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PROPERTIES OF SIX DOF MEASUREMENTS FOR ROBOTICS AND CONTROL

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Abstract: The paper is focused on the analyze of the accuracy and linearity of the six degrees-of-freedom (DoF) measurement system for the sampling of structural dynamic properties in robotics, engineering constructions and for control operation in space. The subject of this measurement device is the sampling and information processing used in the conversion of the 2-D CCD array images into three axial and three angular displacement values. Every 2- CCD array image consists of one, alternatively four light spot produced by light rays from four laser sources. These light beams form the edges of a pyramidal shape with one, alternatively four 2-D arrays forming its base and the intersection of laser light rays is forming its apex. The analyze of the accuracy and the linearity is based on algorithms for direct and inverse transformation for the computation of three axial shiftings and three angular displacements values in order to determine the relative location and orientation of a floating 2-D coordinate system against fixed 3-D coordinate system of laser rays.

Keywords: Accuracy; Linearity; Direct and Inverse Transformation; Sampling of Six DoF (Degrees of Freedom) Information; Measurement of Three Axial Shiftings and Angular Displacements.

1. INTRODUCTION

The six degree of freedom (DoF) measurement system for the sampling and information processing about three axial and three angular displacement values is proposed for the measurement of structural dynamic properties in engineering constructions and for control operation in space. The subject of this modular portable device is the sampling and information processing used in the conversion of 2-D CCD array image into three axial and three angular displacement values. Every 2-D CCD array image consists of four light spots produced by light rays from four laser sources. These light rays form the edges of a pyramidal shape with 2-D array forming its base and the point of the intersection of the laser light rays is forming its apex.

The function of modular portable device is derived from the pyramid modular sensory system for robotics and human-machine interface, which enables to compose for example force-torque transducers of various properties and multi DOF hand controllers [4]. This is done by means of a 2-D CCD array (CCD - Charge Coupled Device) and with appropriate changes by means of the PSD element (PSD - Position Sensitive Device), and four light rays creating the shape of pyramid. Simple modular construction enables low cost customization, according to the demanded properties: A -stiff module of two flanges connected by means of microelastic deformable medium; B -compliant module of two flanges connected by means of macroelastic deformable medium; C -the module of the 2-D CCD array; D -the module of insertion flange with basic light sources configuration and focusing optics; F -the module of the plane-focusing screen; H -the module of the optical member for the magnifying or reduction of the light spots configuration. The problem of the customization of six-DoF sensory systems according to the enhanced accuracy and operating frequency of scanning of the six-DoF information is possible to improve by means of the module of insertion flange with the configuration of light sources with strip diaphragms, creating the light planes with strip light spots and by means of the module of the single or segmented linear or annular CCD or PSD elements with higher operating frequency, respectively using the module of two, parallel working, concentric CCD annulars with higher reliability, see [3].

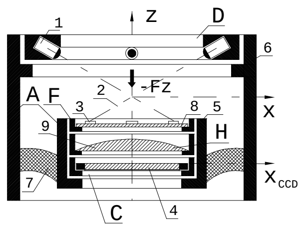

Fig. 1. Six-component force-torque transducer.

The explanation of the sampling is introduced on the force-torque transducer, see Figure 1 composed from the modules A,C,D,F,H, of a modular sensory system. Laser diodes 1 emit the light rays 2 creating the edges of a pyramid intersecting the plane of the 2-D CCD array, here alternatively the focusing screen 8 with light spots 3. The unique light spots configuration changes under axial shifting and angular displacements between the inner flange 5 and the outer flange 6 connected by means of elastic deformable medium 7. An alternatively inserted optical member 9 (for the magnification of micromovement, or the reduction of macromovement) projects the light spots configuration from the focusing screen onto the 2-D CCD array 4. Four light rays simplify and enhance the accuracy of the algorithms for the evaluation of the six-DOF information. The algorithms for the computation of three axial shiftings and three radial displacements values is based on the inverse transformation of the final trapezoidal position of four light spots related to the original square light spots position in the plane coordinate system x_{CCD}, y_{CCD} on the 2-D CCD array. This algorithm determines the relative location and orientation of a floating 2-D coordinate system against a fixed 3-D coordinate system corresponding to the apex of the pyramid shape, or contrary. The information about three axial shiftings and three angular displacements is sampled and converted according to a calibration matrix to acting forces Fx, Fy, Fz and torques Mx, My, Mz.

