Spatial motions transformers for incorporation into robot systems – review of the Bulgarian experience

Emilia Abadjieva[1, 2*]

[1]Institute of Mechanics – Bulgarian Academy of Sciences, Sofia, Bulgaria
[2]Center of Competence MIRACLe – Mechatronics Clean Technologies, Sofia, Bulgaria
*abadjieva@gmail.com

Abstract: This work is a review of research carried out by the author on the synthesis and design of the spatial gear mechanisms, oriented for incorporation in various technical devices, especially in robotic systems. It contains also a description of the innovative and inventive activities of the author over the years. The study illustrates the elaborated through the years, basic algorithms for the synthesis of spatial motions transformers (in particular Spiroid and Helicon gear sets), which are based on the mathematical model for synthesis upon a pitch contact point. The content of the solution of the two main tasks of the synthesis - synthesis of the pitch configurations and synthesis of the active tooth surfaces configures the mentioned above algorithm. Through it, real models of Spiroid and Helicon gear transmissions are synthesized and elaborated by 3D printing subsequently, which are designed for incorporation into robots of various purposes

1 Introduction

The process of joining Bulgaria to the European Union is accompanied by continuous growth and the extreme importance of the increasing competitiveness of Bulgarian companies and their ability to withstand competitive pressure and market forces. That is why the implementation of scientific achievements and new technologies and the development of innovative potential are crucial for strengthening Bulgarian manufacturing and from there - increasing employment and achieving economic growth [1, 2]. Following the defined objectives from the program for economic reform, adopted by the European Council at Lisbon in 2000, extended in Gothenburg, and improved at Stockholm and Barcelona, the actions of the member countries of the European Union should be directed towards identifying the priority areas, among which the *encouragement of innovations* is an essential one. The Lisbon process requires to be found tools for the encouragement of competitive industries with the potential for future development that could have a significant impact on the change of the economy. A key tool to achieving the high competitiveness of a national economy is the development and consistent application of the policies for the implementation of national innovations. Without going into details on the Bulgarian national innovation policy, we will note that by Decision № 723 / 2004 of the Council of Ministers an *Innovation strategy of the Republic of Bulgaria and the measures for its realization* are accepted. The main goals of this first innovation strategy are related to creating conditions for stimulation of the scientific research with a view to creating innovative technologies and products and their subsequent implementation. In the discussed strategy, a series of measures for its implementation are intended. Among them, the most significant is *to optimize the relationships: science-technology-innovation*. By Decision № 875/2015 of the Council of Ministers the new project - an innovation strategy for smart specialization 2014 -2020 is approved. Its goal is: *By 2020 Bulgaria should move into the group of "moderate innovators"*.

The objectives and measurements, contained in both national innovation strategies, are presented to a maximum extent by the author of this study in the field of hyperboloid gear transmissions. This current research provides a review of the author's approach through the last 20 years to the synthesis of crossed axes gear mechanisms, as well as their implementation as drives of actuators and transport devices into robotic systems.

2 Methods

2.1 Spiroid and Helicon gears- specific characteristics

The spatial transformation of rotations with constant angular velocities between fixed crossed axes is realized by three-link gear mechanisms, known as hyperboloid gears. This name is related to the form of their axodes (see Fig. 1), which are two mating hyperboloids of revolution, whose geometric axes coincide with the rotation axes. The contact line of the hyperboloids is the axis of the screw motion of the rotation links. The dimensions and the geometry of the hyperboloids, which are determined uniquely, depend on the parameters that are defining the dimensions and the structure of the gear set, as well as the gear ratio that characterizes the type of rotation transformation.

Skew-axes gear pairs transforming rotations using conjugate tooth surfaces are widely used among known motion transformers. They could realize the exact motion law (i.e. the gear ratio) they are designed to. The successful use of hyperboloid gears with new kinematic and strength characteristics in the industry makes slow progress because:

- common principles of transformation of rotations between skewed axes are not well examined;
- approaches to the mathematical modelling of synthesis of these types of mechanisms are not defined.

Spiroid[1] and Helicon gear pairs, which are the objects of this study, belong to one of the most progressive and comparatively less applied in the engineering practice type of skew-axes gears. These types of transmissions are known from [3-9, 11-13], etc. The first patents are introduced in the USA by Illinois Tool Works, Chicago. The firm has constructed the series of power classes and exactness tolerances classes of Spiroid gears and has organized the manufacture of Spiroid gear trains with a general function.

