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AUTOMATED GENERATION OF WORKPIECE LOCATING SCHEME IN FIXTURE DESIGN

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This paper proposes a methodology which aims to fill the gap in the area of automated fixture design. The approach is based on detailed consideration, analysis, and synthesis of all operating requirements related to automated definition of possible workpiece locating schemes for machining processes. Reviewed in the paper are the system concept, functions, and a case study.

Key words: fixture, locating, locating error.

INTRODUCTION

Fixtures is widely used in manufacturing, e.g. machining (Figure 1.a), inspection (Figure 1.b), assembly (Figure 1.c), and welding (Figure 1.d). Fixture is one of essential components in manufacturing. It is used for efficient and reliable locating of workpiece, as well as for supporting, and clamping, in a way which provides machining within predefined tollerances [12]. Although the primary function of fixture is precise locating and clamping of workpiece, there are many additional criteria regarding ergonomics which should be met. Finally, one of the most important requirements of every fixture is cost-efficiency, which means that it should not increase costs of manufacture due to e.g., protracted fixture assembly, costly materials, costs of fixture manufacture, etc. Costs related to fixture design and manufacture can contribute up to 20% to total manufacturing costs. This contribution does not only pertain to material costs, and costs of fixture manufacture and assembly, but also to the costs of fixture design. Lower costs of fixture design contribute to significant financial effects. Another important aspect related to fixture design is that it embodies many conflicting requirements, bearing in mind that fixture solution must meet a number of mutually exclusive requirements. For example, heavy fixture might be desireable considering workpiece stability. However, the increased fixture weight contributes to additional costs, due to higher material costs, and more difficult fixture handling. All this contributes to complexity of fixture design. In addition, fixtures directly influence the quality of machining, productivity, and product cost [17].

There exist two approaches to solving this problem. One is based on the development of flexible fixtures, while the other leans on simplification of design process. Simplification of the design process is primarily centered on design automation, i.e., the development of CAFD (Computer Aided Fixture Design) systems [18].

Asante [01] presented a model that combines contact elasticity with finite element methods to predict the contact load and pressure distribution at the contact region in a workpiece-fixture system. Dai et al. [02] described a modular element database creation method, which can be used effectively for integrating with a Computer-Aided

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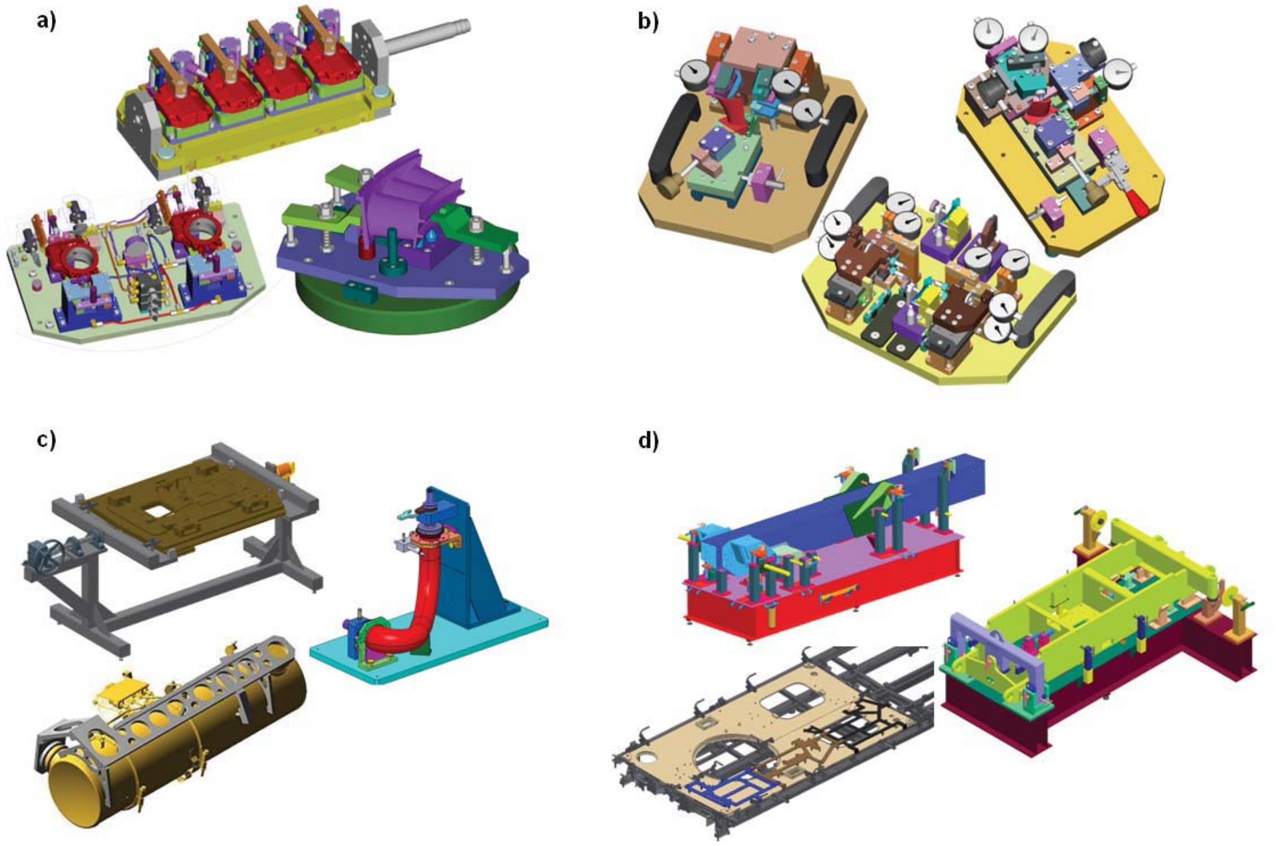


Figure 1. Fixtures
a) Machining fixtures [24], b) Inspection fixtures [24], c) Assembly fixtures [25, 26, 27],
d) Welding fixtures [25].