The generalization of described method for macro environment led to the customization of measurement of six-component information according to the size and position of measured object by means of three universal portable modules and their combination, see in [6],[7]:

- The portable module Ap of four lasers 3 with the presetting control 1 of the angle 2s, which contains mutual opposite light rays 2, see Figure 2.

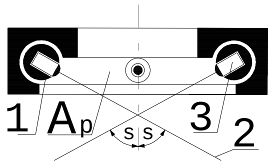

Fig. 2. The portable module Ap of four lasers.

- The portable module Bp is used for the ground plane sampling at large fluctuation of measured values of the light spot 7 positions from the laser light ray 6. This module consists of the 2-D array 3 with focusing optics 2, flange 1 and with the stand 4 placed in four corners of the quadrangle. Every board 5 for the imagination of the light spot position has the coordinate system x, y, see Figure 3.

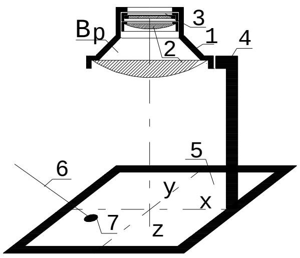

Fig. 3. The portable module Bp for the ground plane sampling

- The portable module Cp for the direct sampling of small or medial fluctuation of measured values of the light spot 3 position from the laser light ray 2 which is imagined on the translucent screen 4. This module consists of the 2-D CCD array 6 with focusing optics 5 and of the flange 1, see Figure 4. The module Cp is placed and centered in the axis of the module Ap. This configuration enables the sampling of small and medium fluctuation of the light spot position.

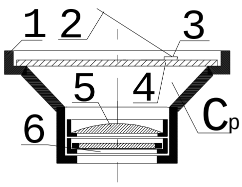

Fig.4. The portable module Cp for the direct sampling.

Various configurations of portable measurement modules enable the sampling of the six DoF macromovement and the sampling of the micro movement, as for example the sampling of structural dynamic properties of engineering constructions, or the motion control in 3-D space.

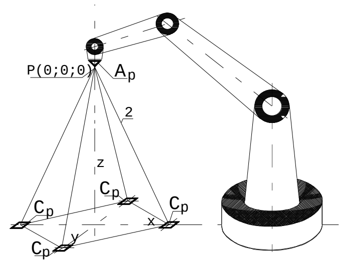

Fig. 5. The Sampling of the Robot's End Effector Movement.

The use of universal portable modules enables the six-DOF measurement of the robot's end effector vibrations in the start and stop position, or the sampling at the movement from the point to the point. This method enhances structural recognition of the multi component measurements and improves the quality of diagnostics. The portable module Ap of four lasers is fastened on the robot's end effector, see Figure 5 and four portable modules Cp for the direct sampling of measured values are placed in corners of square basic position. An interesting task is to sample the changes in six DoF characteristics courses for various loading of the robot's end effector.

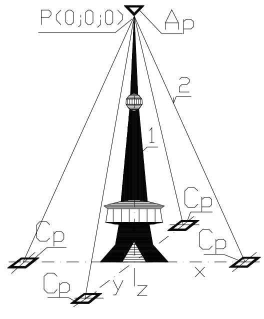

Fig. 6. The Six-DOF Measurement of Engineering Constructions.

Another example is the sampling of structural dynamic a properties of engineering construction. This is introduced on the transmitting tower 1 see Figure 6. The portable module Ap of four lasers is fastened on the apex of the transmitting tower. Four portable modules Cp for direct sampling of medium and big fluctuation of light spots are positioned by means of geodetic tools into the points of the laser light rays 2 intersection with ground plane. Significant advantage of this method is easy conversion of the module Cp or Bp for the difference in elevation to the level of the ground plane. This is needed namely at the sampling of skyscrapers, where in the vicinity of a measured object are another buildings with various level. The sampling of dynamic properties of the tower is possible to improve on synchronous way by parallel measurement in various distances between the bottom and the apex of the tower. Mutual configuration of portable modules Bp or Cp where the plane of focusing screen of the module Cp is in the ground plane x,y of the module Bp enables the sampling for small and medium fluctuation of the light spot position with improved accuracy.

