

## THE METHOD OF A MATERIAL LOSS DETECTION FOR CYLINDRICAL SHAPE PARTS OF ELEMENTS WITH A 3D SCANNING APPLICATION

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**Abstract:** In order to prepare a refurbishing process of an element with a CAM software, a detection of material loss is needed (according to wear and damage), with a simultaneous proper description of its placement and a range. The material loss detection method for cylindrical shape parts of elements (MLDMCS) is based on a comparison of a CAD model design representation and a model gained from a 3D laser scanning. MLDMCS is implemented as the one of the author overhaul computer aided software (CAO) modules. Specified solution is based on cylindrical coordinate system and specific division of this cylindrical space in to the unit volumes (like voxels in Cartesian coordinate system). Retrieved data from examination with the MLDMCS can be used for milling in order to prepare a surface for cladding or cladding itself in order to regenerate element surface with III generation of refurbishing technological operations preparation (e.g. technologies preparation aspects [6]) and applied machine tools.

**Key words:** Overhaul, refurbishing CAD, CAM, material loss detection, Siemens NX.

### 1. INTRODUCTION

The MCDMCS was invented after lecture of article [9] where; workstation to refurbish ship components with preparation turning and cladding is presented. Nowadays solutions applied in industry are based only on a human perception and a manual description of a placement and depth of material loss in a surface layer. However both a conventional (manual) and CNC machine tools are used for a technological operations that prepare a surface layer (machining) for cladding. Actual state of an art is mainly oriented to an image recognition algorithms and software that reveals a material loss with a 3D scanning but only with a point cloud – cad model comparison (distribution map – e.g. GEOMAGIC Qualify) without gain of the specific data (depth, area, volume) that gives a possibility to automatically

modify a CAD pattern model in order to prepare a refurbishing operation in CAM software with offline G-code generation trough a postprocessor. The method presented in this paper shows a possibility of wide range automation in technological operations of refurbishing preparation. The solution also focuses on the method application exclusively to a refurbishing, unlike qualification and a manufacturing quality control. MLDMCS is a part of technical mean recirculation methodology that characterize with four main directions of automation development, (disassembly preparation, analysis of cost effectiveness for refurbishing, elements technical state examination, automation of preparation to an element refurbishing process) supported with methods applied trough computer aid and new technologies. Paper will present limitations of MLDMCS in future application.

### 2. THE METHOD DESCRIPTION

The method of material loss detection for cylindrical shape parts of elements with a 3D scanning application MLDMCS is based on specified model gained from 3d scanning. Data loss during transformation from point cloud to solid model is inevitable. However there is a possibility to detect a material loss with a diameter tolerance (set as input). The tolerance should be adapted to tolerance of element part which is tightly bounded with it gauge and a class of manufacturing accuracy (typical machine class range (IT5–IT12)). However the main application of proposed method is a refurbishing process. According to wear and proper set of tolerance should bring at least 0.2mm of depth detection accuracy for typical mechanical parts, with possible standard measuring tools support. Standard measuring will also will be executed faster after material loss detection, because material loss will be initially revealed during examination (area and depth). As larger are overall dimensions of element the method will be more sufficient and easier to

apply, with condition that 3D scanner will characterize with mobile design (set of point clouds from a series of multiple positions scanning).

## 2.1. The method stages

Main stages were set for a method application. The first stage is assignment of models to their variables in an algorithm (Boolean operations):  $\theta$  – pattern solid body,  $\psi$  – sample solid body (from a 3D scanning). Then the second stage is set of the detection volume and dimensions of unit volume (solid model of unit volume assignment –  $\chi$ ).

All input variables are presented in Tab 1, from which no. 4, 5, 6 have no unit because divisions are applied in order to calculate dimensions presented in description column.

Table 1. Set of input data variables

| No. | Variable   | Units | Description                                 |
|-----|------------|-------|---|
| 1.  | $d$        | mm    | Diameter upper limit tolerance dimension    |
| 2.  | $l$        | mm    | Detection volume length                     |
| 3.  | $x_0$      | mm    | Position of detection unit volume in X axis |
| 4.  | $p_\alpha$ | -     | Angular division – $\alpha_p$               |
| 5.  | $p_x$      | -     | Length division – $x_p$                     |
| 6.  | $p_d$      | -     | Diameter division – $r_p$                   |
| 7.  | $T$        | mm    | Diameter tolerance                          |

