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Faculty of Engineering
Department of Mechanical Engineering

PROCEEDINGS OF THE 3rd INTERNATIONAL SCIENTIFIC CONFERENCE ON ADVANCES IN MECHANICAL ENGINEERING (ISCAME 2015)

19 November, 2015 Debrecen, Hungary

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Scientific Program Committee

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THE BIJECTIVITY OF MONGE PROJECTIONS IN THE PRODUCTION PROCESS OF THE ARCHED WORM GEAR

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Abstract
The development of computer-aided image analysis opened a very wide possibility for the utilisation of CCD cameras and the application of image analysis and evaluation software. During picture evaluation carried out by machines the problem is that we have to reproduce the curves from two perpendicular pictures. This problem awaits a solution in several parts of engineering research work [8]. We have defined the method to reconstruct spatial curves from two perpendicular pictures [1, 3, 10]. Two photos have been taken with CCD cameras from the perpendicular direction of the cutting edge that give us two perpendicular pictures to get the Monge projection, from which the cutting edge or its interpolated spatial curve can be reconstructed. The reconstruction can be guaranteed by properly – suitable for the requirements – placing the cameras in the worm gearing box. The condition of the reconstruction is that the interpolation curve fitted to the cutting edge of the worm should not have a tangent in profile position. The present paper describes the formulation of these requirements with mathematical devices.

Keywords: *cutting edge, hob, wear, CCD cameras, Monge-cuboid.*

1. INTRODUCTION

The most important research field of the group of researchers at the Department of Production Engineering at Miskolc University is the arched worm gear drive pairs [3, 5, 6, 7]. The cylindrical helicoidal surface is generated by a circle with radius ρ_{ax} in axial section.

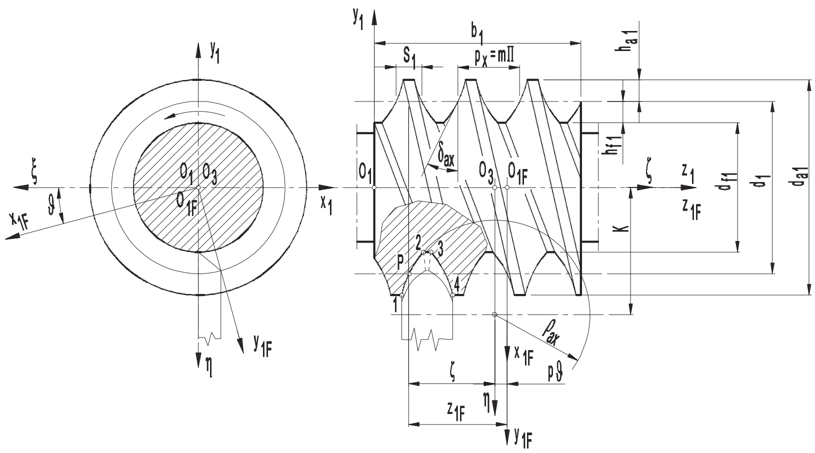

Figure 1 The cylindrical worm with circle profile in axial section [5]

The right-hand side surface of the worm in the rotating coordinate system $K_{F1}(x_{F1}, y_{F1}, z_{F1})$ can be written in the following form

$$\left.\begin{aligned} x_{1F} &= -\eta \cdot \sin\vartheta \\ y_{1F} &= \eta \cdot \cos\vartheta \cdot \\ z_{1F} &= p \cdot \vartheta - \sqrt{\rho_{ax}^2 - (K-\eta)^2} \\ t_{1F} &= t_{sz} = 1 \end{aligned}\right\}, \tag{1}$$

where η and ϑ are parameters of the helicoidal surface, p is the screw parameter of the helix on the worm, ρ_{ax} is the radius of the tooth profile in axial section, K is the distance between the centre of profile circle and worm ace.

The cutting edge V of the hob created from the worm can be obtained as an intersection of the backward grinded side surface R and the face surface H, while it must fit the replacing worm surface.