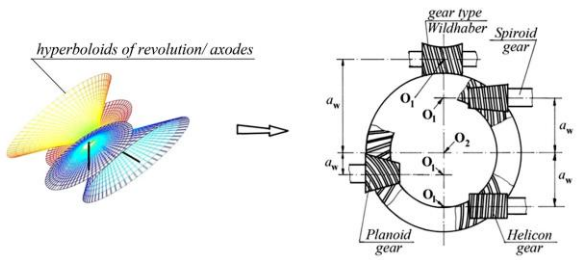

Fig. 1. Family of skew-axes gears.

Among progressive combinations of spatial gears, Spiroid and Helicon gears occupy one essential place [14]. The placement of the mesh region, geometry, and technology of elaboration of these hyperboloid gears is the reason they are treated as a hybrid between hypoid gear sets and worm ones. For this reason, Spiroid and Helicon gear sets obtain constructive, technological, and exploitation characteristics that make them suitable for application as power and kinematic gear mechanisms, which ensure the smooth and noiseless rotations transformation and with a possibility to realize mating without a backlash between mating tooth surfaces. A possible interval or reduction angular velocity ratios is $i_{12} \in [10, \ 200]$. This does not limit the possibility of obtaining gear sets with angular velocity ratios not belonging to this interval. The typical characteristic of the Spiroid and Helicon gears is a big number of simultaneously contacting teeth. The number of simultaneously contacting teeth of Spiroid and Helicon gears is 3-4 times bigger than for worm gears for angular velocity ratios in the interval $[10, \ 60]$. The mentioned specific characteristics of these gear sets are the main reasons for their successful integration into the construction of the robotic systems.

[1] Spiroid and Helicon are a trademark registered by the Illinois Tool Works, Chicago, Ill.

2.2. Synthesis of Spiroid and Helicon gears using a pitch contact point

Two approaches [1, 2], oriented to the mathematical modelling, to the synthesis of hyperboloid gear sets: „*upon a pitch contact point*" and „*upon a mesh region*" respectively, are known. Here, the focus will be put on the first approach, which is characterized by a certain universality and the possibility of realizing an optimization of the synthesized transmissions. The mathematical model for synthesis *upon a pitch contact point* is based on the assumption that the necessary quality characteristics (that define concrete exploitation and technological requirements to the active tooth surfaces) are guaranteed only at one concrete point P of the active tooth surfaces Σ_1 and Σ_2, and in its close vicinity. According to this model, the common contact point P of the conjugate tooth surfaces Σ_1 and Σ_2 is the common point of both circles H_i^c ($i = 1, \ 2$) which are called *a pair of pitch circles* $(H_1^c : H_2^c)$. The point P is called *a pitch contact point*, the plane T_m including the tangents to H_i^c $(i = 1, \ 2)$ at the point P – *a pitch plane*, and $m - m$ is the *pitch normal* to T_m at the point P. The pair of rotation surfaces that include the corresponding pairs of pitch circles and whose common normal at the point P is the straight-line $m - m$, are an analog of H_i^c $(i = 1, \ 2)$ and are called *pitch surfaces* H_i^s $(i = 1, \ 2)$. The pair of circles $(H_1^c : H_2^c)$ is directly related to the evaluation of the pitch and the tooth module of the designed gear set. The pitch circles and surfaces' parameters define the dimensions of the reference surfaces, i.e., the blank proportions of the gears depend on them. These parameters are used when the mountings' dimensions of the synthesized gear-set are calculated.

Thus, the mathematical model for synthesis based on a pitch contact point ensures the solution to two basic problems:

- synthesis of the pitch configurations;
- synthesis of the active tooth surfaces.

Pitch configurations synthesis: essence, definition, and mathematical modeling. The present paper treats the kinematic theory of the spatial rotations transformation in the context of defining the geometric and kinematic essence of basic elements of the mathematical models for the synthesis of hyperboloid gears and their role in solving the gears' synthesis. One of the most important elements are so-called *pitch configurations* (*pitch circles and pitch surfaces*) and deal with one actual but still disputable (as content and terminology) part of the meshing theory.

From the performed analysis of the above publications and the corresponding comments, it can be concluded that:

- If the law of transformation of rotations $i_{12}=\omega_1/\omega_2=const.$ ($\overline{\omega}_i$ - angular velocity of the rotating link i) between fixed and crossed axes $1-1$ and $2-2$ (the shortest distance between them is $a_w=const.$ and the angle between them is $\delta=\angle(\overline{\omega}_1,\overline{\omega}_2)=const.$) is given, and if the position of a point (treated as a point of contact of conjugate tooth surfaces Σ_1 and Σ_2) in the fixed space is known, then the diameters and the mutual position of the circles H_i^c $(i=1,\ 2)$ are completely and uniquely determined. The circumferential velocity vectors $\overline{V}_i$ $(i=1,\ 2)$ of the common point P, and the relative velocity vector $\overline{V}_{12}$ at the same point, (i. e. the plane T_m where the coplanar vectors $\overline{V}_i$ $(i=1,\ 2)$ and $\overline{V}_{12}$ lie), as well as the normal $m-m$ to T_m at the point P are determined uniquely, too.

