machining error $\boldsymbol{\delta}\mathbf{m}$ of the workpiece. Machining error denotes the relative motion of the cutting tool with respect to the processing datum. In a workpiece this machining error can be depicted as the change in $\mathbf{r}_p$ as shown in Figure 3. Note that $\mathbf{r}_p$ denotes the location of the processing datum in GCS. If the WCS and GCS are identically oriented and the datum related error is neglected the following relationship can be written.

$$\boldsymbol{\delta}\mathbf{m}=\mathbf{B}\ \boldsymbol{\delta}\mathbf{p} \tag{5}$$

where $\mathbf{B}$ is the position matrix of the processing point and is given by

$$\mathbf{B}=\begin{bmatrix} 1 & 0 & 0 & 0 & z & -y \\ 0 & 1 & 0 & -z & 0 & x \\ 0 & 0 & 1 & y & -x & 0 \end{bmatrix}$$

with x, y and z being the coordinates of the point considered.

3. Deterministic location

When positioned in a fixture the workpiece surface is made to contact all the locators. Deterministic location is said to be achieved if the workpiece is held in a unique position when all fixture elements are made to contact the workpiece surface. In other words deterministic location means that the workpiece cannot make an infinitesimal motion while maintaining contact with all the locators. Asada and Andry (1985) showed that for deterministic location the Jacobian matrix should have a full rank. In other words, for deterministic location,

$$\begin{aligned} &rank\,(\mathbf{J}) = 3 && \text{for 2D} \\ &rank\,(\mathbf{J}) = 6 && \text{for 3D} \end{aligned} \tag{6}$$

4. GA based fixture layout optimization

4.1 Working of GA

Traditional optimization techniques based on mathematical principles suffer from many limitations that include dependence of convergence on the chosen initial solution, getting stuck to a sub optimal solution, problem specific nature of the algorithms and inefficient handling of problems with discrete variables (Deb, 2005).

New evolutionary techniques are found to perform better in this context compared to traditional methods. One such technique is the GA. GA is a computerized search and optimization algorithm based on the mechanics of natural genetics and selection. GA operates on a population of potential solutions applying the principles of "survival of the fittest" to produce better approximation solutions. At each generation, a new set of approximation is created by the process of selecting individuals according to their level of fitness in the problem domain and breeding them together using operators borrowed from the natural genetics. This process leads to the evaluation of population of individuals that they were created from just as in natural adaptation. The working of GA is as follows.

a. Initialization and representation

A population of solutions is created randomly. Each entry in the population is called a 'chromosome'. The population thus generated will contain N_P number of chromosomes where N_P is the population size specified. N_P =50 in this work. The chromosome can be represented using binary or real coding. In the present problem, real variable coding is used. Length of a chromosome depends on the number of variables used in the problem. Variables in this problem are the locator coordinates. This study considers the 3-2-1 locating scheme hence there are six locators with X,Y and Z coordinates to be determined. So the problem is of dimension 18.

b. Evaluation of fitness

Each chromosome is evaluated for its fitness. The fitness function $F(x)$ is derived from the objective function $f(x)$ of the problem. For maximization problems, fitness function is the same as the objective function. For minimization problems the fitness function is defined as

$$F(x) = \frac{1}{1 + f(x)} \tag{7}$$

c. Testing for termination criteria

The algorithm can be terminated by specifying different conditions like the number of generations, specific objective value, improvement of objective function in successive generations etc. The GA keeps searching the solution space for the best solution. After certain number of generations, the chromosomes become similar. Beyond a certain point in time, a condition will be reached that no better solution can be found. Hence to save time, certain number of generations be specified so as to stop the search. Otherwise the algorithm will keep running without finding any better solution. In the present work, the algorithm has been programmed to stop if the objective function value remains same for 50 consecutive generations. This is called stall generations Ns. If the condition is not satisfied a new generation is formed and the process repeats till the maximum number of generations (N_G) is reached. In this work, N_G=150.

d. Creation of new generation

GA essentially performs three operations to create a new generation. These are Reproduction, Cross over and Mutation.

Reproduction:

At this stage 'parent' chromosomes are selected from the population based on their fitness and a mating pool formed. The probability of a chromosome for selection depends on its fitness F_i. The probability for selecting the i^{th} chromosome

$$p_i = \frac{F_i}{\sum_{j=1}^{N_P}} \tag{8}$$

where ‘N_P’ denotes the population size.
In reproduction, good chromosomes in a population are assigned a larger number of copies to form the mating pool. In this study the rank based Roulette wheel selection method is adopted for selecting chromosomes for reproduction.