Another examples concerning the analyze of structural dynamic properties with similar configuration of the portable modules according to Figure 6 is the sampling of structural dynamic properties of the bridge construction loaded by moving cars or train or the sampling of structural dynamic properties of various constructions, for example the parts of the airplane at static loading or aerodynamic proof.

2. THE EXACT MODEL OF THE ACCURACY

The accuracy of the six-DoF pyramid sensor is investigated like the influence of the deflection of the independent variable, here the coordinates of four light spots positions Δxi, Δyi, where i=A,B,C,D on the dependent variable consisting of three axial shiftings x, y, z and three angular displacements fi, theta, omega in the working range of the CCD or the PSDs.

There is the m = 8 the number of the independent variable $q_m = (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D)$ and the n = 6 is the number of the dependent variable z_n = (x, y, z, fi, theta, omega), where the inverse transformation is z_n = F-1 (q_m), and the direct transformation is q_m = F(z_n). The magnitude of the deflection will be chosen according to working inaccuracy of the CCD or the PSDs array. The basic inaccuracy for the CCD array is given by the size of the pixel (the smallest light sensitive element of the CCD array). The size of one pixel is Δq = 0,0035mm up to 0.012mm and it is approximately equal for both coordinates x,y. Then the size of the Δq/2 is chosen 0.005mm.

There are two possible ways for the evaluation of the accuracy - the linear model and the exact model. The first way is linear model of the accuracy, derived from the inverse transformation z_n = F-1(q_m). Essential disadvantage of the linear model are complicated relationships for the inverse transformation, impossible to process by means of current computing tools for PC. The second way – for the analyzing of the accuracy was chosen exact model, because there is processed the simulator of the direct transformation q_m. = F(zn) and the inverse transformation z_n =F-1(q_m).

The program for the evaluation of the accuracy is running in two variants, eligible by means of the menu “accuracy point – accuracy courses”. The first variant is the evaluation of the accuracy for only one isolated position of the point of the dependent variable z_n = (x, y, z, fi, theta, omega), see Figure 7 and [5], [7], [8].

The evaluation of the six-DoF sensor accuracy for isolated point is processed in following steps:

```
The evaluation of the influence of the laser light spots
deflectioni on the 2-D CCD array for the input of optional "error deflection values"
based on the difference between the results
of the direct transformation and the inverse transformation.

Input for the value x [mm] (def=-22.2):  6.00
Input for the value y [mm] (def=-39.704):  -4.00
Input for the value z [mm] (def=119.9):  110.00
Input for the angle fi [deg] (def=30):  -30.0
Input for the angle theta [deg] (def=45):  40.00
Input for the angle omega [deg] (def=45):  35.00
Input for the deflection of the x coordinate for the point A of the 2-D CCD array (def=0):  0.05
Input for the deflection of the y coordinate for the point A of the 2-D CCD array (def=0):  0.05
Input for the deflection of the x coordinate for the point B of the 2-D CCD array (def=0):  -0.05
Input for the deflection of the y coordinate for the point B of the 2-D CCD array (def=0):  0.05
Input for the deflection of the x coordinate for the point C of the 2-D CCD array (def=0):  -0.05
Input for the deflection of the y coordinate for the point C of the 2-D CCD array (def=0):  0.05
Input for the deflection of the x coordinate for the point D of the 2-D CCD array (def=0):  -0.05
Input for the deflection of the y coordinate for the point D of the 2-D CCD array (def=0):  0.05

The evaluation of the influence of optional "error deflection values"
for only one point:

error in x coordinate  6.9287e-005


error in y coordinate    0.0504


error in z coordinate   -0.0604


error in fi coordinate    0.0094


error in theta coordinate    0.0093


error in omega coordinate   -0.0100
```

Fig. 7. The Command Windows in MATLAB for the Evaluation of the Six DOF Sensor Accuracy in Isolated Point.