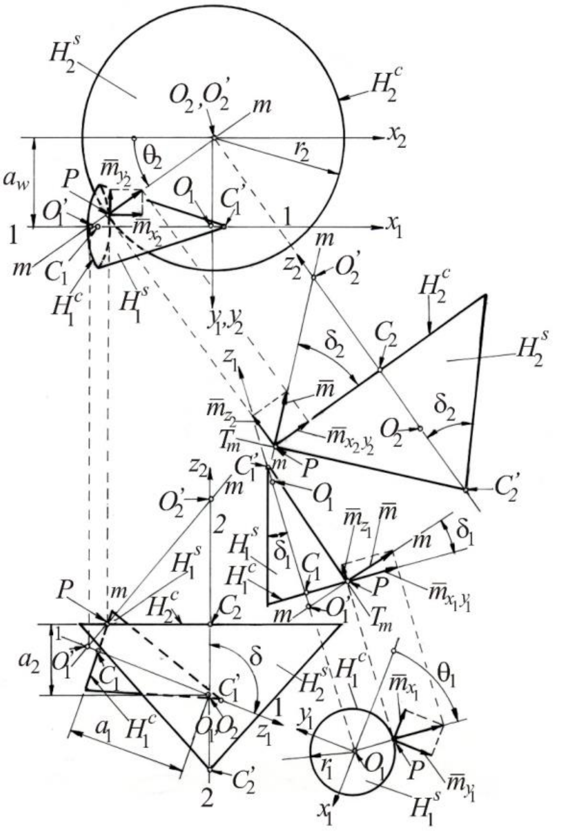

Fig. 2. Externally contacting pitch circles H_i^c $(i=1,\ 2)$ and pitch surfaces H_i^s $(i=1,\ 2)$ with a normal orientation, corresponding to hyperboloid gears with external meshing.

- It is sufficient to know the mutual position of the crossed axes of rotation $1-1$ and $2-2$, and the position of the point P (as a common point of the tooth surfaces Σ_1 and Σ_2) in the fixed space, for the circles H_i^c $(i=1,\ 2)$ to be completely and uniquely determined (as diameters and mutual position). The plane T_m formed by the tangents to the circles H_i^c $(i=1,\ 2)$ at the point P, as the normal $m-m$ to T_m at the point P is uniquely determined, too.

In the most common case, the defined pitch configurations do not coincide with elements of the axodes of this class gear mechanisms, the axodes being hyperboloids of revolution. Let two crossed axes $1-1$ and $2-2$, representing the axes of rotations of the movable links of a three-link gear mechanism, be given in the fixed space. Their mutual position is defined by the angle $\delta=const.$ (the angle between the angular velocity vectors $\overline{\omega}_1$ and $\overline{\omega}_2$ of the movable links $(i=1,\ 2)$) and the shortest distance $a_w=const$. The concrete study is realized when $\delta\in(0,\pi)$. Each pitch circle H_i^c lies in a plane perpendicular to the axis of rotation i - i of the movable link i and has a radius equal to the distance from the point P to the axis i - i. The pitch plane T_m is determined by the tangents to the circles H_1^c and H_2^c at the pitch contact point P. Besides, the pitch normal $m-m$ to T_m is determined at P. The study performs using the notations and the coordinate frames $S_1(O_1,x_1,y_1,z_1)$ and $S_2(O_2,x_2,y_2,z_2)$, introduced in Fig. 2 [13]. The dimensions and the mutual position of H_1^c and H_2^c are completely determined by the cylindrical coordinates a_i, r_i, θ_i $(i=1,\ 2)$ of the contact point P in the systems S_i $(i=1,\ 2)$ and by the angles δ_i $(i=1,\ 2)$ between the planes of H_i^c $(i=1,\ 2)$ and the normal $m-m$. The pitch surfaces H_i^s $(i=1,\ 2)$ - analogs of the pitch circles are illustrated in Fig. 2. The points of intersection $C_i^{'}$ $(i=1,\ 2)$ of the axes of rotation i - i $(i=1,\ 2)$ and the plane T_m are the tips of the pitch cones H_i^s $(i=1,\ 2)$. Fig. 2 is oriented to the synthesis of pitch configurations whose common position in the fixed space ensures the possibility to design a big diversity of hyperboloid gears [13]. There, geometric pitch configurations with normal orientation in the fixed space are shown. These pitch configurations are typical for the traditional constructive types of spatial gears (hypoid ones, Spiroid and Helicon ones, etc.). They are characterized by: $\delta=\pi/2$ and $\delta\neq\pi/2$; $z_{2,C_2}>0$; $\angle\left(\overline{C_1C_1^{'}},\overline{O_1z_1}\right)=0^o$; $\angle\left(\overline{C_2C_2^{'}},\overline{O_2z_2}\right)=180^o$.