Cross over:
The crossover operation involves in two chromosomes exchanging certain part of their genetic information to produce new chromosomes. To retain some goodness already present in the mating pool only a certain percentage of chromosomes are involved in cross over. This is given by the value of cross over probability p_c. Cross over operation for real and binary coding are done differently. In binary coding single point crossover, multipoint crossover and uniform crossover are commonly used techniques. In real value coding the methods of cross over include discrete cross over, line cross over and intermediate cross over. Discrete cross over is used in this study.

Mutation:
After cross over is performed, the chromosomes undergo mutation. This operator makes local changes in a chromosome to hopefully create a better chromosome. Similar to the cross over operation a random number is generated and if the number is less than the mutation probability p_m (p_m= 0.02 in this work) mutation is performed. Otherwise the chromosome is unchanged. In this work an Incremental operator is used for mutation. The incremental operator works as follows.
An increment value ‘δ’ is chosen depending on the problem domain and bounds. A particular variable in the chromosome is chosen randomly. Mutation operator either adds or subtracts this value from the variable to form a new chromosome
Let ‘a b c’ be the string before mutation. The string after mutation can be
‘a+ δ b c’ or ‘a- δ b c’

Flowchart shown in Figure 5 outlines the GA process.

```
Simple Genetic Algorithm ( )
{
        initial Population;
        evaluate population;
        While termination criterion not reached
        {
                reproduction;
                perform crossover and mutation;
                evaluate population;
        }
}
```

Figure 4. Genetic algorithm

4.2 Application of GA to layout optimization
As stated earlier this work considers the source error present in the locators in form of geometry and set up. When a workpiece is loaded into this fixture and machined it results in deviation of the actual dimensions from the desired ones. With the manufacturing tolerances (*mtol*) being specified it is mandatory that the deviations should lie below the tolerance specifications. The influence of source error of a locator on the overall machining error depends on its position in the layout. The objective is to find the location of each error containing locator so as to minimize the resultant error. In this context the problem statement can be made as follows.
Arrive at a deterministic layout which, for given source errors results in the least dimensional error of the critical machining feature while complying with the tolerance requirements .In other words,

Determine
$L_{x,y,z}(i)$
so as to minimize

$$\delta\mathbf{m}_j = \begin{Bmatrix} \delta x \\ \delta y \\ \delta z \end{Bmatrix}_j = \mathbf{B}_j\,\delta\mathbf{p} = \begin{bmatrix} 1 & 0 & 0 & 0 & z & -y \\ 0 & 1 & 0 & -z & 0 & x \\ 0 & 0 & 1 & y & -x & 0 \end{bmatrix}\left\{-\mathbf{J}^{+}\,\mathbf{N}^{T}\delta\mathbf{s}\right\} \tag{9}$$

with $\delta\mathbf{s} = \left[\delta\mathbf{s}_1 \ldots \delta\mathbf{s}_i\right]^T$
subject to
$(x,y,z)_{i\,max} \geq (x,y,z)_i \geq (x,y,z)_{i\,min}$

δx (or) δy (or) $\delta z \leq$ mtol
where
i=1:6
j=A,B,C

In execution, layouts are generated randomly (initial population) with the bounds specified for each locator. Magnitude of source error in each locator is specified by the user. Each of these locators is first checked for the condition of deterministic location discussed in Section 3. With these inputs the GA runs for the specified number of generations and arrives at the optimal layout – the layout with least machining error of the feature considered. Flow chart shown in Figure 5 explains the method adopted.

5. Numerical illustration

To illustrate the above mentioned procedure, a rectangular block studied by Qin *et al*. (2008) is presented. A through slot is to be milled on a workpiece of dimensions 220 mm ×122 mm ×112 mm. The critical machining feature in this case is the distance between the far edge of the workpiece and the slot, shown as 25±0.006 in Figure 7. Since the workpiece is located based on the 3-2-1 locating principle there are six locators in total. The normal vectors and the assumed errors in each locator are given in Table 1. Using equation (9) the overall machining error is computed at the three processing datum points A,B and C whose coordinates are (220,122,112), (110,122,112), (0,122,112) respectively. For each layout the maximum of errors among A, B and C are calculated and GA is used to arrive at the minimum of this maximum error. Corresponding layout is the optimal layout.