In the third stage, the primary input data are used in order to solve following equations. First the cylindrical surface (a surface model –  $\zeta$ ) is created with a minimal radius, then a surface area is automatically gained from a 3D model as  $S_\zeta$  variable. After an each radius incrementing and Boolean operation as:

$$\zeta = \zeta_i \cap \psi \quad (1)$$

and while  $S_\zeta = 0$ , a Boolean operation is repeated and a radius is incremented by specified value:

$$r_{min} = r_\zeta + \left( \frac{d}{2 \cdot p_d} \right) \cdot (i-1) \Leftrightarrow S_\zeta > 0, \quad i \in (i..p_d) \quad (2)$$

where:  $i$  – iteration value for which Surface area is greater than 0;  $S_\zeta$  – surface area of cylindrical surface for radius incrementing;  $r_\zeta$  - initial cylindrical surface radius for a radius incrementing.

In fourth stage the unit volume is created with volume value presented with expression:

$$V_p = \widehat{r}_s \cdot r_p \cdot x_p \quad (3)$$

Furthermore dimensions are calculated according to the table 2 (fig 2b). Created unit volume defines a division of a detection volume. Unit volume dimension are used for generating parametrical solid model of a unit volume used for further Boolean operations. In the fifth step the 3D matrix is created with the specified layers set, in target of data record that corresponds to translation through  $x_i$  and rows angular translation  $\alpha_i$ . The first layer contains variable  $u$  value equals 1 when a detected volume is grater then volume deviation  $O_v$ , what corresponds to a diameter tolerance. The volume is being measured after subtraction Boolean operation of a unit volume solid –  $\chi_{ij}$  (target) and a sample solid –  $\psi$  (tool). The data matrix assignment can be formulated as:

$$M[i, j, 1] = 1 \Leftrightarrow V'_{\chi_{ij}} > 0 \quad (4)$$

For volume  $V'_{\chi_{ij}}$  of a solid which is a result of Boolean operation of a unit volume solid and a sample solid – the equation interpretation is presented as:

$$V'_{\chi_{ij}} = V(\chi'_{ij}) = V(\chi_{ij} \cap \psi) \quad (5)$$

where:  $i$  – angle  $\alpha$  division index (angular unit volume position);  $j$  – X axis division index (X axis unit volume position);  $\chi_{ij}$  - solid created according to a unit volume dimensions (unit volume);  $\chi'_{ij}$  solid obtained as a result of subtraction of a unit volume solid and a sample solid;  $\psi$  - sample solid (obtained from 3D scanning of a worn and damaged element). In the rest of cases a matrix is filled in first layer with a zero value. The second matrix layer contains values of  $V'_{\chi_{ij}}$  obtained from subtraction Boolean operation:

$$M[i, j, 2] = V'_{\chi_{ij}} \quad (6)$$

The matrix next layer contains values of a  $x_0$  dimension between volume unit and coordinate system origin:

$$M[i, j, 3] = x_0 \quad (7)$$

The fourth and fifth matrix layer contains accordingly, to an axis coordinates indexes of a unit volume position:

$$M[i, j, 4] = i \quad (8)$$

and

$$M[i, j, 5] = j \quad (9)$$

The next two layers contain dimensions of a unit volume solid:

$$M[i, j, 6] = x_p \quad (10)$$

and

$$M[i, j, 7] = \alpha_p \quad (11)$$

The last layer contains a data of a material loss depth, detected in a specific unit volume, filled during a detection stage:

$$M[i, j, 8] = g_{ij} \quad (12)$$

Table 2. Set of secondary data as an input to method algorithm

| No. | Variable   | Units           | Equations   | Description                                     |
|-----|------------|-----------------|---|---|
| 1.  | $r_p$      | mm              | $r_{\max} - r_{\min}$   | Range of radiuses – unit volume dimension       |
| 2.  | $\alpha_p$ | °               | $\frac{360}{p_\alpha}$  | Unit volume angle range – unit volume dimension |
| 3.  | $x_p$      | mm              | $\frac{l}{p_x}$   | Length of unit volume – unit volume dimension   |
| 5.  | $v_p$      | mm <sup>3</sup> | $\frac{(r_{\max}^2 - r_{\min}^2) \cdot \alpha_p \cdot \pi \cdot x_p}{360}$  | Volume of unit volume                           |
| 6.  | $O_v$      | mm <sup>3</sup> | $\frac{\left( \left( \frac{d}{2} \right)^2 - \left( \frac{d}{2} - \frac{T}{2} \right)^2 \right) \cdot \alpha_p \cdot \pi \cdot x_p}{360}$ | Volume deviation of unit volume                 |
| 7.  | $\Omega$   | -               | $p_\alpha \cdot p_x$  | Total unit volumes quantity                     |