The radius-vector $\overline{O_1P}$ and the unit vector $\overline{m}$ of the normal $m-m$ are expressed by a_1, r_1, θ_1 and a_2, r_2, θ_2, and using a_w and δ.

Thus, the following set of equations is obtained:

$$\begin{aligned}
&r_1\cos\theta_1 = r_2\cos\theta_2\cos\delta + a_2\sin\delta,\\
&r_1\sin\theta_1 = a_w - r_2\sin\theta_2,\\
&a_1 = r_2\cos\theta_2\sin\delta - a_2\cos\delta,\\
&\cos\delta_1\sin\theta_1 = \cos\delta_2\sin\theta_2,\\
&\sin\delta_1 = \sin\delta_2\cos\delta + \cos\delta_2\cos\theta_2\sin\delta,\\
&\cos\delta_1\cos\theta_1 = \sin\delta_2\sin\delta - \cos\delta_2\cos\theta_2\cos\delta.
\end{aligned} \qquad (1)$$

Later, the study of the system (1) will be realized by taking into account the following geometric conditions

$$\theta_1 \in \left[0,\frac{\pi}{2}\right], \qquad \theta_2 \in \left(0,\frac{\pi}{2}\right], \qquad \delta_1 \in \left[0,\frac{\pi}{2}\right),$$

$$\delta_2 \in \left[0,\frac{\pi}{2}\right], \qquad a_w > 0, \qquad r_i > 0, \qquad a_i \geq 0,$$

($i=1,\ 2$). Each of the last three equations in (1) is a consequence of the other two, i.e. (1) is a set of 5 independent equations with 10 unknowns: δ, a_w, δ_1, r_1, a_1, θ_1, δ_2, r_2, a_2, θ_2. Therefore, each solution of (1) is a function of 5 of them (we will consider them as free ones). We suppose that the independent (free) parameters are δ, a_w, δ_1, r_1 and a_1. We will look for analytical relations that have to be fulfilled so that set (1) has a solution. Let us pay attention not only to the cases oriented to the synthesis of Spiroid and Helicon classical interpretation gears [3 - 9] but also to such essential for the practice cases of orthogonal hyperboloid gears ($\delta = \pi/2$). For those two cases in the system (1) are substituted sequentially, when $a_1 \neq 0$ - $\delta_1 \neq 0$ (Spiroid drive), and $\delta_1 = 0$ (Helicon drive). Then after the calculation of the parameters, the corresponding geometric pitch configurations can be easily visualized [1, 13] as it is shown in Fig. 3 and Fig. 4.

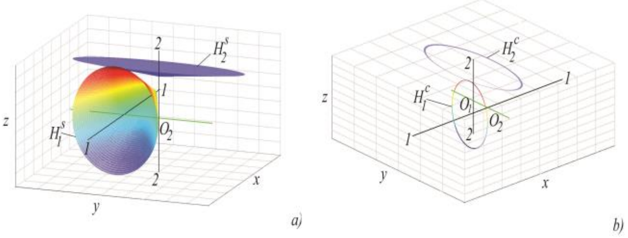

Fig. 3. Pitch configurations for orthogonal Spiroid gears: a) pitch surfaces H_i^s $(i=1,\ 2)$; b) pitch circles H_i^c $(i=1,\ 2)$; $a_w = 3{,}25$ mm; $\delta = 90^\circ$; $\delta_1 = 5^\circ$; $r_1 = 4$ mm; $a_1 = 9{,}5$ mm; $\delta_2 = 84^\circ$; $a_2 = 3{,}9983$ mm; $r_2 = 10{,}003$ mm.