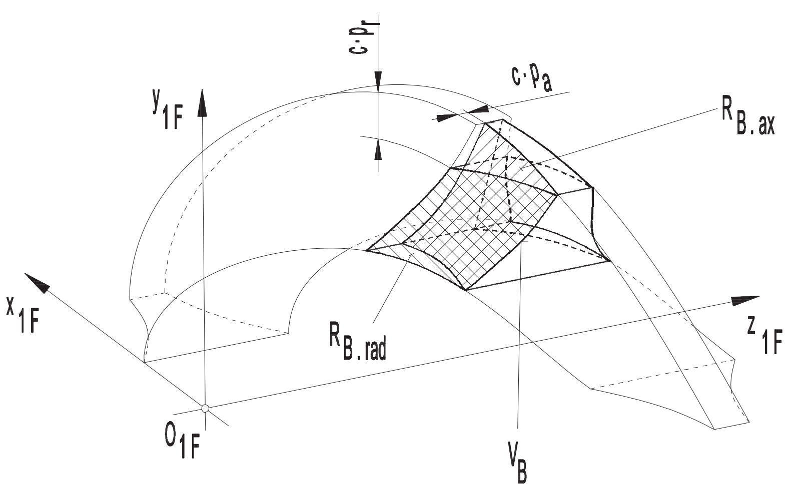

Figure 2 The cutting edge of the tooth surfaces of the hob in the rotation coordinate system [5]

The equation of the face surface is

$$\left.\begin{aligned} x_h &= -\eta \cdot \sin(\vartheta + \varphi_{oh}); \\ y_h &= +\eta \cdot \cos(\vartheta + \varphi_{oh}); \\ z_h &= -p_h \cdot \sin(\vartheta + \varphi_{oh}); \end{aligned}\right\} \tag{2}$$

The cutting edge V can be obtained as an intersection of the three surfaces:

- the relief side surface R, and/or Rb;
- the face surface H;
- the tooth surface of the substituting worm J and/or B.

The equation of the cutting edge in the examined case is the following:

$$\left.\begin{aligned} x_v &= -\eta \cdot \sin \frac{\sqrt{\rho_{ax}^2 - (K-\eta)^2} - z_{ax}}{p + p_h} \\ y_v &= \eta \cdot \cos \frac{\sqrt{\rho_{ax}^2 - (K-\eta)^2} - z_{ax}}{p + p_h} \\ z_v &= -p_h \cdot \frac{\sqrt{\rho_{ax}^2 - (K-\eta)^2} - z_{ax}}{p + p_h} \end{aligned}\right\} \qquad (3)$$

We have done an analysis method of the wearing of the cutting edge of the hob in case of arched worm in our research work.
The wearing of the cutting edge of the hob is checked by CCD cameras in the production process to achieve precision manufacturing.

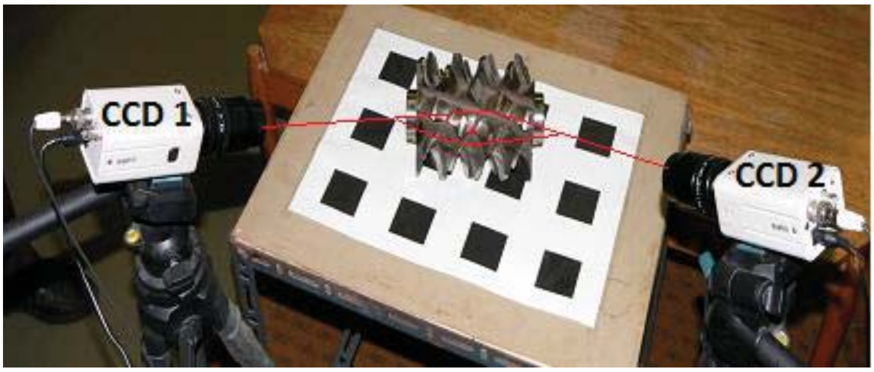

Figure 3 The measuring of the cutting edge with correctly placed CCD cameras

2. THE METHOD OF CORRECTLY PLACED CCD CAMERAS

There is a possibility for in-process cutting edge monitoring dimension inspection. During picture evaluation by machines the reconstruction of the cutting edge from two pictures without other information is not guaranteed. Correctly placed CCD cameras can solve this problem [3]. Our method describes the possibility to achieve such positions of CCD cameras, in which the reconstruction of the spatial curve can be carried out only with two pictures are fitted to the cutting edge of the hob. We consider the two pictures done by perpendicularly placed CCD cameras, as a Monge-projection of the cutting edge of the hob.
The representation of a point in Monge projection unambiguous provided the well-known conventions are fulfilled [9]. For example the representation of a circle of general position and the profile line is not bijective [9, 10]. Two perpendicular projections are not different in practice, if they can be translated to each other [4, 5, 6, 7].
We consider those Monge projections identical, which can be translated to one another. Projection lines and image planes go through the origin point in a fixed Descartes coordinate system. The Monge projections are determined by their projection lines [10]. The number of Monge projections to a given curve can be described by using three free real parameters that we have defined (Figure 4). The first direction angel is α and β is the second direction angel of the first projection line v_1,