Design system and for modelling fixture subassemblies. Deng and Melkote [03] presented a model-based framework for determining the minimum required clamping forces that ensure the dynamic stability of a fixture-workpiece system. DeMeter [04] presented an approach to determine support location that minimises the maximum displacement. Finite element analysis was used to find displacements. Gologlu [05] developed a knowledge-based methodology for setup planning and datum selection incorporating machining and fixturing constraints. Hazarika et al. [06] developed a setup planning system for machining prismatic parts considering fixturing aspect. The proposed setup planning system provides inputs to fixture designer in terms of recommended depth of cut and feed, fuzzy clamping forces, approximate optimal locator and clamp layout, and sizes of the locators and clamps. Kaya [07] used a genetic algorithm-based continuous fixture layout optimization method, but the dynamic effects of the workpiece were not considered. King and Hutter /8/ proposed a approach for generating optimal fixturing locations to secure workpieces ideally with respect to maximum stiffness, resistance to slip and stability. Kulankara et al. 09] applied the genetic algorithm for fixture layout and clamping force optimization to a compliant workpiece. In their model, an iterative algorithm that minimizes the workpiece's elastic deformation by alternatively varying the fixture layout and clamping force is proposed. Li and Melkote [10] presented a fixture layout and clamping force optimal synthesis approach that accounts for workpiece dynamics during machining. They used the contact elasticity modeling method that accounts for the influence of workpiece rigid body dynamics during machining. Menassa and DeVries [11] used finite element analysis for calculating deflections using the minimisation of the workpiece deflection at selected points as the design criterion. The design problem was to determine the position of supports. Sanchez et al. [13] calculated the contact load at the fixture-workpiece interface using a simple and direct mathematical tool along with the finite element analysis, which simplifies the deformation minimisation problem. They also ascertained the interpolating functions which relate the clamping position with respect to the load contact in order to define valid clamping regions. Tan et al. [14] described the modeling, analysis, and verification of optimal fixturing configurations by the methods of force closure, optimization and finite element modeling. Tao et al. [15] presented a geometrical reasoning methodology for determining the optimal clamping points and clamping sequence for arbitrarily shaped workpieces. Vallapuzha et al. [16] presented a genetic algorithm-based optimization method that uses spatial coordinates to represent the locations of fixture elements. They optimized the locator's position and ignored the clamp's position. Vukelic et al. [19] used a combination of feature-based, knowledge-based and geometry-based methodology for development complex system for fixture selection, modification, and design. Wang et al. [20] developed an intelligent fixturing system to adjust the clamping forces adaptively to achieve minimum deformation of the workpiece according to cutting forces. Linear static finite element analysis was used to find the workpiece deformation. Wardak et al. [21] used a finite element analysis and optimisation algorithms to design optimal fixturing layouts for the drilling processes. Xie et al. [22] introduced another experimental investigation to evaluate the coefficients of the static friction of workpiece-fixture element pairs. Yeh and Liou [23] used the finite element analysis to establish an analytical model to describe the clamping conditions between the workpiece and fixture elements in a modular fixturing system and to estimate the contact stiffness.

- The discussed investigations suffer from two major disadvantages:They are based on 3-2-1 locating method and complete restriction of workpiece degrees of freedom using locating elements. Thereby, they disregard the fact that this significantly increases fixture costs by shear increase of constituent fixture elements. In addition, there is an increased possibility of machining errors.
- The influence of locating error is completely disregarded. The fact that locating error greatly impacts the total machining error. On the other side, in contrast to all other errors which occur prior to or after the machining, locating error is unique in that it can be exactly determined at all times. Therefore, its numerical value and impact on the total machining error are known.

As can be seen, there is still a need for reliable methods which help designers to plan fixtures on conceptual level, where the key task is to identify most adequate fixture structure, i.e. locating workpiece surfaces which satisfy particular criteria.