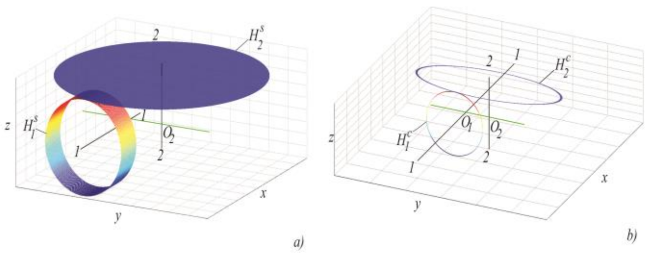

Fig. 4. Pitch configurations for gears of type Helicon: a) pitch surfaces H_i^s $(i=1,\ 2)$; b) pitch circles H_i^c $(i=1,\ 2)$; $a_w = 3{,}25$ mm; $\delta = 90^\circ$; $\delta_1 = 0^\circ$; $r_1 = 4$ mm; $a_1 = 9{,}5$ mm; $\delta_2 = 90^\circ$; $a_2 = 4$ mm; $r_2 = 10{,}041$ mm.

Synthesis of Tooth Surfaces. The algorithm for the synthesis of pitch configurations is based on the principles of geometric synthesis. Therefore, it cannot directly define the kinematic characteristics of the synthesized mechanisms, since the law of motion transformation is not presented in the algorithm. When the law of motion transformation is included in the pitch configuration algorithm, the configurations start a common rotation. Thus, a sliding velocity vector $\overline{V}_{12}$ can be defined at their common point. The magnitude and the direction of $\overline{V}_{12}$ are important since they determine the geometric parameters of the conjugated tooth surfaces Σ_1 and Σ_2 of the pinion and gear. The synthesis of the pinion thread surface Σ_1 is of essential interest when the manufacture of the gear-pair is based on Olivier's second principle. The synthesis of tooth surfaces upon a pitch contact point does not require knowing an analytic expression for the active flanks. The synthesis of the surface Σ_1 can be reduced to determine its basic geometric characteristics at the pitch point P. Thus, the synthesis algorithm comprises analytical relations defining a sufficient number of parameters of the active flanks Σ_1 by means of which the conditions for the design of both the Spiroid pinion and the Spiroid hob are created. Here, should especially be noted, that the specific constructive characteristics, which are necessary for the design and elaboration of the Spiroid pinion and Spiroid hob with convolute, Archimedean, or involute active tooth surfaces of the pinion threads, are determined by using the calculated parameters in the pitch contact point. The Spiroid hob is used for Spiroid gear Σ_2 tooth cutting. Here, some of the analytic relations included in algorithms and computer programs for Spiroid and Helicon gear synthesis are presented. Expressions given below correspond to gears with right-hand pinion threads and left-hand gear teeth. The directions of the angular velocities vectors

$\overline{\omega}_1$ and $\overline{\omega}_2$, shown in Fig. 5, correspond to the mentioned orientation of the tooth surfaces Σ_1 and Σ_2.

(a) *Helix angle of the pinion thread flank.* This angle gives the direction of the helix of the helical flank Σ_1 in the pitch point P. β_1 is the angle between the tangent $t-t$ to the helix L_1 in P and the straight line $PO_1^{'}$ passing through P and the concluding angle δ_1 with the axis $1-1$ (see Fig. 5):

$$\beta_1 = \arctan\frac{i_{12}r_1 - r_2\cos\mu}{r_2\sin\mu},\quad \mu = \arcsin\frac{\sin\theta_2\sin\delta}{\cos\delta_1}. \tag{2}$$

(b) *Axial helical parameter and axial module.* The axial helical parameter is a basic geometric parameter of the pinion. By using it, the pinion helix pitch can be determined. Its expression is [1]:

$$p_s = \frac{r_1 r_2\cos\delta_1\sin\mu}{i_{12}r_1 - r_2\cos\mu}. \tag{3}$$

Assuming $\delta = \pi/2$ and $\delta_1 = 0$ in (2) and (3), analytical expressions for β_1 and p_s corresponding to the Helicon pinion are obtained.

By using equation (3), it is easy to determine the axial pitch and axial module of the Spiroid pinion.

$$P_s = 2\pi\frac{p_s}{z_1},\quad m_s = 2\frac{p_s}{z_1}. \tag{4}$$

Here z_1 is the number of Spiroid pinion threads (z_2 - the number of Spiroid gear teeth).

The axial pitch and the axial module are basic geometrical characteristics of the gear sets of the considered class.