1. The input is the (dependent variable) coordinate of the point ${}_{dir}z_n$ ≡ (x, y, z, fi, theta, omega). By means of the direct transformation are computed coordinates of the points A,B,C,D ≡ $(x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D)$ for the working space q_m (independent variable) on 2-D CCD array of the six-DOF sensor. The position of the dependent variable x, y, z, fi, theta, omega is possible to choose by means of the Command Windows in MATLAB, alternatively to use the default values.
2. The position of every point A,B,C,D ≡ $(x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D)$ is possible to decline by the chosen distance ±Δx, ±Δy, for example by the half size of the pixel Δq/2 =±0.005mm. The file Command Windows in MATLAB enables to insert the declination of coordinates $(x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D)$ in one or in both directions of axes x,y for every point.

```
The evaluation of the influence of the laser light spots deflection
on the 2-D CCD array for the input of optional "error deflection values"
based on the difference between the results
of the direct transformation and the inverse transformation.

Input for the value x [mm]  (def=-22.2):  -35.00
Input for the value y [mm]  (def=-39.704):  28.00
Input for the value z [mm]  (def=119.9):  105.00
Input for the angle fi [deg]  (def=30):  -35.55
Input for the angle theta [deg] (def=45):  42.50
Input for the angle omega [deg] (def=45):  28.05


Input for the deflection of the x coordinate for the point A of the 2-D CCD array (def=0):  0.05
Input for the deflection of the y coordinate for the point A of the 2-D CCD array (def=0):  0.05
Input for the deflection of the x coordinate for the point B of the 2-D CCD array (def=0):  -0.05
Input for the deflection of the y coordinate for the point B of the 2-D CCD array (def=0):  -0.05
Input for the deflection of the x coordinate for the point C of the 2-D CCD array (def=0):  0.05
Input for the deflection of the y coordinate for the point C of the 2-D CCD array (def=0):  0.05
Input for the deflection of the x coordinate for the point D of the 2-D CCD array (def=0):  -0.05
Input for the deflection of the y coordinate for the point D of the 2-D CCD array (def=0):  0.05


Input range min. (def=-5):  -12
Input range max. (def=5):  12
Input step (def=0.01):  0.02
>>
```

Fig. 8.: The Command Windows in MATLAB for the Variation of the Accuracy Evaluation of the Six DOF Sensor Accuracy in Courses for Six Variables.

3. By means of the inverse transformation are computed dependent variable coordinates ${}_{inv}z_n$ = (x, y, z, fi, theta, omega) for chosen declined points q_m in the working space of the six-DoF sensor.

4. The last step is the evaluation of the difference between the result value of the direct and the inverse transformation $\Delta z = \left| {}_{dir}z_n - {}_{inv,declined}z_n \right|$.

5. The analyze of the accuracy in elected point is processed for every dependent variable z_n = (x, y, z, fi, theta, omega).

The evaluation of the courses of the accuracy for every dependent variable z_n = (x, y, z, fi, theta, omega) is processed in elected ranges by following steps with an input by means of the MATLAB menu according to Figure 8.:

1. The input "range" of the dependent variable x, y, z, fi, theta, omega is possible to choose by means of the Command Windows in MATLAB from the minimal to maximal value of the range with the middle point ${}_{dir}z_n$. Similar is elected the input "step" value. Alternatively you may to use default values for the ranges and the step.

2. By means of the direct transformation are computed coordinates of the points A,B,C,D ≡ (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D) for every point ${}_{dir}z_n$ of the working space of the six-DOF sensor. The position of every point A,B,C,D ≡ (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D) is possible to decline by the chosen distance $\pm\Delta x$, $\pm\Delta y$, for example by the half size of the pixel $\Delta q/2 = \pm 0.005$mm. The file Command Windows in MATLAB enables to insert the declination of coordinates (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D) of the point q_m in one or in both directions of axes x,y for every point. All following steps are running in loops.