Table 3. Set of output data with equations for their determination

| No. | Variable            | Unit            | Description   | Equation  |
|-----|---------------------|-----------------|---|---|
| 1   | $\Omega_u$          | -               | Total quantity of unit volume with detected material loss                                   | $\Omega_u = \sum_{i=1}^{n=p_\alpha} \sum_{j=1}^{k=p_x} M[i, j, 1]$            |
| 2   | $W_{\Omega_u}$      | %               | Factor of percentage participation of unit volume in total unit volume quantity             | $W_{\Omega_u} = \frac{\Omega_u}{\Omega} \cdot 100\%$                          |
| 3   | $P_u$               | cm <sup>2</sup> | Surface area of material loss that correspond to unit volume distribution                   | $P_u = \frac{\pi \cdot d \cdot l}{p_\alpha \cdot p_x} \cdot \Omega_u$         |
| 4   | $W_{P_u}$           | %               | Factor of percentage participation of surface area in total surface area of element         | $W_{P_u} = \frac{S}{P_u}$   |
| 5   | $V_u$               | cm <sup>3</sup> | Summary volume of material loss after Boolean operation of subtraction on unit volumes      | $V_u = \sum_{i=1}^{n=p_\alpha} \sum_{j=1}^{k=p_x} V'_{x_{ij}}$                |
| 6   | $M_u$               | kg              | Summary mass of material loss depend on volume and density of assigned material to 3D model | $M_u = V_u \cdot \rho$  |
| 7   | $W_{M_u} (W_{V_u})$ | %               | Mass (volume) percentage share of material loss according to total element mass (volume)    | $W_{M_u} (W_{V_u}) = \frac{M}{M_u} \left( \frac{V}{V_u} \right)$              |
| 8   | $G_{sr_u}$          | mm              | Average depth of material loss  | $G_{sr_u} = \frac{\sum_{i=1}^{n=p_\alpha} \sum_{j=1}^{k=p_x} g_{ij}}{\Omega}$ |

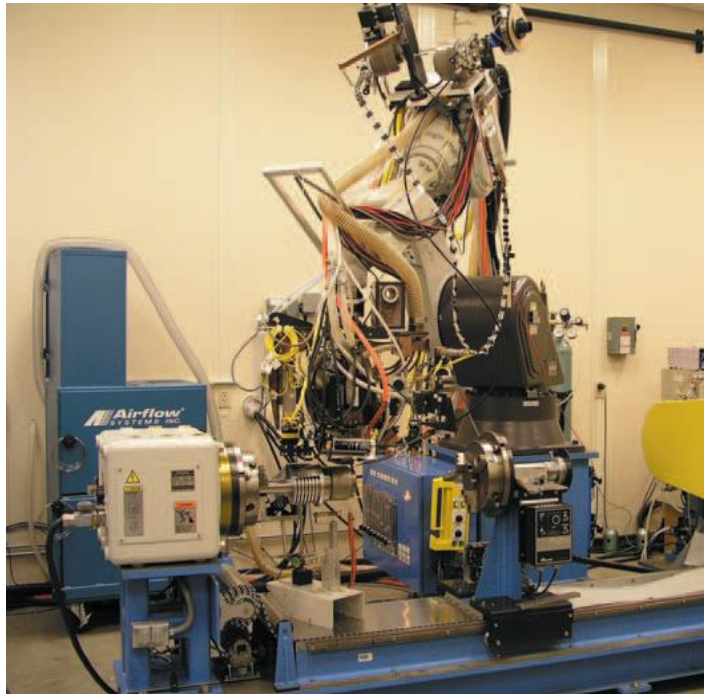


Fig 1. Robotic Laser Cell (RLC), [9]