(c) *Pinion thread pressure angles.* When meshing mutually enveloping surfaces Σ_1 and Σ_2, it is possible to obtain singular points in the mesh region. Such points exist if the relative velocities of the conjugate tooth surface contact points are zero [1]:

$$\overline{V}_{r,i} = \overline{0}. \tag{5}$$

Depending on the normal vector $\overline{n}_i$ to the meshed surfaces at their common point, two types of singular points exist:

- *singular points of first order called ordinary nodes* if $\overline{n}_i \neq \overline{0}$, and consequently $\dot{\overline{n}}_{r,i} = \overline{0}$, where $\dot{\overline{n}}_{r,i}$ is the relative velocity vector of the top of the normal vector in its relative motion;
- *singular points of second order called points of undercutting* when $\overline{n}_i$ does not exist.

Singular points of first order should be eliminated from the mesh region since they increase specific friction, reduce lubrication and heat transfer, and as a result, they decrease the loading capacity of the gear pair (because of the increased relative sliding).

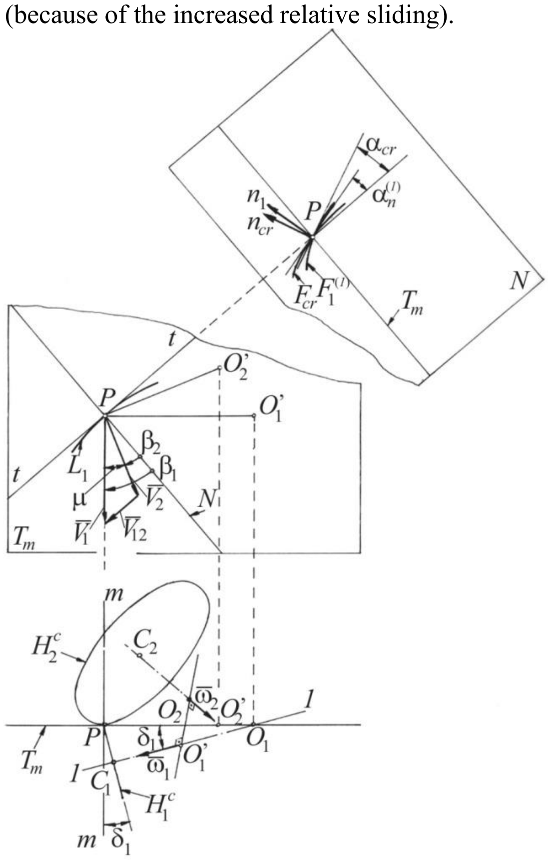

Fig. 5. Spiroid gear tooth geometry.

In the cases of Spiroid gear synthesis, using a pitch contact point P, the aim is to eliminate the ordinary nodes in the pitch point vicinity.

To carry out this task, a limiting direction of the normal vector $\overline{n}_1$ with respect to the tooth surface Σ_1 at the point P is sought. Here, it is considered that a point of Σ_1 is an ordinary node. The analytic expression of the angle between this vector and the plane T_m (see Fig. 5) [1] is given:

$$\alpha_{cr} = \arctan\left\{\frac{\sin\beta_1[r_1\cos\delta_1 + a_w\cot\delta(A) + a_1(B)]}{r_1\sin\delta_1 + a_1\cos\beta_1 - a_w\cot\delta\tan\theta_1\cos\delta_1}\right\},$$
$$A = \cot\beta_1 + \tan\theta_1\sin\delta_1,$$
$$B = \cot\beta_1\tan\theta_1 - \sin\delta_1. \tag{6}$$

The point P will not be an ordinary node if the normal vector $\overline{n}_1$ to Σ_1 shifts with respect to the critical normal vector $\overline{n}_{cr}$ by the tooth standard profile angle α. As a result, the pinion thread becomes non-symmetric in the normal section and the real profile angles in the normal section of the thread (i.e., the pressure angles) are of the form:

$$\alpha_n = \alpha \mp |\alpha_{cr}|, \tag{7}$$

The smaller value of α_n determines the orientation of the surfaces Σ_1. They belong to the pinion threads when the pinion meshes with the Spiroid gear's corresponding surfaces Σ_2 and the angular velocity vectors are those shown in Fig. 5.

(d) *Special force angle.* The special force angle α_{12} is the angle between the vector of the force transferred from Σ_1 to Σ_2 and the circumferential velocity vector of the pitch contact point P, being a point of Σ_2:

$$\cos\alpha_{12} = \cos\beta_2 \cos\alpha_n, \quad (8)$$

where $\beta_2 = \beta_1 - \mu$. The value of the special force angle has a critical effect on the conditions of force transmission between the conjugated surfaces Σ_1 and Σ_2. It also affects the synthesized mechanical transmission efficiency. The basic geometric-kinematic characteristics, which are part of the analytical algorithm for optimization synthesis, are presented.