WORKPIECE LOCATING

The purpose of workpiece locating is to bring it into correct and definite position prior to clamping, i.e., to restrict some but not all workpiece degrees of freedom, thus allowing proper machining. The number of degrees of freedom to be restricted depends on the shape of workpiece and the measure to be achieved by machining (Figure 2 and Figure 3). Locating variants and primary locating surface are determined depending on workpiece shape and geometric specifications. Hereby, conditions of stability,

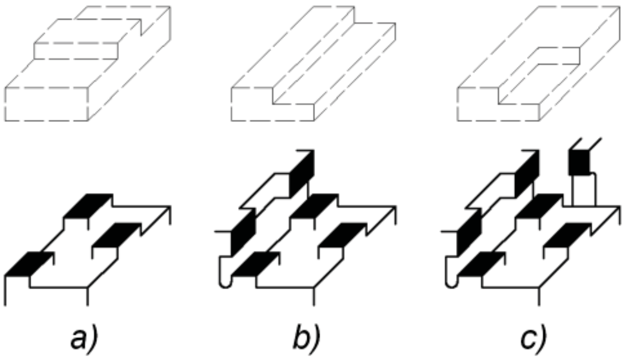


Figure 2. Locating of a prismatic workpiece
a) restriction of 3 degrees of freedom, b) restriction of 5 degrees of freedom, c) restriction of 6 degrees of freedom

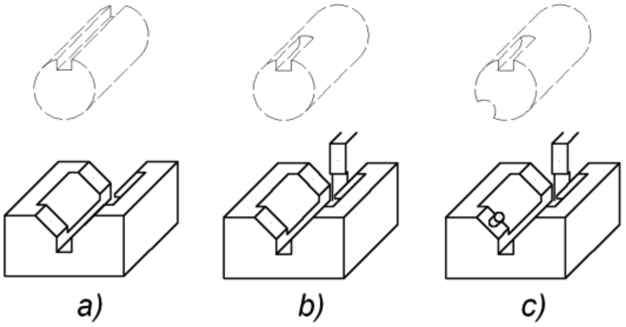


Figure 3. Locating of a cylindrical workpiece
a) restriction of 4 degrees of freedom,
b) restriction of 5 degrees of freedom,
c) restriction of 6 degrees of freedom

machining precision, and the ability to machine larger number of surfaces in one locating, are to be observed.

LOCATING ERRORS

Most accurate machining is performed in cases when it is possible to use a single primary locating surface. However, in most cases it is not possible to machine workpiece on a machine tool using just one primary locating surface. Primary locating surfaces should be chosen in a way which allows rapid and easy workpiece locating. The selection of primary locating surfaces should allow construction and technological base to match. This allows more accurate machining due to avoidance of locating errors.

During workpiece machining there are deviations from the required geometry and nominal measures defined by the engineering drawing. Machining errors are common to every machining process which involves transformation of geometry, dimensions, or material structure. The basic criterion of machining accuracy requires that the total machining error (Δ) must be less than the allowed machining tollerance (T), i.e.:

$$\Delta < T \qquad (1)$$

The errors which occur prior to and during machining process depend on a large number of factors. These errors are numerous and they involve: geometric machining erros (ΔGME), methodical errors (ΔME), locating errors (ΔLE), clamping errors (ΔCE), tool setup errors (ΔTSE), elastic deformation errors (ΔEDE), thermal deformation errors (ΔTDE), machining allowance errors (ΔMAE), wear errors (ΔWE), internal stress errors (ΔISE), and errors of cutting system dynamics (ΔCSDE).

Calculations should take into account that all these errors are random variables, which means that the possibility of the total machining error equals:

$$\Delta = \sqrt{\sum_{i=1}^{n} \Delta_i^2} \qquad (2)$$

i= (GME, ME, LE, CE, TSE, EDE, TDE, MAE, WE, ISE, CSDE).

As mentioned before, with the exception of locating errors (ΔLE), the rest of these errors are not always possible to calculate. For that reason these errors are not dealt with individually, but are considered as a cummulative error:

$$\Delta_{CUM} = \sqrt{\sum_{j=1}^{n} \Delta_j^2} \qquad (3)$$

j= (GME, ME, CE, TSE, EDE, TDE, MAE, WE, ISE, CSDE).

Including equation (3) into equation (1) yields:

$$\Delta LE + \Delta CUM < T \qquad (4)$$

Cummulative error is approximated as the mean economic accuracy of a particular machining process. The economic accuracy of machining can be expressed as the machining tolerance grade which is possible to achieve through particular machining processes. Presented in Table 1 are international tolerance grades (IT) for economic accuracy, i.e., the cummulative error for particular machining types.
Locating errors occur either due to adoption of auxiliary seat, or due to a clearance between the locating surfaces on the workpiece, and the corresponding fixture elements (locating elements which are interfacing locating surfaces).

Table 1. Cummulative error for particular types of machining

Type of machining		Cummulative error
Turning	rough	12÷14
	semi-finish	9÷11
	finish	6÷8
Drilling		11÷13
Countersinking		9÷10
Reaming		6÷8
Milling	rough	12÷14
	semi-finish	10÷11
	finish	8÷9

Workpiece can be located so that its locating error equals zero (ΔLE=0), or is different from zero (ΔLE≠0). From the machining accuracy point of view, zero locating error is preffered. It is possible under certain conditions to have locating error which is different from zero - its sum with the Cummulative error (ΔCUM) lower than the machining tolerance (T), i.e., ΔLE+ΔCUM<T.

However, such fixture could have lower price, or significantly higher productivity, thus representing a better solution compared to the previous one which features ∆L=0. Locating surfaces should be always chosen so that they do not impact the total machining error.