In the present case GA is run for 10 times and optimal layouts are obtained. Table 2 shows the layouts and error values corresponding to each run. It can be seen that among the 10 runs, run 10 gives the least value of error (0.00227 mm). The convergence pattern of GA corresponding to this run is shown in Figure 8.

Comparing the error values with the required tolerance on the critical dimension (0.006 mm) it can be seen that all the layouts are valid for the present case (maximum error being 0.003553 mm in Run 1).

Table 1 Normal vectors and errors in locators

Locator	Normal vector	Source error (mm)	Positional constraints used in optimization
L_1	(0,0,1)	0.001	53 ≥ x≥ 10, 101 ≥ y≥ 62, z=0
L_2	(0,0,1)	0.002	190 ≥ x≥ 125.5, 101 ≥ y≥ 62, z=0
L_3	(0,0,1)	0.003	115 ≥ x≥ 66, 59 ≥ y≥ 10,z=0
L_4	(0,-1,0)	0.004	90 ≥ x≥ 20, y= 122, z=56
L_5	(0,-1,0)	0.001	180 ≥ x≥ 95, y= 122, z=56
L_6	(1,0,0)	0.002	x=0 , 102 ≥ y≥ 30, z=56

6. Results and discussion

The machining error is of the form

$$\delta \mathbf{m}_j = \begin{Bmatrix} \delta x \\ \delta y \\ \delta z \end{Bmatrix}_j$$

The vector consists of machining error in the X, Y and Z directions. However in this study the machining error relates to the deviation of the distance of the slot from the top edge of the workpiece shown as 25±0.006. Hence the Y component of the machining error, δy is of interest. For each layout generated $\delta \mathbf{m}_j$ is computed using Equation (5) and GA is invoked to arrive at the minimum machining error.

Many GA runs are performed and the results of 10 such runs are given in Table 2. The least machining error varies from a minimum of 0.00318 mm (Run 10) to a maximum of 0.003553 mm (Run 1). Other values of machining error are near identical. Interestingly Run 2, Run 3 and Run 6 have exactly same value of machining error (0.0032 mm). This proves that the fixture optimization problems are multimodal in nature. For the same or near the same objective value (δy in this case) the layouts are different. This means that given the locator error and bounds on locator positions, f different layouts are possible for the same machining error. This provides the user with the flexibility of choosing layouts without imposing too much restriction.

The relative impact of each locator error on the resultant machining error is worth considering. For doing this, the layout with the least error, the one obtained in Run 10 is taken. First, error of locator 1 is increased in steps of 10% till the error value is doubled. Error values of all other locators remain the same as given in Table1. Change of δy with increasing error value of locator 1 is computed. The process is repeated for other locators while keeping same the error of all but that locator. The results are plotted in Figure 7.

It can be seen that effect of locator 4 is more pronounced followed by locator 3 and locator 2. Locator 5 has little impact on the change of the machining error while the influence of locator 6 is not seen to affect the machining error. This means that locator 4 should be produced with stricter tolerance or should be set up more precisely since the impact of it is seen to be more considerable than others.

As the optimization process continues, chromosomes tend to become similar. Because of this the objective function, in this case the machining error, tends to remain at a value without any further improvement. The objective function is then said to have converged. As discussed in Section 4 the optimization process is terminated based on either the number of stall generations or the maximum number of generations. Figure 8 shows the convergence of GA. Figure 8a corresponds to run 10 that returned the least error among the 10 runs. It can be seen that the machining error value steadily falls for the first 96 generations and remains unchanged thereafter. Since the stall generation value has been specified as 50, the process continues for further 50 generations and stops at generation number 146. As mentioned earlier, the least machining error obtained in the process is 0.00318 mm. To study the effect of increase in population size, GA is run with N_P increased to 70 and the corresponding convergence pattern is shown in Figure 8b. The least error obtained here is 0.0331 mm after 148 iterations.