3. By means of the inverse transformation are computed dependent variable coordinates ${}_{inv}z_n$ = (x, y, z, fi, theta, omega) for every declined point q_m of the working space of the six-DOF sensor.

4. The last step is the evaluation of the difference between the result values of the direct and the inverse transformation $\Delta z = \left| {}_{dir}z_n - {}_{inv,declined}z_n \right|$.

5. The analyze of the accuracy is processed for every dependent variable z_n = (x, y, z, fi, theta, omega) and we obtain six graphic tables every with 5 courses. This is the evaluation for elected range of every variable. The final result is possible to obtain by means of the "loop of the loops" between all variables.

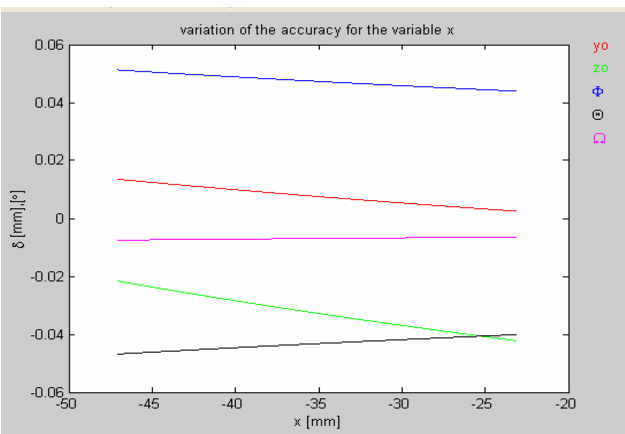

Fig. 9. The Variation of Six DoF Sensor Accuracy in the Course

The second variant is the evaluation of the courses, one example is depicted in Figure 9. for every dependent variable z_n = (x, y, z, fi, theta, omega).

The result of the investigation of the six-DOF sensor accuracy is that this sensor maintains the order of magnitude of inserted inaccuracy. It means that inserted inaccuracy $\pm$0.05mm caused the changes in the order of the magnitude e-2.

3. THE EXACT MODEL OF THE LINEARITY

The first variant, the linearity for every dependent variable x, y, z, fi, theta, omega, is investigated separately. Here the courses of the points A, B, C, D are imagined for constant increments of sampling in every separated dependent variable z_n, see in Figure 10 for the omega. The

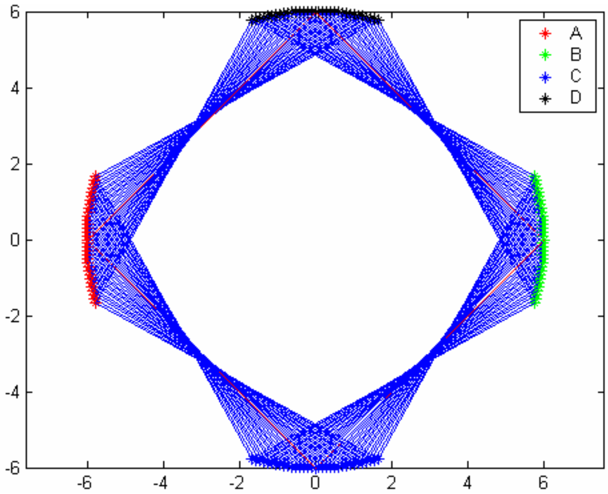

Fig. 10. The linearity of the points A,B,C,D motion for constant increments in dependent variable omega in the coordinate frame x,y.

The investigation of the points A,B,C,D motion for common constant increment of sampling is possible for all dependent variables simultaneously. For dependent variable x, y, z, omega are increments of the points A,B,C,D constant.