and γ is the third direction angel of the second projection line of v_2. The triplet of all numbers (α, β, γ), which gives the Monge projection, creates the Monge cuboid.

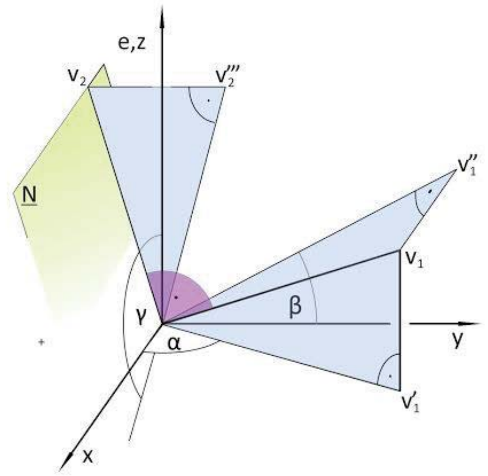

Figure 4 The first direction angel α and the second direction angel β of the first projection line v_1 and the third direction angel γ of the second projection line v_2 [10]

The inner points of the Monge cuboid satisfy the following condition

$$0<\alpha<\pi,\ 0<\beta<\pi/2,\ \pi/2<\beta<\pi,\ 0<\gamma<\pi. \quad (4)$$

The border points on the Monge cuboid satisfy the following conditions

- $0<\alpha<\pi$, $\beta=\pi$, $0<\gamma<=\pi$,
- $0<\alpha<\pi$, $0<\beta<\pi/2$, $\pi/2<\beta<=\pi$, $\gamma=\pi$,
- $\alpha=\pi$, $\beta=\pi/2$, $0<\gamma<\pi/2$, $\pi/2 <\gamma<\pi$,
- $\alpha=0$, $\beta=\pi/2$, $\gamma=\pi/2$
- $\alpha=\pi$, $\beta=0$, $\gamma=\pi$. (5)

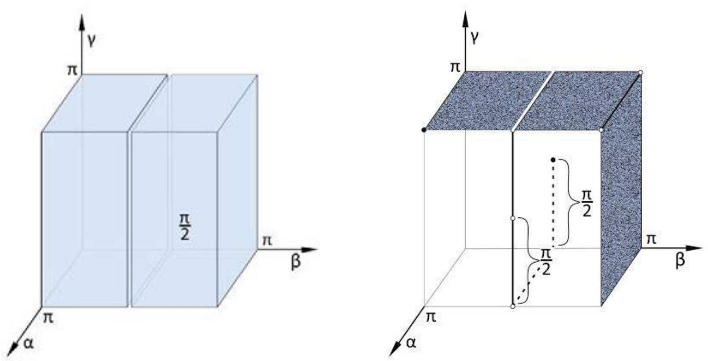

Figure 5 The inner points and border points of the Monge cuboid [10]

This method does not discuss all Monge projections, but discusses all two perpendicular projections, which is relevant in engineering work. The examination of the bijectivity with respect to a given curve gives us the same result if the first and second images are changed.

If the Monge projection of the curve of the cutting edge of the hob does not have a tangent in the situation of the profile line, then any part of the curve can be reconstructed from two pictures without any further information. All these situations provide us with correctly placed CCD cameras.

3. THE METHOD OF THE CUTTING EDGE ANALYSIS

Using cubic interpolation Bezier curve fitted to the cutting edge of the hob is recommended to do the examination in our research work [8]. Fitting the cubic Bezier curve to proportionally selected four points on the cutting edge gives us a correctly approaching spatial curve.