Table 2 GA based optimal position of locators and corresponding machining error

G.A Run	Locator 1			Locator 2			Locator 3			Locator 4			Locator 5			Locator 6			Least error (mm)
	x	y	z	x	y	z	X	y	z	x	y	z	x	y	z	x	y	z	
1	38.1	66.7	0.0	135.4	96.3	0.0	92.6	54.1	0.0	22.3	122.0	56.0	115.5	122.0	56.0	0.0	81.1	56.0	0.003553
2	15.3	69.6	0.0	169.1	69.1	0.0	77.7	31.8	0.0	22.7	122.0	56.0	137.9	122.0	56.0	0.0	60.6	56.0	0.00320
3	26.4	66.5	0.0	129.3	83.1	0.0	70.3	31.4	0.0	36.4	122.0	56.0	168.2	122.0	56.0	0.0	95.3	56.0	0.00320
4	37.1	88.9	0.0	143.0	85.5	0.0	91.2	57.5	0.0	56.3	122.0	56.0	162.7	122.0	56.0	0.0	84.1	56.0	0.00322
5	40.1	98.8	0.0	147.2	80.0	0.0	81.9	51.8	0.0	39.0	122.0	56.0	167.4	122.0	56.0	0.0	73.3	56.0	0.00323
6	15.6	95.1	0.0	176.6	65.2	0.0	94.7	43.6	0.0	43.5	122.0	56.0	179.4	122.0	56.0	0.0	40.2	56.0	0.00320
7	18.5	64.6	0.0	129.8	96.4	0.0	87.6	53.0	0.0	28.6	122.0	56.0	134.8	122.0	56.0	0.0	68.1	56.0	0.00331
8	48.3	84.7	0.0	180.7	92.0	0.0	100.7	44.6	0.0	30.1	122.0	56.0	167.8	122.0	56.0	0.0	81.9	56.0	0.00318
9	29.4	91.3	0.0	157.0	92.2	0.0	76.6	57.7	0.0	49.5	122.0	56.0	174.3	122.0	56.0	0.0	56.9	56.0	0.00331
10	28.5	67.2	0.0	183.9	69.8	0.0	96.3	28.4	0.0	23.9	122.0	56.0	176.4	122.0	56.0	0.0	83.0	56.0	**0.00318*