Moderate nonlinearity is in the points A,B, respectively C,D motion for the angle fi, respectively for the angle theta, see in Figure 11. There are depicted courses of the diagonal difference $u_{1,i+1} - u_{1,i}$ respectively $u_{3,i+1} - u_{3,i}$ for dependent variable fi, respectively theta

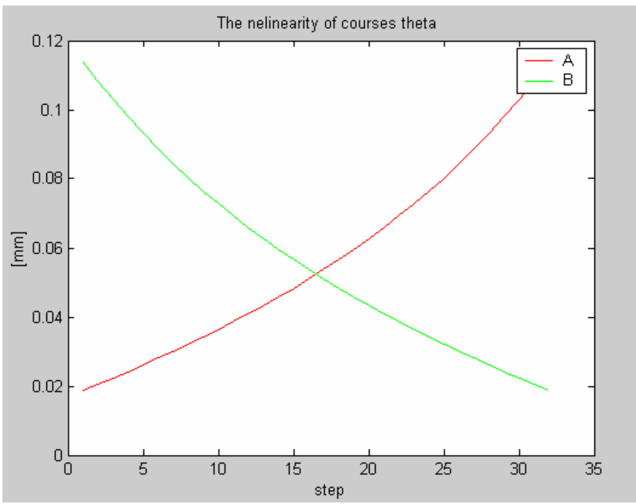

Fig. 11. The nonlinearity in the points A,B motion for the angle fi.

For the second and the third variant of the analyzing of the linearity was chosen exact model, using

- the simulator for direct transformation $q_{m}. = F(z_n)$.
- the simulator of inverse transformation of the point $q_{i,m,\rho}$: $z_n=F^{-1}(q_{i,m,\rho})$, forwarded point $z_n=F^{-1}(q_{i+1,m,\rho})$, and backwarded point $z_n=F^{-1}(q_{i-1,m,\rho})$.
- The symbol ρ is used for the designation of the declination from basic points A,B,C,D for the linearity investigation in the direction of the derivation from the axis x chosen by the angle alfa = [0; 2π].

The program for the evaluation of the linearity is running in two variants, eligible by the:

- investigation of the linearity in isolated "point", or by the
- investigation of the linearity in the ranges of the "courses".

The second variant is the evaluation of the six-DOF sensor linearity in the vicinity of isolated point. This is processed in following steps:

The input is the (dependent variable) coordinate of the point ${}_{dir}z_n \equiv$ (x, y, z, fi, theta, omega). By means of the direct transformation are computed coordinates of the points A,B,C,D ≡ (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D) from the working space q_m (independent variable) on 2-D CCD array of the six-DOF sensor. The investigation of the linearity in the vicinity of the point of the dependent variable x, y, z, fi, theta, omega is possible to choose by means of the Command Windows in MATLAB using the default values, see Figure 12.

```
Input for the value x [mm] (def=-22.2):  -15.40
Input for the value y [mm] (def=-39.704):  45.00
Input for the value z [mm] (def=119.9):  126.50
Input for the angle fi [deg] (def=30):  42.50
Input for the angle theta [deg] (def=45):  32.50
Input for the angle omega [deg] (def=45):  -49.30

Input direction of derivation..alfa [degree] = 25.54

input deviation on CCD array :  .15

linearity in x coordinate  2.1316e-014

linearity in y coordinate  2.1316e-014

linearity in z coordinate  2.8422e-014

linearity in fi coordinate     0

linearity in theta coordinate  7.1054e-015

linearity in omega coordinate     0
```

Fig. 12. The investigation of the linearity in the vicinity of the point of dependent variable x, y, z, fi, theta, omega in MATLAB.

1. The position of every point A,B,C,D ≡ (xA, yA, xB, yB, xC, yC, xD, yD) is declined for the computing of the linearity by differences Δx, Δy expressed by means of polar coordinates allocated by means of the command window. where is asked "Input direction of derivation alfa in [degrees]", with following input of deviation ρ on the 2-D CCD array in [mm]:

- Forwarded point is allocated by differences

Δx = ρ.cos(alfa), and Δy = ρ.sin(alfa).

- Backwarded point is allocated by differencesd

Δx = (-ρ).cos(alfa), and Δy = (-ρ).sin(alfa)

2. By means of the inverse transformation are computed dependent variable coordinates ${}_{inv}\mathbf{z}_n$ = (x, y, z, fi, theta, omega) for chosen points $\mathbf{q}_{i,m,\rho}$: $\mathbf{z}_{i,n}=\mathbf{F}^{-1}(\mathbf{q}_{i,m,\rho})$, forwarded point $\mathbf{q}_{i+1,m,\rho}$: $\mathbf{z}_{i+1,m}=\mathbf{F}^{-1}(\mathbf{q}_{i+1,m,\rho})$, and backwarded point $\mathbf{q}_{i-1,m,\rho}$: $\mathbf{z}_{i-1,n}=\mathbf{F}^{-1}(\mathbf{q}_{i-1,m,\rho})$.