SYSTEM STRUCTURE

The structure of system for automated generation of workpiece locating schemes (locating surfaces) is shown in Figure 4. The system takes following input information:

- machining process to be performed on a workpiece,
- required number of degrees of freedom to be restricted on a workpiece,
- workpiece locating method,
- basic locating characteristic (locating from external surface, locating from internal surface, locating from internal and external surfaces),
- possible characteristic workpiece locating schemes,
- characteristic dimensions of workpiece surfaces from which it is possible to locate workpiece,
- geometric specification of workpiece (tolerances) for the chosen characteristic workpiece surfaces.

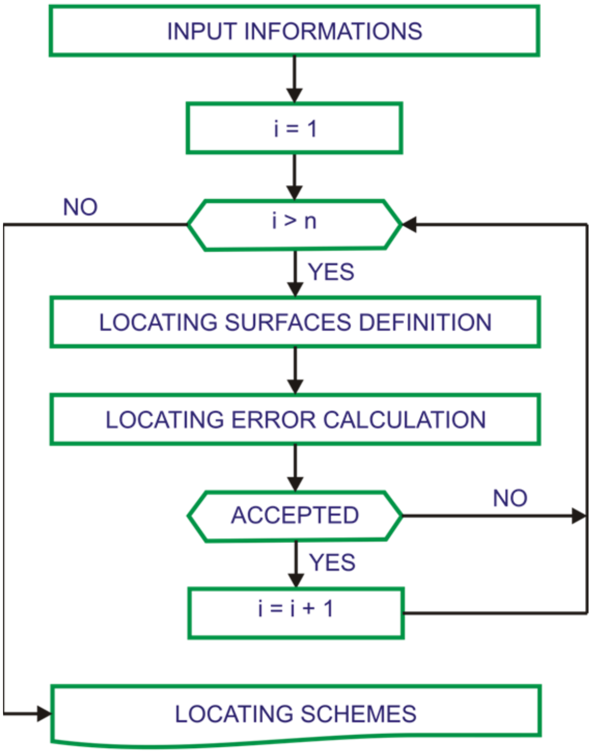


Figure 4. System structure

Based on workpiece orientation during machining process on a particular machine tool, workpiece surfaces, given machining measures and their geometric specifications, possible locating surfaces are generated, while taking into consideration the required number of degrees of freedom to be restricted on the workpiece. Once possible locating schemes have been defined, the resulting locating error is checked for all generated solutions, and all the solutions, if any, which satisfy requirement of zero or sufficiently small locating error, are selected. Based on the calculated workpiece locating errors, the system outputs one or several possible locating schemes.

CASE STUDY

On the workpiece shown in Figure 5 drilling process is performed which consists of eight holes 10 H10 on the 118±0.3 mm diameter.