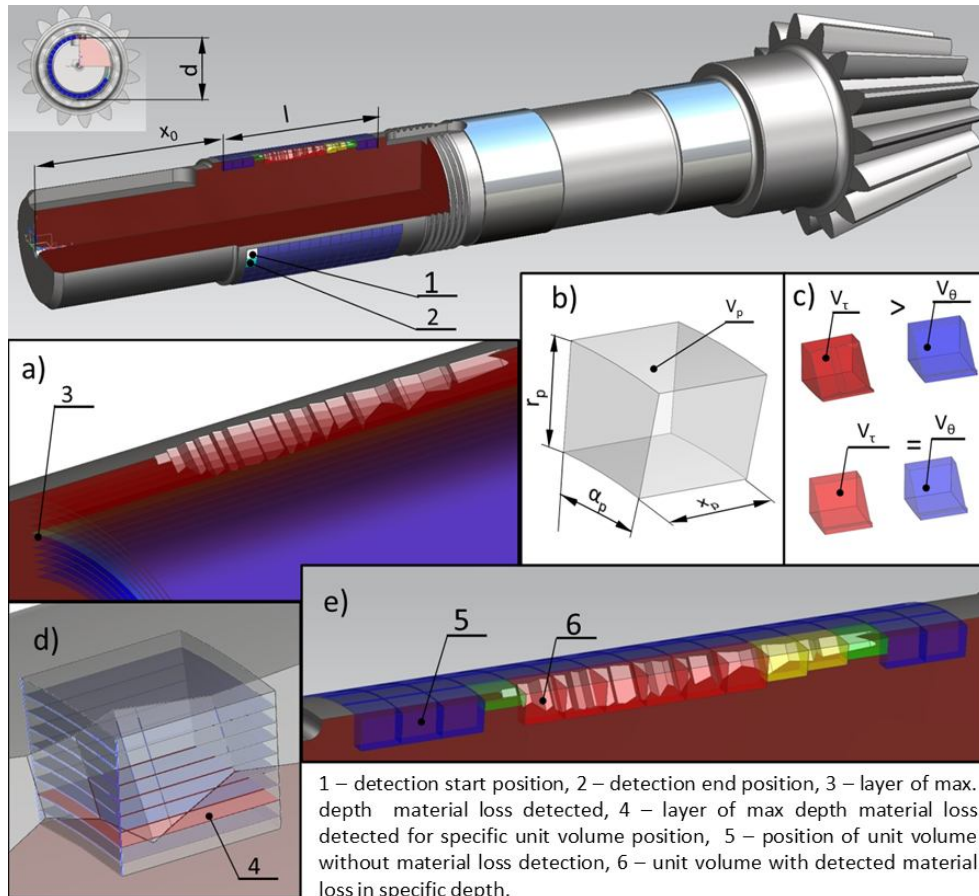


Fig 2. The material loss detection method for cylindrical parts of elements (MLDMCS):  
a) detection of maximum depth for selected detection area, b) unit volume with dimensions set,  
c) volumes comparison on during elimination stage, d) depth detection of material loss in unit volume, e) set of unit volumes with detected depth