There are evaluated differences $\Delta\mathbf{z}_{i+1,i;\rho}=[\mathbf{F}^{-1}(\mathbf{q}_{i+1})-\mathbf{F}^{-1}(\mathbf{q}_{i})]$, and $\Delta\mathbf{z}_{i,i-1;\rho}=[\mathbf{F}^{-1}(\mathbf{q}_{i})-\mathbf{F}^{-1}(\mathbf{q}_{i-1})]$ between elected $\mathbf{F}^{-1}(\mathbf{q}_i)$, forwarded $\mathbf{F}^{-1}(\mathbf{q}_{i+1})$ and backwarded $\mathbf{F}^{-1}(\mathbf{q}_{i-1})$. Resulting differences

$$\Delta\mathbf{z}_{i+1,i,i-1;\rho} = [\mathbf{F}^{-1}(\mathbf{q}_{i+1})-\mathbf{F}^{-1}(\mathbf{q}_{i})]-[\mathbf{F}^{-1}(\mathbf{q}_{i})-\mathbf{F}^{-1}(\mathbf{q}_{i-1})] = \\ = \Delta\mathbf{z}_{i+1,i}-\Delta\mathbf{z}_{i,i-1}$$

describe the nonlinearity.

3. The analyze of the linearity in elected point z_n is processed for every dependent variable z_n = (x, y, z, fi, theta, omega). For linear characteristic is the difference $\Delta\mathbf{z}_{i+1,i,i-1;\rho}$ = **0**. The deviation from the linear course is characterized by the magnitude $\Delta\mathbf{z}_{i+1,i,i-1;\rho}$ and the slope of the course is characterized by the magnitude $\Delta\mathbf{z}_{i+1,i}$, or by the magnitude of the $\Delta\mathbf{z}_{i,i-1}$.

The third variant is the evaluation of the courses of the linearity for every dependent variable z_n = (x, y, z, fi, theta, omega) in elected ranges. The investigation of the linearity courses is possible to choose by means of the Command Windows in MATLAB file linearity.m, alternatively is possible to use the default values pressing the Enter key, see Figure 13 The result is the output as for example the Figure 14. It is processed in following steps:

The input is the range of the coordinates of the point x, y, z, fi, theta, omega elected in the MATLAB Command Window. By means of the direct transformation are computed coordinates of the points A,B,C,D ≡ (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D) for every point ${}_{dir}z_n$ of the working space of the six-DOF sensor.

1. The input "range" of the dependent variable x, y, z, fi, theta, omega is possible to choose by means of the Command Windows in MATLAB from the minimal to maximal value with the middle point ${}_{dir}z_n$. Similar is elected the input "step" value. Alternatively you may to use default values for the ranges and the step pressing the Enter key.

```
Input for the value x [mm] (def=-22.2):  -30.00
Input for the value y [mm] (def=-39.704):  36.55
Input for the value z [mm] (def=119.9):  125.50
Input for the angle fi [deg] (def=30):  25.00
Input for the angle theta [deg] (def=45):  -35.00
Input for the angle omega [deg] (def=45):  42.05
Input direction of derivation..alfa [degree] = 54.5
input deviation on CCD array :  0.15
Input range xomin (def=-5):
Input range xomax (def=5):
Input step (def=0.01):
Input range yomin (def=-5):
Input range yomax (def=5):
Input step (def=0.01):
Input range zomin (def=-5):
Input range zomax (def=5):
Input step (def=0.01):
Input range fimin (def=-5):
Input range fimax (def=5):
Input step (def=0.01):
Input range thetamin (def=-5):
Input range thetamax (def=5):
Input step (def=0.01):
Input range omegamin (def=-5):
Input range omegamax (def=5):
Input step (def=0.01):
```

Fig. 13. The investigation of the courses of the linearity for every dependent variable z_n = (x, y, z, fi, theta, omega) in elected ranges in MATLAB

2. The position of every point A,B,C,D ≡ (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D) is declined for the computing of the linearity by differences Δx, Δy allocated by means of the command window, where is asked “Input direction of derivation alfa in [degrees]”, with following input of the deviation ρ on the 2-D CCD array in [mm]:

- Forwarded point is allocated by differences

Δx = ρ.cos(alfa), and Δy = ρ.sin(alfa).