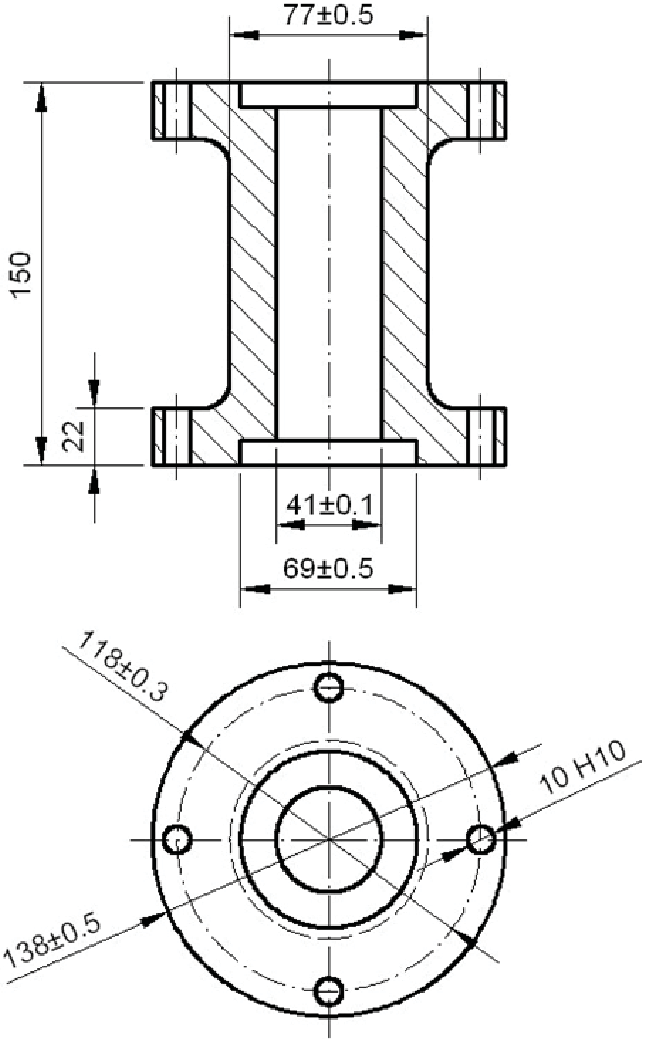


Figure 5. Workpieces used in case study

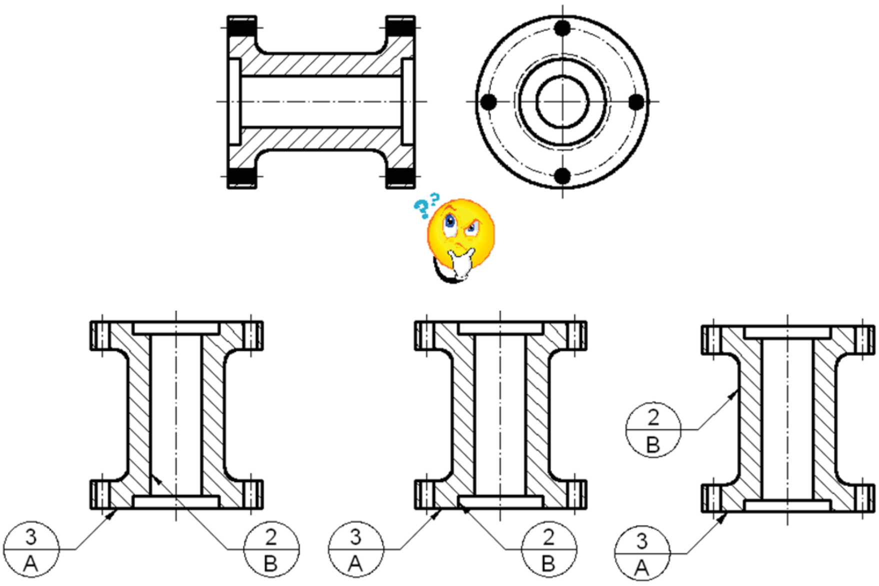
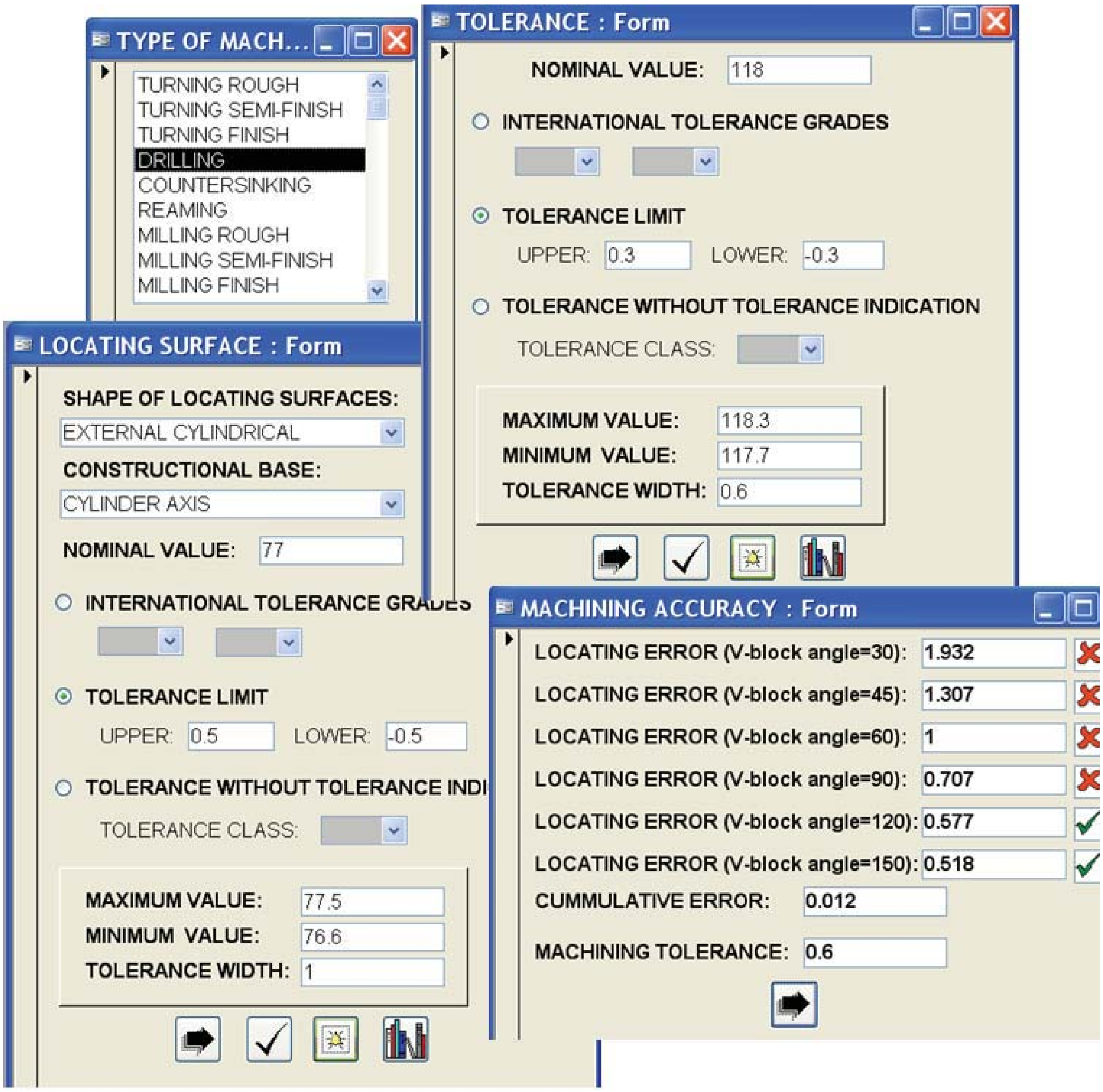