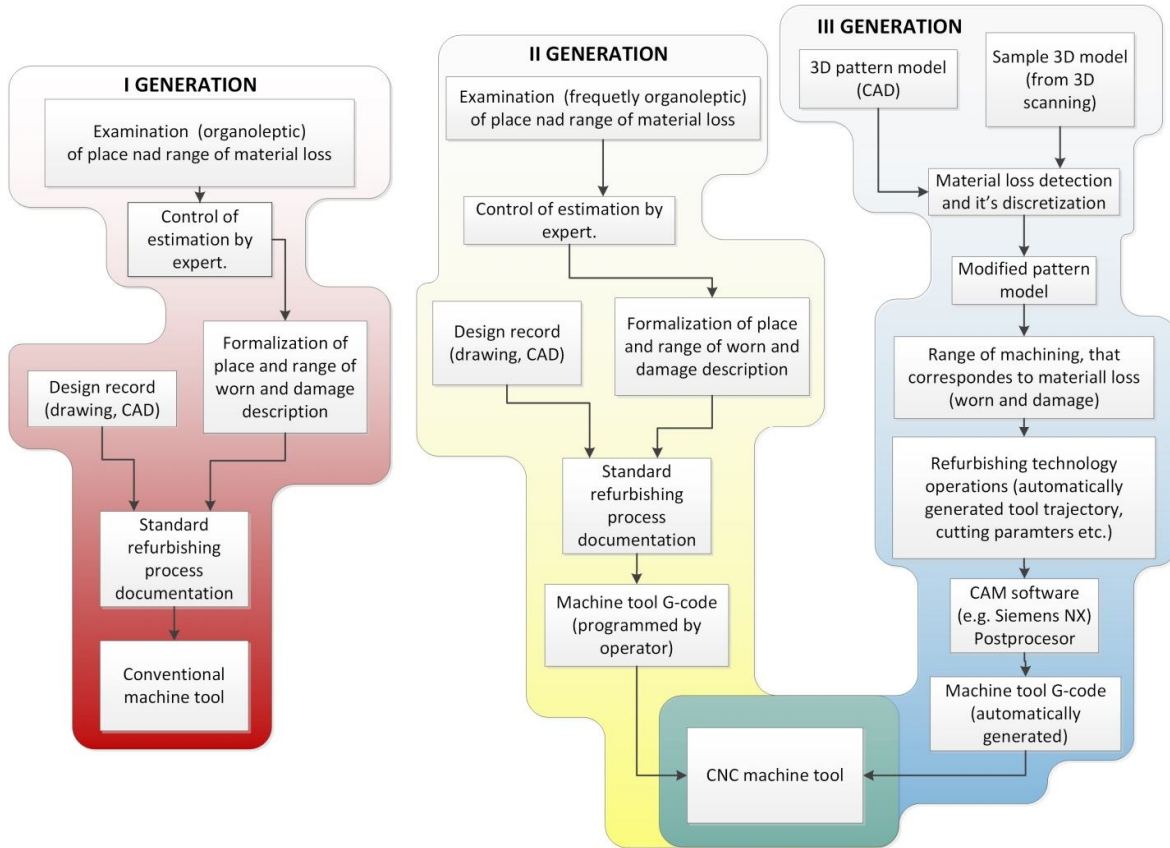


Fig 3. Methods generations used for machining operations preparation in refurbishing technologies and applied types of machine tools: I generation – with conventional machine tools, II and III generation with application of CNC machine tools

The sixth step of MLCMDS is an iterative Boolean subtraction of a unit volumes solid  $\chi_{ij}$  and a pattern solid  $\theta$ :

$$V_{\chi_{ij}}'' = V(\chi_{ij}'') = V(\chi_{ij} - \theta) \quad (13)$$

where:  $\chi_{ij}''$  solid that is a result of subtraction of a unit volume solid and a pattern solid

In the seventh step a comparison is provided for check if material loss is a part of element geometry (for ex. keyway in shaft). This step is called elimination step because, elimination is applied with modification of the first layer in the detection matrix (1 to 0 values). The equation representation is:

$$M[i, j, 1] = 0 \Leftrightarrow V_{\chi_{ij}}'' < V_{\chi_{ij}}'' - O_v \quad (14)$$

In the eighth step only for those unit volumes that are represented in a detection matrix with a value 1 in the first a depth detection will be executed, with incrementing of a cylindrical surfaces sectors radius that correspond to a unit volume dimensions (fig 2d). After that check of condition is executed. If a total area after subtraction of a surface sector and sample solid is greater than 0, then a proper data of a depth of is written in the eighth of detection matrix layer.

$$g_{ij} = r_{\max} - r_{\zeta_{xij}} \Leftrightarrow S_{\zeta_{xij}} > 0 \quad (15)$$

where:  $r_{\zeta_{xij}}$  – radius of surface sector for a specific unit volume (with its position) and for a specific radius incrementing;  $S_{\zeta_{xij}}$  – area of a surface sector for a specific volume and for a specific radius incrementing

At ninth step the solid can be inserted with dimensions of unit volume and correction of a depth value, to obtain a 3D representation of a material loss on sample unit (fig 2e). The detection matrix that gathers all data is designed to provide easy access to selected data. The detection matrix is also needed for generate a material loss distribution map in 2D and 3D.

In order to retrieve a useful data from an examination of material loss detection with proposed method, further transformations of data have to be executed. Data gathered in a detection matrix in a tenth and last stage is used for calculating the output data, which describes a material loss of an element. The data gathered in the table 3 no. 6,7, are calculated with values of a total mass, total volume and assigned material density of an element. This data can be automatically decoded at once from a solid model (e.g. Siemens NX with author software) or read from data base records. In a result, proposed method can

bring wide range of automation (implemented in software) in material loss detection process.