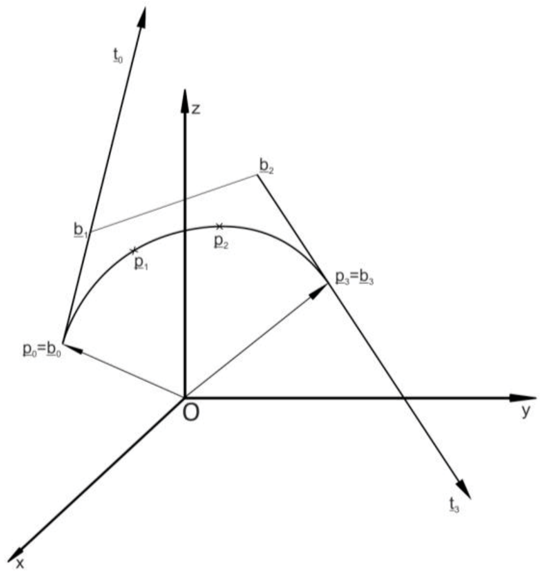

Figure 6 The connection of the Hermite arc and the Bezier curve

The Bezier curve is interpolated to the given points $\underline{p}_0$, $\underline{p}_1$, $\underline{p}_2$, $\underline{p}_3$ using parameters u_0, u_1, u_2, u_3, where $u_i \neq u_j$, if the $i \neq j$, and $u_0 = 0$, $u_3 = 1$.
We are looking for control points $\underline{b}_0$, $\underline{b}_1$, $\underline{b}_2$, $\underline{b}_3$, that determine the Bezier curve fitting to points $\underline{p}_0$, $\underline{p}_1$, $\underline{p}_2$, $\underline{p}_3$, so

$$\underline{b}(u_i)=\underline{p}_i \quad (i=0,\dots,3). \tag{6}$$

The equation of the Bezier curve is determined in the following formula

$$\underline{b}(u)=\sum_{j=0}^{n} B_j^n(u)\,\underline{b}_j\ , \tag{7}$$

where $B_j^n(u)=\binom{n}{j}u^j(1-u)^{n-j}$ are Bernstein polynomial.

As it was mentioned earlier, the Bezier curve fitting to given points can be described in the following equation in case (i=0,...,3)

$$\underline{b}(u_i)=\sum_{j=0}^{n} B_j^n(u_i)\,\underline{b}_j\ . \tag{8}$$

Using the $\underline{b}(u_i)=\underline{p}_i$ (i=0,…,3) equation we can get the following linear inhomogeneous equation system

$$\begin{bmatrix} \underline{p}_0 \\ \underline{p}_1 \\ \underline{p}_2 \\ \underline{p}_3 \end{bmatrix} = \begin{bmatrix} B_0^3(u_0) & B_1^3(u_0) & B_2^3(u_0) & B_3^3(u_0) \\ B_0^3(u_1) & B_1^3(u_1) & B_2^3(u_1) & B_3^3(u_1) \\ B_0^3(u_2) & B_1^3(u_2) & B_2^3(u_2) & B_3^3(u_2) \\ B_0^3(u_3) & B_1^3(u_3) & B_2^3(u_3) & B_3^3(u_3) \end{bmatrix} \cdot \begin{bmatrix} \underline{b}_0 \\ \underline{b}_1 \\ \underline{b}_2 \\ \underline{b}_3 \end{bmatrix}. \tag{9}$$

The $u_i \neq u_j$ condition provides us with the result of the unambiguous solution to $\underline{b}_i$. So we receive the $\underline{b}_i$ control points of the interpolation Bezier curve fitting to point $\underline{p}_0$, $\underline{p}_1$, $\underline{p}_2$, $\underline{p}_3$.

The connection between the Bezier curve and the Hermite arc can be written in the following formula

$$\begin{aligned} \underline{p}_0 &= \underline{b}_0, \\ \underline{t}_0 &= 3\cdot\underline{b}_1 - 3\cdot\underline{b}_0, \\ \underline{p}_3 &= \underline{b}_3, \\ \underline{t}_3 &= 3\cdot\underline{b}_3 - 3\cdot\underline{b}_2. \end{aligned} \tag{10}$$

when the Hermite arc are given with points $\underline{p}_0$, $\underline{p}_3$ and then tangents $\underline{t}_0$, $\underline{t}_3$, where $u\in[0,1]$.
The Hermite arc can be written in parametric form, as

$$\underline{r}(u)=\underline{a}_3\cdot u^3+\underline{a}_2\cdot u^2+\underline{a}_1\cdot u+\underline{a}_0, \tag{11}$$