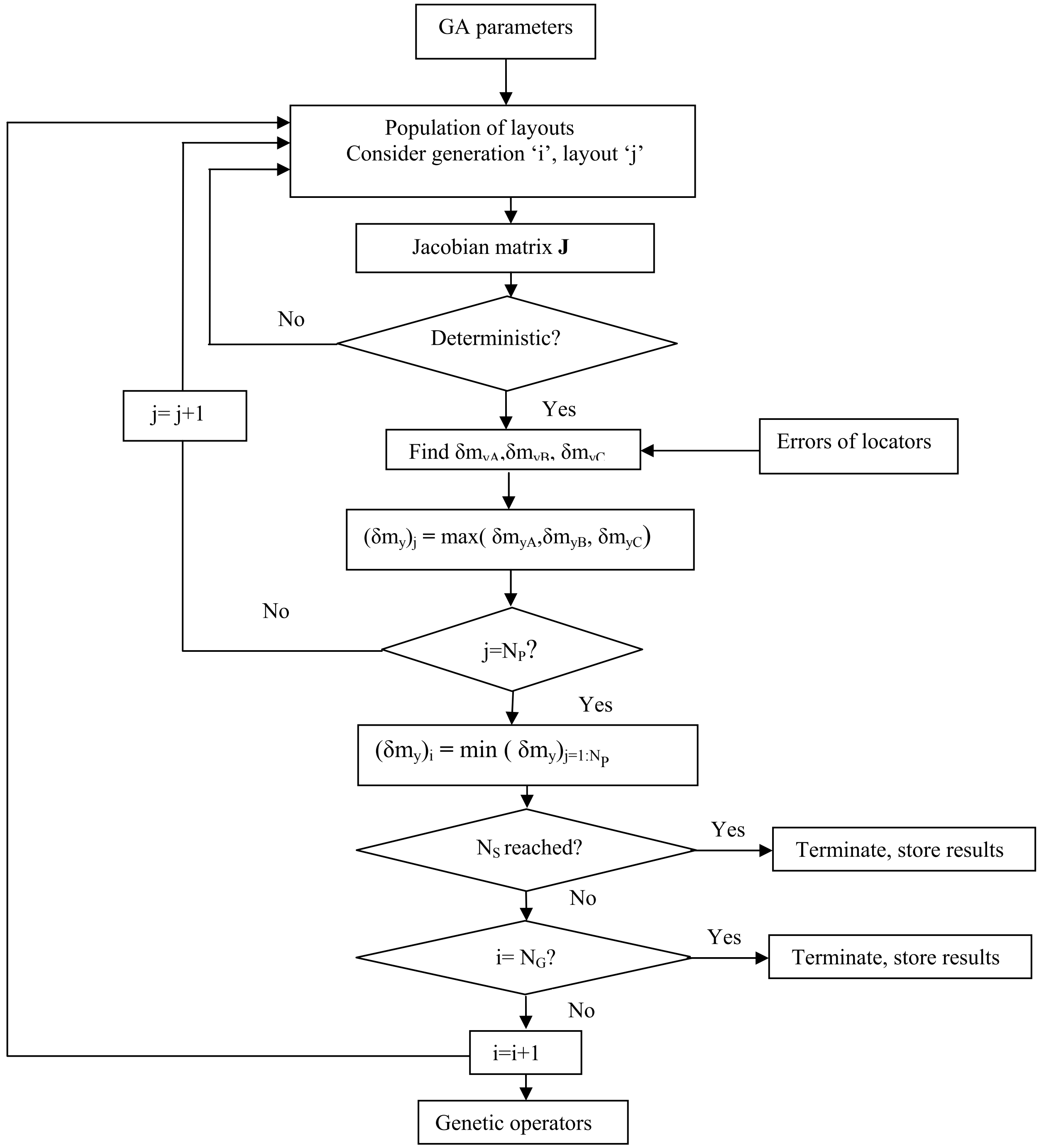

Figure 5. Flow chart of the analysis

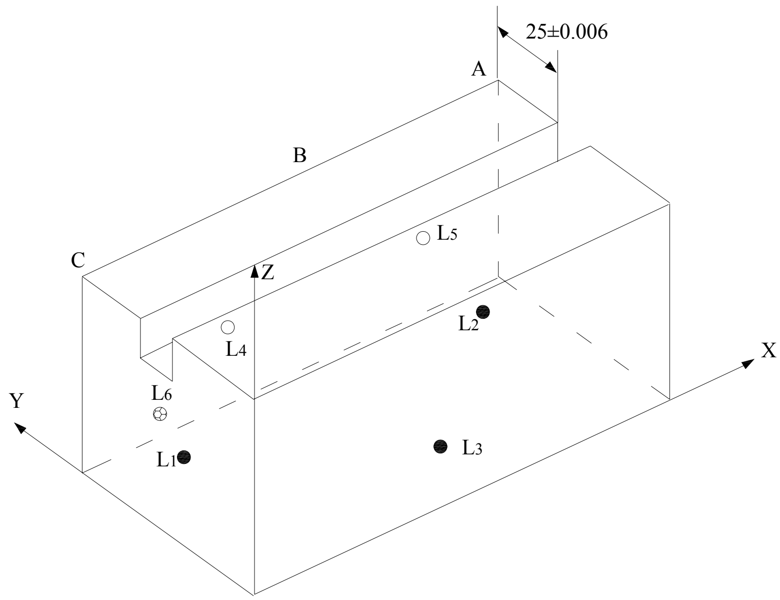

Figure 6. Workpiece fixture system under study

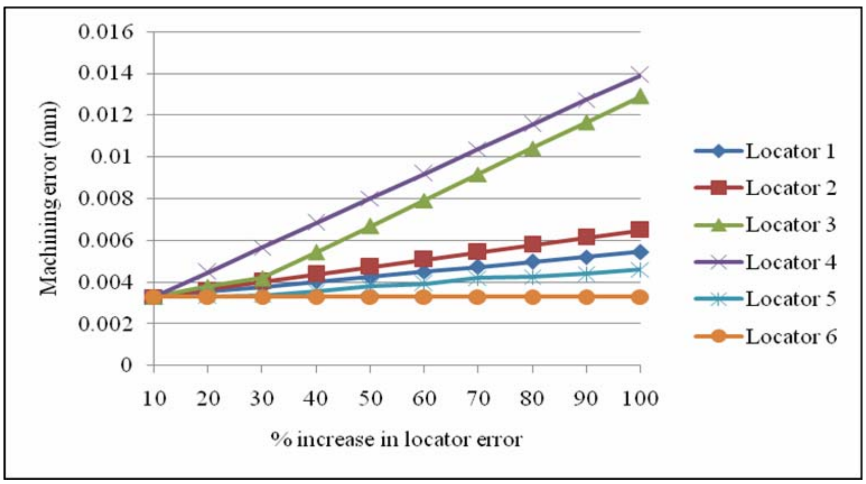

Figure 7. Effect of increase in locator error

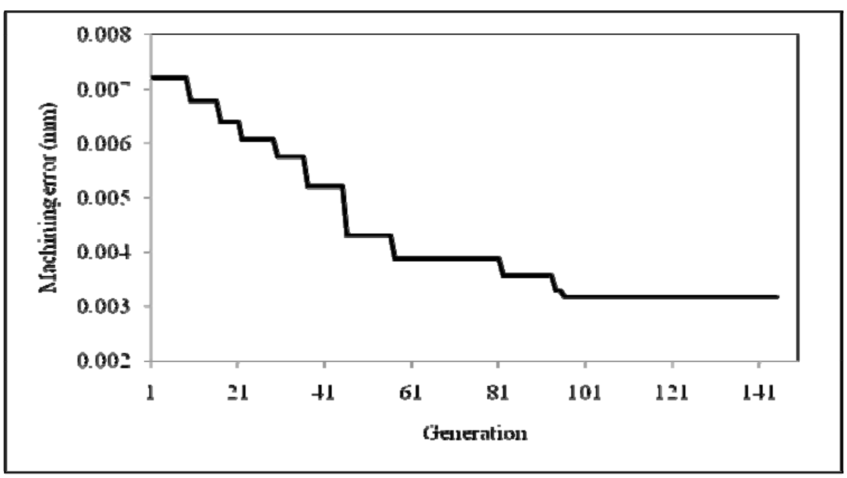

Figure 8a . Convergence of GA (N_P=50)

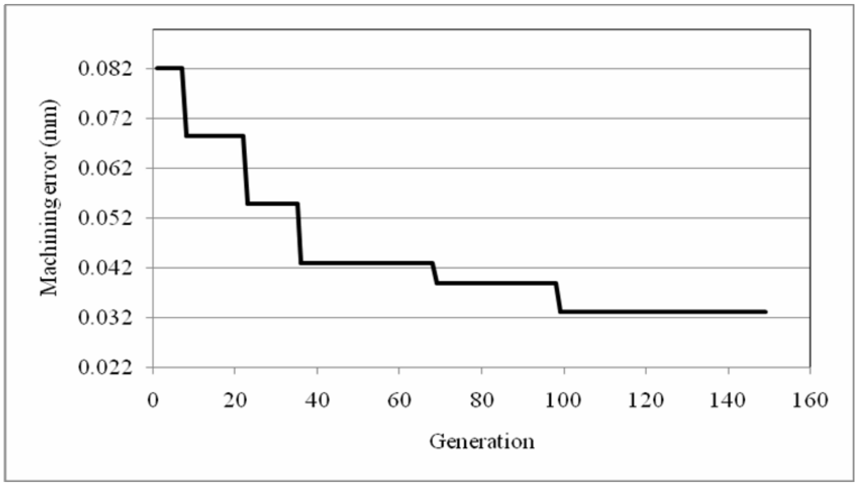

Figure 8b . Convergence of GA (N_P=70)

7. Conclusions

Since the locator error is an important factor contributing to the overall machining error minimization of the contribution of locator error reduces the machining error. In this work an attempt has been made for optimizing the fixture layout taking into consideration the effect locator errors. Deterministic location is ensured throughout the optimization process and minimal machining error is arrived at complying with the machining tolerance specification. This also provides the user with a flexibility in choosing the layout according to the requirements. Also, for a given machining tolerance on workpiece, if the minimum possible error can be found for a given set of locator errors, working backward, it is possible to determine the allowable tolerance on the locator. This may be advantageous in cases where a less strict tolerance on locator will be acceptable thus reducing the cost of manufacture of locators. The model presented here is generic in the sense that the same can be applied to any critical feature of the workpiece by choosing appropriate datum points. Future work will include the determination of the components of machining error caused by machining and clamping forces. The fixture layout would be optimized so as to minimize the overall machining error. In this work the locators are assumed to contain error in their normal direction. A quadratic model would help analyze the case of locators with errors along the tangential directions also.

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