3. Conclusion

Technical applications and results. The described two main tasks, configuring the mathematical model for the synthesis of Spiroid and Helicon transmissions, as well as the based on them software program for the synthesis, are served to the author for the realization of a series of driving for incorporations into different robotic systems: - Helicon gear pairs (three types), dedicated for the walking constructions of the walking robots with 6 and 4 insect type legs [10, 12, 14]; - Two types Spiroid and two types Helicon gear –pairs are synthesized and the elaborated models are realized by a 3D printing. They are intended for incorporation into a bio-robot hand [11]. Further below, only this technical result will be considered.

Spiroid and Helicon gears' models for driving into a finger of a robot-hand. From future humanoid robots, it is expected to realize various complex tasks by interacting with human users. Such types of robots have to be equipped with anthropomorphic multi-fingered hands that are similar to human hands. The main designation of such a humanoid robot's hand is to replace the human presence when performing multiple dangerous tasks in areas such as industrial manufacturing, chemical industry, space, seabed, etc. Another perspective application of the anthropomorphic robot hand is its application in surgery as an extension of the doctor's hands and as a prosthesis for handicapped people. These types of surgical hands designed for exact positioning and manipulation during spinal surgery will increase surgeon precision. Hence, requirements for such robot devices (hands) is to obtain characteristics such as accuracy, smoothness, and exactness.

For this reason, a five-fingered robot hand is developed in Kawasaki&Mouri Laboratory at the Engineering Department of Gifu University [11]. The aim of this hand is to be used as the standard platform for the study of optimal grasping and manipulation of various types of objects. One of the tasks related to the hand is to find out a solution to the problems related to the increment of the overlapping coefficient and also to create preconditions for controlling the backlash between mating gears which are implemented into the fingers of this hand (see Fig. 6).

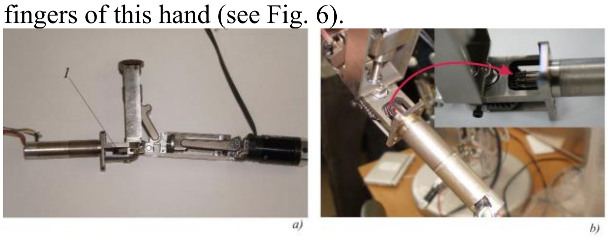

Fig. 6. Finger pattern of the robot hand: a) forefinger; 1-bevel gear; b) bevel gear with straight teeth: $m = 0{,}5$ mm; $i_{12} = 4$; $z_1 = 10$; $z_2 = 40$.

The idea to incorporate Spiroid or Helicon gear drives into this robot hand is based on the following main points:

-These gears have a conjugate linear contact. They are characterized by a large number of simultaneously meshed tooth surfaces. This is a premise to expect smoother and noiseless rotations transformation, compared with the bevel gears with straight teeth. This is important for the precision action of the gear set when a simple control is used on robotic systems.

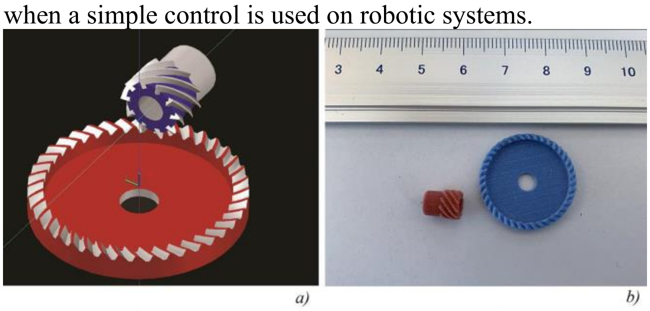

Fig. 7 Hyperboloid gear of type Helicon with: $i_{12} = 4$; $z_1 = 10$; $z_2 = 40$; $m = 0{,}5$ mm ; $a_w = 4mm$ a) 3D CAD model; b) 3D printed model (the shown scale is in mm).

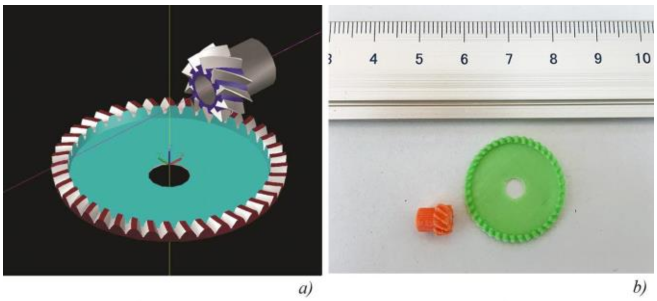

Fig. 8. Spiroid gear drive with $i_{12} = 4$; $z_1 = 10$; $z_2 = 40$; $m = 0{,}5$ mm; $a_w = 4mm$: a) 3D CAD model; b) 3D printed model (the shown scale is in mm).