Tangent vectors can be described in the following form

$$\underline{r}_e(u) = \underline{e}_1\cdot u^2 + \underline{e}_2\cdot u + \underline{e}_3 \tag{12}$$

If we shift tangent vectors to the origin point O, we get the cone of tangents. If profile planes of Monge projections fit in the origin point, they have two, one or zero generator lines of the cone of tangents. If the profile plane of a Monge projection do not contain a tangent vector of the cone of tangents, the description of any part of the curve is bijective.

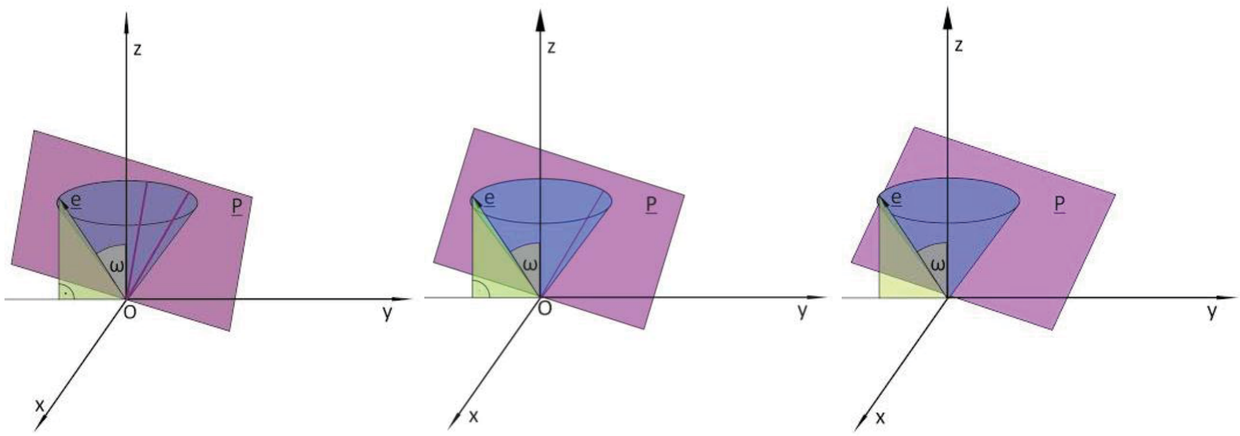

Figure 7 The profile plane contains one or two tangent vectors and does not contain a tangent vector of the Hermite arc

If the profile plane of the Monge-projection of the spatial curve does not contain a tangent vector of the curve, the description of any part of the curve is bijective [1, 10].
Normals $\underline{n}$ (n_x, n_y, n_z) of these planes are perpendicular to the tangents that satisfy the following equation:

$$\underline{n} \cdot \underline{r}_e(u) = 0, \tag{13}$$

We are looking for normal vectors $\underline{n}$ (n_x, n_y, n_z) of profile planes of Monge projections, to which the equation of the second degree considering u in case the given e_{ij} does not have any solutions. In this case the profile planes do not have tangent vectors of the given curve, so the description of the curve is bijective.
The condition can be written in a simplified way in the following form

$$c_1 \cdot n_x^2 + c_2 \cdot n_y^2 + c_3 \cdot n_z^2 + c_{12} \cdot n_x \cdot n_y + c_{13} \cdot n_x \cdot n_z + c_{23} \cdot n_y \cdot n_z < 0 \tag{14}$$

where

$$\begin{aligned} c_1 &= e_{2x}^2 - 4 \cdot e_{1x} \cdot e_{3x}, \\ c_2 &= e_{2y}^2 - 4 \cdot e_{1y} \cdot e_{3y}, \\ c_3 &= e_{2z}^2 - 4 \cdot e_{1z} \cdot e_{3z}, \\ c_{12} &= 2 \cdot e_{2x} \cdot e_{2y} - 4 \cdot e_{1x} \cdot e_{3y} - 4 \cdot e_{1y} \cdot e_{3x}, \\ c_{13} &= 2 \cdot e_{2x} \cdot e_{2z} - 4 \cdot e_{1x} \cdot e_{3z} - 4 \cdot e_{1x} \cdot e_{3z}, \\ c_{23} &= 2 \cdot e_{2y} \cdot e_{2z} - 4 \cdot e_{1y} \cdot e_{3z} - 4 \cdot e_{1z} \cdot e_{3y}. \end{aligned} \tag{15}$$