Figure 6. Possible workpiece locating strategies



TURNING ROUGH
TURNING SEMI-FINISH
TURNING FINISH
DRILLING
COUNTERSINKING
REAMING
MILLING ROUGH
MILLING SEMI-FINISH
MILLING FINISH

NOMINAL VALUE: 118

○ INTERNATIONAL TOLERANCE GRADES

● TOLERANCE LIMIT

UPPER: 0.3 LOWER: -0.3

○ TOLERANCE WITHOUT TOLERANCE INDICATION

TOLERANCE CLASS:

MAXIMUM VALUE: 118.3
MINIMUM VALUE: 117.7
TOLERANCE WIDTH: 0.6

SHAPE OF LOCATING SURFACES: EXTERNAL CYLINDRICAL

CONSTRUCTIONAL BASE: CYLINDER AXIS

NOMINAL VALUE: 77

○ INTERNATIONAL TOLERANCE GRADES

● TOLERANCE LIMIT

UPPER: 0.5 LOWER: -0.5

○ TOLERANCE WITHOUT TOLERANCE INDI

TOLERANCE CLASS:

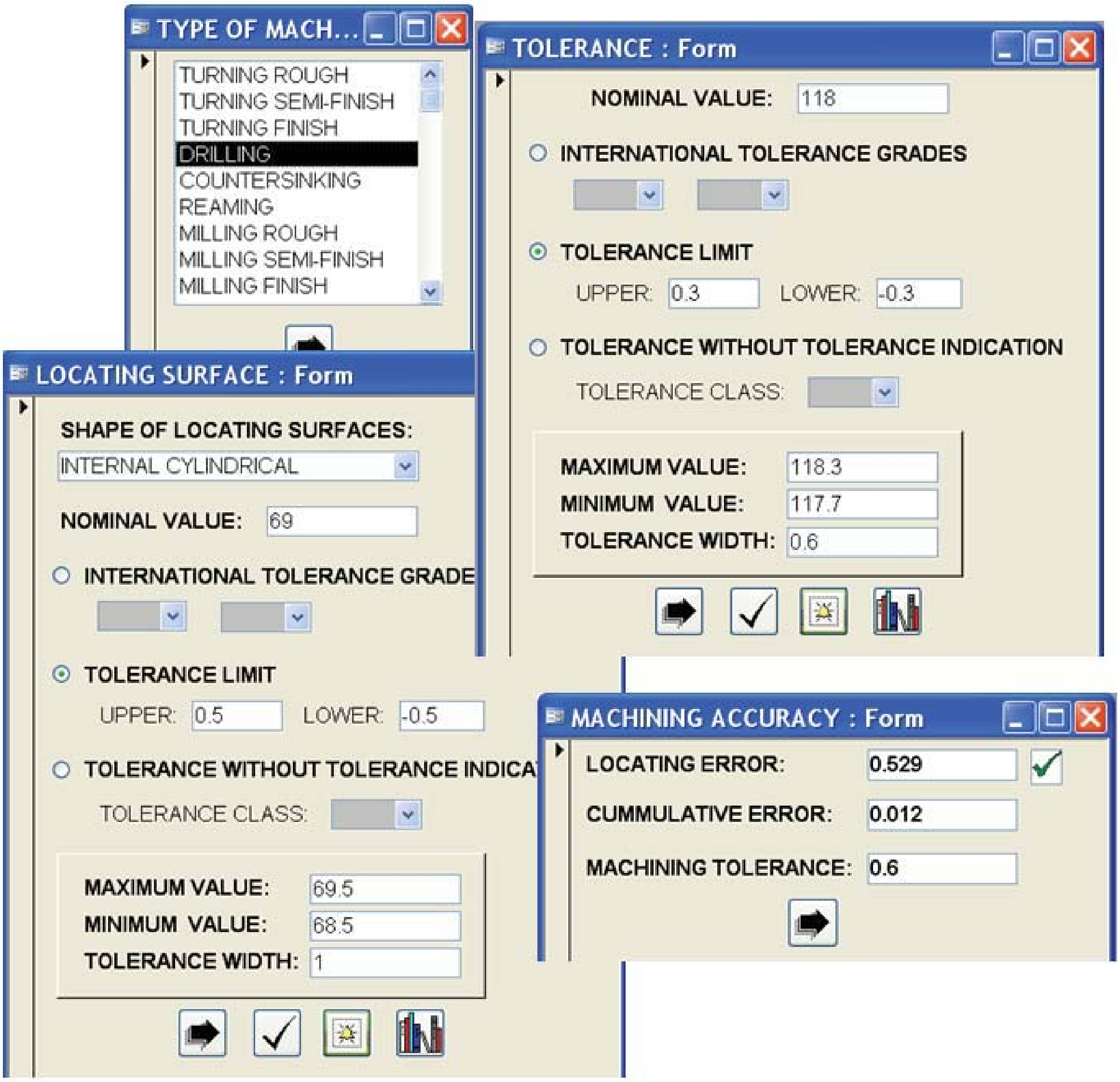
MAXIMUM VALUE: 77.5
MINIMUM VALUE: 76.6
TOLERANCE WIDTH: 1