-The other essential characteristic of the considered class of spatial gears is the simplicity of backlash regulation. This is related to the constant axial pitch of the Spiroid pinion and the conic form of the Spiroid pinion reference surface. Thus, the backlash control between the tooth flanks is obtained by pinion displacement along its axis. Since the Helicon gear is disk-shaped, the backlash control is performed by gear displacement along its axis. This is why these gear pairs are successfully applied when the accurate work of the mechanism requires meshing without backlash.

-The manufacturing technology of these types of gear drives ensures high accuracy of coincidence of the geometry of the pinion with the geometry of the hob that cuts the driven gear. This is a guarantee for the practical realization of gears with a minor deviation of the accomplished gear ratio from the given theoretical one. The purpose of the realized study is to replace a bevel gear (Fig. 6) with kinematically equivalent hyperboloid gears of type Helicon and type Spiroid. The gear set shown in Fig. 7 and 8 are specially synthesized by choosing the optimal structure and geometrical characteristics and it is CAD modeled and 3D printing manufactured. The goal is a smooth integration into the already existing robot hand, which will result in its technical precision. Activities related to its manufacture and integration into the robot are forthcoming.

This work has been accomplished with the financial support by the Grant No BG05M2OP001-1.002-0011-C02 financed by the Science and Education for Smart Growth Operational Program (2014-2020) and co-financed by the European Union through the European Structural and Investment funds.

The author wants to express her gratitude to her late father Prof. Valentin Abadjiev for his constant support, guidance, and work through the years in her growth as a scientist.

References

1. V. Abadjiev, E. Abadjieva. One Approach to the Synthesis, Design, and Manufacture of Hyperboloid Gear Sets with Face Mating Gears. Part 1. Basic Theoretical and CAD Experience J. Theor. and App. Mech., 46 (2), 3-26 (2016)
2. V. Abadjiev, E. Abadjieva. One Approach to the Synthesis, Design and Manufacture of Hyperboloid Gear Sets with Face Mating Gears. Part 2. Review of Practical Realization, J. Theor. and App. Mech., 46 (3), 3-16 (2016).
3. O. Saari, The Mathematical Background of Spiroid Gears, Industrial Mathematical Series, Detroit, 7, 131-144 (1956)
4. W. Nelson, Spiroid Gearing. Part 1 – Basic Design Practices, Machine Design, 136-144 (1961).
5. W. Nelson, Spiroid Gearing. Part 2 – Durability, Strength and Efficiency, Machine Design, 93-100 (1961).
6. W. Nelson, Spiroid Gearing. Part 3 – Materials, Mounting Details, Lubrication, Machine Design, 165-171 (1961).
7. D. Dudley, Gear Handbook. The Design, Manufacture and Application of Gears, Mc Craw Hill Company, N.Y., 1040 (1962)
8. S. Radzevich, Dudley's Handbook of Practical Gear Design and Manufacture, Second Edition, CRC Pres Taylor&Francis Group, 862 (2011).
9. Georgiev, V. Goldfarb, Aspects of Geometric Theory and Investigation of Spiroid Gearswith Cylindric Pinion, Mechanika Machine, Nauka, Moskow, 70-80 (1972) (in Russian).
10. V. Abadjiev, D. Okhotsimsky, A. Platonov. Research on the Spatial Gears and Applications, Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Preprint No 89, Moscow, 25 (1997).
11. E. Abadjieva, V. Abadjiev, H. Kawazaki, T. Mouri. On the Synthesis of Hyperboloid Gears and Technical Application, Proc. of the ASME 2013 International Power Transmission and Gearing Conference, Portland, Oregon, USA, published on CD), (2013).
12. E. Abadjieva, V. Abadjiev, D. Ignatova. 3D Software Technology, Applicable in Elaboration of the Spatial Face Gear Drives for Incorporation into Robot Systems, World J. of Engineering and Technology, 4, 91-99 (2016).
13. V. Abadjiev, E. Abadjieva. Geometric Pitch Configurations – Basic Primitives of the Mathematical Models for the Synthesis of Hyperboloid Gear Drives. Advanced Gear Engineering, Mechanism and Machine Science 51, Springer International Publishing Switzerland, pp. 91-117 (2018).
14. V. Abadjiev, Gearing Theory and Technical Applications of Hyperboloid Mechanisms, Sc. D. Thesis, Institute of Mechanics, Bulgarian Academy of Sciences, Sofia, 309p. |(2007) (in Bulgarian).