Bijective Monge projections are determined by points from the border of the Monge cuboid, which points satisfy the following condition:

If $\alpha=\pi$, $\beta=0$, $\gamma=\pi$, or $\alpha=0$, $\beta=\pi/2$, $\gamma=\pi/2$, or $\alpha=\pi$, $\beta=\pi/2$, $0<\gamma<\pi/2$, $\pi/2<\gamma<\pi$, the

$$c_2 < 0 \tag{16}$$

condition give us bijective Monge projections of the given curve.
If $0<\alpha<\pi$, $\beta=\pi$, $\gamma=\pi/2$, the

$$c_3 < 0 \tag{17}$$

condition give us bijective Monge projections of the given curve.
If $0<\alpha<\pi$, $\beta=\pi$, $\gamma=\pi$, the

$$c_1 \cdot \sin^2\alpha + c_2 \cdot \cos^2\alpha - c_{12} \cdot \sin\alpha \cdot \cos\alpha < 0 \tag{18}$$

condition give us bijective Monge projections of the given curve.
If $0<\alpha<\pi$, $\beta=\pi$, $0<\gamma<\pi/2$, $\pi/2<\gamma<\pi$, the

$$c_1 \cdot \sin^4\alpha/\mathrm{tg}^2\gamma + c_2 \cdot \cos^2\alpha \cdot \sin^2\alpha/\mathrm{tg}^2\gamma + c_3 - c_{12} \cdot \cos\alpha \cdot \sin^3\alpha/\mathrm{tg}^2\gamma + c_{13} \cdot \sin^2\alpha/\mathrm{tg}\gamma - c_{23} \cdot \cos\alpha \cdot \sin\alpha/\mathrm{tg}\gamma < 0 \tag{19}$$

condition give us bijective Monge projections of the given curve.

If $\alpha=\pi/2$, $0<\beta<\pi/2$, $\pi/2<\beta<\pi$, $\gamma=\pi$, the

$$c_1 < 0 \tag{20}$$

condition give us bijective Monge projections of the given curve.
If $0<\alpha<\pi/2$, $\pi/2<\alpha<\pi$, $0<\beta<\pi/2$, $\pi/2<\beta<\pi$, $\gamma=\pi$ the

$$\begin{gathered} c_1 + c_2\cdot(\mathrm{tg}\gamma - \mathrm{ctg}\beta\cdot\mathrm{ctg}\alpha)^2/(\mathrm{ctg}\beta+\mathrm{ctg}\alpha\cdot\mathrm{tg}\gamma+\mathrm{tg}\beta)^2 + \\ c_3\cdot\mathrm{ctg}^2\alpha/(-\mathrm{tg}\beta-\mathrm{ctg}\beta)^2 + \\ c_{12}\cdot(\mathrm{tg}\gamma-\mathrm{ctg}\beta\cdot\mathrm{ctg}\alpha)/(\mathrm{ctg}\beta+\mathrm{ctg}\alpha\cdot\mathrm{tg}\gamma+\mathrm{tg}\beta) + c_{13}\cdot\mathrm{ctg}\alpha/(-\mathrm{tg}\beta-\mathrm{ctg}\beta) + \\ c_{23}\cdot\mathrm{ctg}\alpha\cdot(\mathrm{tg}\gamma - \mathrm{ctg}\beta\cdot\mathrm{ctg}\alpha)/(\mathrm{ctg}\beta + \mathrm{ctg}\alpha\cdot\mathrm{tg}\gamma + \mathrm{tg}\beta)\cdot(-\mathrm{tg}\beta - \mathrm{ctg}\beta) < 0 \end{gathered} \tag{21}$$

condition give us bijective Monge projections of the given curve.
If $\alpha=\pi/2$, $0<\beta<\pi/2$, $\pi/2<\beta<\pi$, $\gamma=\pi/2$ esetén $\underline{n}(0, -\sin\beta, \cos\beta)$, the