## 2.2. The MLDMCS method limitations

The solution of data collection in database is selected because 3D model of a material loss distribution in some cases (great division numbers  $\alpha_p$  and  $x_p$ ), can occupy large HDD space. The MLDMCS method presents necessity for division in to two main phases. In order to preserve a time reduction of a material loss detection (geometrical transformations and Boolean operations) the main phases are: detection volume set and deepest material loss detection for a total volume (without reference to a pattern solid), elimination of material loss that is defined with a pattern solid and comparison with pattern solid and material loss detection for each unit volume beside of those which are eliminated during previous phase. The MLDMCS method characterize with limitations. The main limitations are: necessity of sample post production geometry preservation (lack of element global deformation) or straighten operation execution for globally deformed element. Proposed mathematical model is established for a 3D sample model which is a result of 3D scanning without a data loss. In practical approach data loss will always be a part of scanning process, especially during a stage of a surface fitting to triangularized model. To prevent detect the whole area as material loss during initial detection is recommended to set deviation value  $O_v$ , with correspondence to element part tolerance. It's recommended also to use typical auto surfacing tool with high surface detail reconstruction (e.g. in GEOMAGIC Software). Additionally a macro file can be prepared to transform a triangularized model in to surface model with set of parameters that can be modified to change accuracy, dependent on element manufacturing accuracy (IT) and overall dimensions. Proper set of a scanning device for 3D scanning process is also a crucial aspect (minimization of measurement uncertainty propagation dependent on scanning angle and distance from scanned object (e.g. of that influence [3]), proper object coverage with antireflection substance or bright paint for dark colours objects). In the MLDMCS method the angular division can affect the angular accuracy of detection. However it's a not important factor in relation to turning technological operation.

## 3. IMPACT OF MLDMCS TO FUTURE INDUSTRIAL APPLICATION

Accuracy of proposed solution strongly depends on future development of computing power and 3D scanning technologies progression. Proposed solution can be applied with 3D laser scanner (laser spot) or

structural light scanner. The second one will be faster in measurement process than the first one, as well as volume will not be limited unlike scanners with closed measuring chamber design. Well know Moore's law shows possibility of high improvement in to industrial application of proposed method during next decade, even if time of measurement and transfer from point cloud to solid model will be a major factor. Mentioned accuracy nowadays makes impossible to use proposed solution in quality control of elements builder below IT10 of tolerance for  $\varnothing 40$  diameter. However to automatically detect a material loss for preparation of element refurbishing process; accuracy is acceptable to apply MLDMCS even today (worn and damage in surface layer can be detected). In fig 3. the III generation of methods generations used for machining operations preparation in refurbishing technologies proposed by author is presented. I and II generation are common in industry. However the main difference is that human participation in process of refurbishing operation preparation (e. g. milling a surface layer in specific area in order to execute cladding operation) is reduced. III generation bring a solution that can give a possibility to use advanced CAM software in order to generate tool paths automatically and offline. Even prepare such operation in CAM software in outside of plant, because main operation preparation procedures are made in abstract. As well as cladding operation and preparation machining operation can be made on workstation similar to presented in fig 1, as well as scanning process can be automated in wide range. Future automation in that matter will be similar to proposed in article, furthermore it's a solution to which industry will develop, because it leads to: refurbishing process time reduce, repeatable results (impossible to sustain with organoleptic estimation), gathering historical data that can be applied for setting limit quantity of refurbishing processes that can be executed on a specific element, especially when proper knowledge representation is provided (e. g. knowledge based system [4]). One of the important aspect is a possibility to in a basis of gathered data prevent failures of exploitation object with describing with higher accuracy it reliability characteristics, [8] (also with renewal approach). Especially Weibull distribution can be adapted with empirical support for similar exploitation objects. Data could be also a support for similar exploitation objects in order to prepare (with automation) a technical state of an exploitation object prognosis [10] Gathered result in database can also be applied in redesigning and modernizing of technical mean system to minimize wear. Redesigning could be then based on gathered data with support of additional methods like: active synthesis of mechanical systems [1] and according to



apply modification to drive systems a comparative synthesis method [2].

#### 4. CONCLUSIONS

The method is already verified on two separate samples, what will be presented in separate article. Presented workstation for turning and cladding should cooperate with proper software [7] in which the method is already implemented) that apply III generation of refurbishing operation preparation. Presented method is programmed in algorithm with order presented in article and is developed with CAD/CAM integration (e.g. models of integrations [5]). Presented limitations should help in implementation of MLDMCS in industry. Similar model can be used for material loss detection for planes, with modification form angle  $\alpha$  to Y axis. Initially, there was a need to relay on cylindrical coordinate system which is not implemented in most CAD software (common is a Cartesian coordinate system), so in practical application the MLDMCS implemented in software forced to define a proper coordinate system. Further research will be also oriented to detect material loss on freeform models. The tool path generated for preparation machining operations can be also used for cladding reconstruction operations with reverse direction (with incrementing of radius) and with change singular pass depth of thickness of layer. Properly turned surface layer (with a third degree curve revolve) can help distribute heat during cladding and preserve element against global deformation caused by heat influence zone.

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