LOCATING ERROR (V-block angle=30): 1.932 ✗
LOCATING ERROR (V-block angle=45): 1.307 ✗
LOCATING ERROR (V-block angle=60): 1 ✗
LOCATING ERROR (V-block angle=90): 0.707 ✗
LOCATING ERROR (V-block angle=120): 0.577 ✓
LOCATING ERROR (V-block angle=150): 0.518 ✓
CUMMULATIVE ERROR: 0.012
MACHINING TOLERANCE: 0.6

Figure 7. Machining accuracy checked according to locating strategy no. 1

In Figure 6 three possible workpiece locating strategies are shown. In all the three cases locating elements are used to restrict five degrees of freedom. In the example from Figure 6, there is a locating error in all three cases due to the fact that constructive and technological bases are not identical. In these three examples, surface A is the primary locating surface (restricting 3 degrees of freedom), while surface B is the secondary locating surface (restricting 2 degrees of freedom). Locating errors for all three conceptual variants are different and are always ∆L≠0.

During system operation, the user firstly defines the machining surfaces by entering or selecting parameters. These surfaces are defined by entering characteristic dimensions and geometric specifications, as well as the number of possible locating strategies. Following this, the number of possible locating schemes is defined for each locating strategy, as well as the number of degrees of freedom which need to be restricted, and the locating method. Selection of basic locating characteristics and characteristic locating scheme is performed for all the possible locating strategies. After this follows the defining of characteristic dimensions and allowed deviations of the characteristic workpiece surfaces from which the locating is performed. Once the required parameters have been selected or entered, the system presents a form from which the designer is informed whether the workpiece can be located so that the requested machining process can meet the tolerances.



TOLERANCE : Form

NOMINAL VALUE: 118

○ INTERNATIONAL TOLERANCE GRADES

● TOLERANCE LIMIT

UPPER: 0.3 LOWER: -0.3

○ TOLERANCE WITHOUT TOLERANCE INDICATION

TOLERANCE CLASS:

MAXIMUM VALUE: 118.3

MINIMUM VALUE: 117.7

TOLERANCE WIDTH: 0.6

LOCATING SURFACE : Form

SHAPE OF LOCATING SURFACES: INTERNAL CYLINDRICAL

NOMINAL VALUE: 69

○ INTERNATIONAL TOLERANCE GRADE

● TOLERANCE LIMIT

UPPER: 0.5 LOWER: -0.5

○ TOLERANCE WITHOUT TOLERANCE INDICA

TOLERANCE CLASS:

MAXIMUM VALUE: 69.5

MINIMUM VALUE: 68.5

TOLERANCE WIDTH: 1

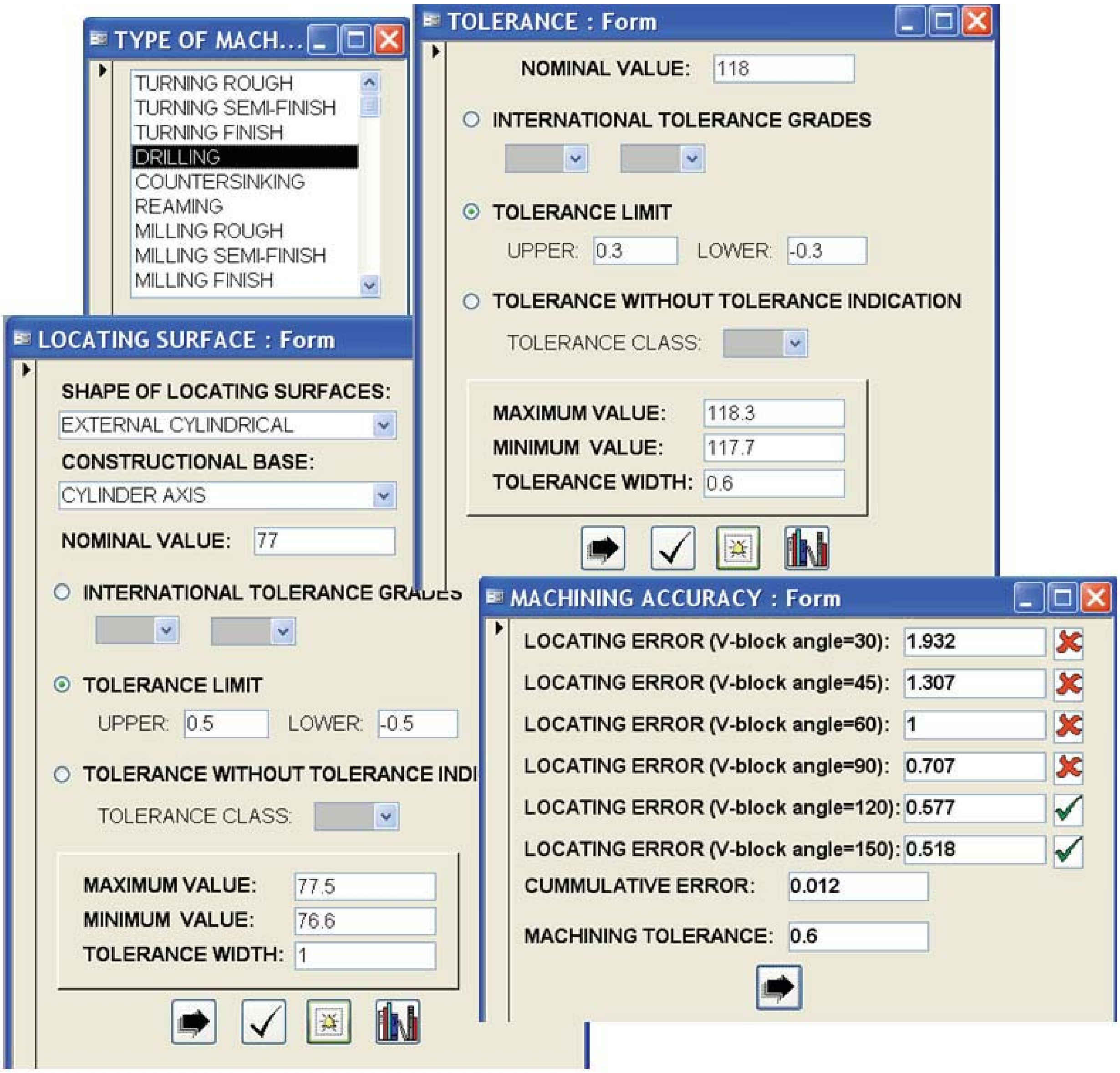
MACHINING ACCURACY : Form

LOCATING ERROR: 0.529 ✓

CUMMULATIVE ERROR: 0.012

MACHINING TOLERANCE: 0.6

Figure 8. Machining accuracy checked according to locating strategy no. 2



TOLERANCE : Form

NOMINAL VALUE: 118

○ INTERNATIONAL TOLERANCE GRADES

● TOLERANCE LIMIT

UPPER: 0.3 LOWER: -0.3

○ TOLERANCE WITHOUT TOLERANCE INDICATION

TOLERANCE CLASS:

MAXIMUM VALUE: 118.3
MINIMUM VALUE: 117.7
TOLERANCE WIDTH: 0.6

LOCATING SURFACE : Form

SHAPE OF LOCATING SURFACES: EXTERNAL CYLINDRICAL

CONSTRUCTIONAL BASE: CYLINDER AXIS

NOMINAL VALUE: 77

○ INTERNATIONAL TOLERANCE GRADES

● TOLERANCE LIMIT

UPPER: 0.5 LOWER: -0.5

○ TOLERANCE WITHOUT TOLERANCE INDI

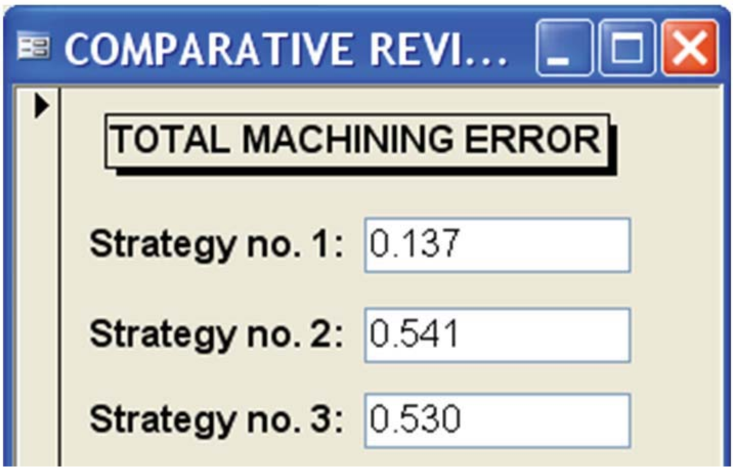
TOLERANCE CLASS:

MAXIMUM VALUE: 77.5
MINIMUM VALUE: 76.6
TOLERANCE WIDTH: 1

MACHINING ACCURACY : Form

LOCATING ERROR (V-block angle=30): 1.932 ✗
LOCATING ERROR (V-block angle=45): 1.307 ✗
LOCATING ERROR (V-block angle=60): 1 ✗
LOCATING ERROR (V-block angle=90): 0.707 ✗
LOCATING ERROR (V-block angle=120): 0.577 ✓
LOCATING ERROR (V-block angle=150): 0.518 ✓
CUMMULATIVE ERROR: 0.012
MACHINING TOLERANCE: 0.6

Figure 9. Machining accuracy checked according to locating strategy no. 3



TOTAL MACHINING ERROR

Strategy no. 1: 0.137

Strategy no. 2: 0.541

Strategy no. 3: 0.530

Figure 10. Comparative review of the possible locating variants

Shown in Fig. 7-9 are characteristic input forms which allow definition of possible locating schemes. In these forms locating error is checked for workpiece location based on: strategy no. 1 (Figure 7), strategy no. 2 (Figure 8), and strategy no. 3 (Figure 9).

Beside allowing machining accuracy checks for each selected locating strategy, the system also provides a unified presentation of results for all chosen locating strategies, thus allowing the designer to opt for the best solution (Figure 10). In this particular example, the best solution from the machining accuracy point of view is locating strategy no. 1.

CONCLUSION

Manual calculation of locating errors is time consuming and susceptible to human error. At the same time, this process is suitable for automation, since it is multi-variant, formalized, and requires voluminous processing. The proposed system was designed in order to reduce processing time and eliminate possible human error. Automated computation demands exact, analytic relations. Automated computation of locating error not only increases the quality, accuracy, productivity, but also reduces the total time, and in this way steps up the cost effectiveness of manufacturing process in general.

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