$$c_2\cdot\sin^2\beta + c_3\cdot\cos^2\beta - c_{23}\cdot\sin\beta\cdot\cos\beta < 0 \tag{22}$$

condition give us bijective Monge projections of the given curve.
If $\alpha=\pi/2$, $0<\beta<\pi/2$, $\pi/2<\beta<\pi$, $0<\gamma<\pi/2$ $\pi/2<\gamma<\pi$

$$\begin{gathered} c_1 + c_2\cdot\mathrm{tg}^2\gamma/(\mathrm{tg}\beta+\mathrm{ctg}\beta)^2 + c_3\cdot\mathrm{tg}^2\gamma\cdot\mathrm{ctg}^2\beta/(-\mathrm{tg}\beta-\mathrm{ctg}\beta)^2 + c_{12}\cdot\mathrm{tg}\gamma/(\mathrm{tg}\beta+\mathrm{ctg}\beta) + \\ c_{13}\cdot\mathrm{tg}\gamma\cdot\mathrm{ctg}\beta/(-\mathrm{tg}\beta-\mathrm{ctg}\beta) + c_{23}\cdot\mathrm{tg}^2\gamma\cdot\mathrm{ctg}\beta/(\mathrm{tg}\beta+\mathrm{ctg}\beta)\cdot(-\mathrm{tg}\beta-\mathrm{ctg}\beta) < 0 \end{gathered} \tag{23}$$

condition give us bijective Monge projections of the given curve.
If $0<\alpha<\pi/2$, $\pi/2<\alpha<\pi$, $0<\beta<\pi/2$,$\pi/2<\beta<\pi$, $\gamma=\pi/2$ the

$$\begin{gathered} c_1\cdot(\mathrm{tg}\alpha\cdot\mathrm{ctg}\gamma + \mathrm{tg}\beta + \mathrm{tg}\alpha\cdot \mathrm{tg}^2\beta\cdot\mathrm{ctg}\gamma)^2/(-\mathrm{ctg}\alpha - \mathrm{tg}\beta\cdot\mathrm{ctg}\gamma - \mathrm{tg}\alpha)^2 + \\ c_2\cdot(\mathrm{tg}\alpha\cdot\mathrm{tg}\beta - \mathrm{ctg}\gamma)^2/(-\mathrm{ctg}\alpha - \mathrm{tg}\beta\cdot \mathrm{ctg}\gamma - \mathrm{tg}\alpha)^2 + c_3 + \\ c_{12}\cdot (\mathrm{tg}\alpha\cdot\mathrm{ctg}\gamma + \mathrm{tg}\beta + \mathrm{tg}\alpha\cdot\mathrm{tg}^2\beta\cdot\mathrm{ctg}\gamma)\cdot(\mathrm{tg}\alpha\cdot\mathrm{tg}\beta - \mathrm{ctg}\gamma)/(-\mathrm{ctg}\alpha - \mathrm{tg}\beta\cdot\mathrm{ctg}\gamma - \mathrm{tg}\alpha)^2 + \\ c_{13}\cdot(\mathrm{tg}\alpha\cdot\mathrm{ctg}\gamma + \mathrm{tg}\beta + \mathrm{tg}\alpha\cdot\mathrm{tg}^2\beta\cdot\mathrm{ctg}\gamma)/(-\mathrm{ctg}\alpha - \mathrm{tg}\beta\cdot\mathrm{ctg}\gamma - \mathrm{tg}\alpha) + \\ c_{23}\cdot(\mathrm{tg}\alpha\cdot\mathrm{tg}\beta - \mathrm{ctg}\gamma)/(-\mathrm{ctg}\alpha - \mathrm{tg}\beta\cdot\mathrm{ctg}\gamma - \mathrm{tg}\alpha) < 0. \end{gathered} \tag{24}$$

condition give us bijective Monge projections of the given curve.

CONCLUSIONS

The aim of the paper was to reconstruct the cutting edge of the hob without any further information is achieved.
The theorem of the insurance of the bijectivity between the spatial curve and its two perpendicular images was shown in this article. Furthermore, the correct positions of the cameras to reconstruct the interpolated curve fitting to the cutting edge of the hob were calculated. The right positions of the CCD cameras can check the wearing in the production process without other information in the gear box.

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