- Backwarded point is allocated by differencesd

Δx = (-ρ).cos(alfa), and Δy = (-ρ).sin(alfa).

3. The file Command Windows in MATLAB enables to insert the declination Δx, Δy of coordinates (x_A, y_A, x_B, y_B, x_C, y_C, x_D, y_D) in chosen direction of derivation alfa and the deviation ρ for investigated point. All following steps are running in loops.

4. Evaluated differences:

$\Delta\mathbf{z}_{i+1,i;\rho} = [\mathbf{F}^{-1}(\mathbf{q}_{i+1}) - \mathbf{F}^{-1}(\mathbf{q}_i)]$, $\Delta\mathbf{z}_{i,i-1;\rho} = [\mathbf{F}^{-1}(\mathbf{q}_i) - \mathbf{F}^{-1}(\mathbf{q}_{i-1})]$

between elected $\mathbf{F}^{-1}(\mathbf{q}_i)$, forwarded $\mathbf{F}^{-1}(\mathbf{q}_{i+1})$ and backwarded $\mathbf{F}^{-1}(\mathbf{q}_{i-1})$ points.

Resulting differences

$$\Delta\mathbf{z}_{i+1,i,i-1;\rho} = [\mathbf{F}^{-1}(\mathbf{q}_{i+1}) - \mathbf{F}^{-1}(\mathbf{q}_i)] - [\mathbf{F}^{-1}(\mathbf{q}_i) - \mathbf{F}^{-1}(\mathbf{q}_{i-1})] =$$
$$= \Delta\mathbf{z}_{i+1,i} - \Delta\mathbf{z}_{i,i-1}$$

describe the nonlinearity.

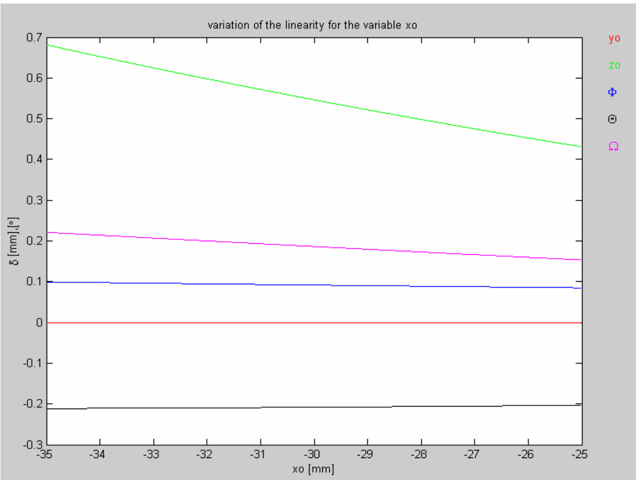

Fig. 14. The investigation of the linearity courses for dependent variable x.

5. The analyze of the accuracy in elected point z_n is processed for every dependent variable z_n = (x, y, z, fi, theta, omega). For linear course is the difference $\Delta\mathbf{z}_{i+1,i,i-1;\rho}$ = **0**. The deviation from the linear course is characterized by the magnitude $\Delta\mathbf{z}_{i+1,i,i-1;\rho}$ and the slope of the course is characterized by the magnitude $\Delta\mathbf{z}_{i+1,i}$, or by the magnitude of the $\Delta\mathbf{z}_{i,i-1}$.

6. The analyze of the linearity is processed for every dependent variable z_n = (x, y, z, fi, theta, omega) and we obtain six graphic tables every with 5 courses. This is the evaluation of the linearity for the range of every variable.

The result of the investigation of this six-DOF sensor is that this sensor is mostly moderately nonlinear.

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