T H E A R C H I V E O F M E C H A N I C A L E N G I N E E R I N G

VOL. LVIII 2011 Number 2

10.2478/v10180-011-0011-9

Key words: measurements, tracking devices, spatial displacement, wire-based sensor, parallel mechanism

MARTA GÓRA *, *MICHAŁ MANIOWSKI* *

VERIFICATION OF 6DOF PLATFORM WITH WIRE-BASED SENSORS FOR SPATIAL TRACKING

The paper presents design and experimental verification of platform mechanism with cost-effective wire-based sensors for measuring of spatial displacement or pose of some moving object. This task, also known as spatial tracking, has a very wide application. The proposed mechanism, guided by the moving object, has a parallel structure with two platforms and at least six wire-based sensors for measuring distances between the platform points. Changes of the platform pose cause corresponding changes of the sensors' wire lengths.

Forward position problem of an equivalent mechanism model with 6 degrees of freedom is described together with analyses of work space limitations and error propagation in a measurement system. A specific application is illustrated for tracking of a wheel knuckle of 5-link suspension mechanism used in passenger cars. The developed device has the following advantages: it can be installed in a wheel cavity; enables dynamic measurements on the road; is cost-effective. Performance of the latest prototype of the wire-based tracker was verified on the basis of measurements on a test rig, where two other measuring devices were used for comparison purposes.

1. Introduction – goal and scope

The paper presents some design details and experimental verification of a successive prototype of a cost-effective mechanism, developed in [3, 4], for measuring of spatial displacement or pose of some moving object without imposing any limitations on its basic features. This task is also known as spatial tracking [1, 9]. The proposed mechanism with six Degrees Of Freedom (DOF) is guided by the moving object. The mechanism has a parallel structure with two platforms and at least six wire-based sensors for measuring distances between the platform points. Changes of position and

* *Cracow University of Technology, Mechanical Department, Al. Jana Pawła II 37b, 31-864 Kraków, Poland; E-mail: mgora@m6.mech.pk.edu.pl; maniowski@m8.mech.pk.edu.pl*

orientation of the measuring platform fixed to the object cause corresponding changes of the sensors' wire lengths.

Kinematic scheme of the proposed measuring system is presented in Fig. 1a. It consists of the moving (tracking) platform *B* attached to the moving object, and the second platform which is fixed to the base or other moving body, when a relative displacement is the case. The variable distances between defined points (A_i and B_i, i = 1, 2...n) of the two platforms are measured by using $n$wire sensors attached to the platforms, Fig. 1b. The wire-based sensor consists of a pulley with spiral spring and an encoder. The considered mechanism can be modeled as 6-DOF parallel manipulators, like Stewart platform [8, 10], because the wires can be seen as extensible legs connecting the platforms by means of spherical (S) joints, Fig. 1.

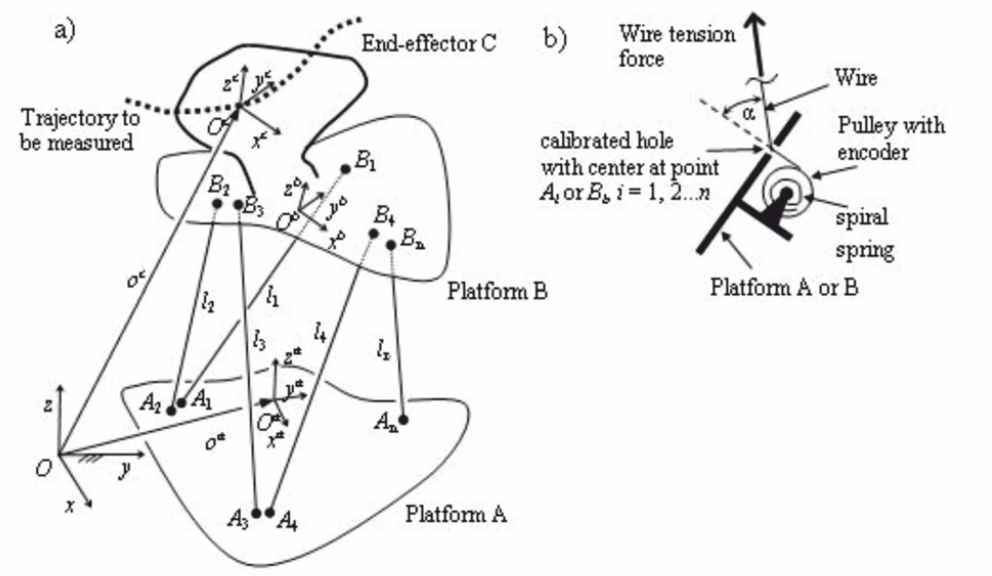

Fig. 1. Kinematic schemes of: a) platform mechanism with wires modeled as S-S legs; b) wire-based sensor attached to a platform

The wires are loaded only by tension resulting from the spring preload force, which is in the range of a few newtons what is enough to eliminate any wire slack under static and dynamic conditions [2]. The net wire load in the mechanism usually does not influence the load distribution at the moving object, not imposing any meaningful limitations on its motion.

It is possible to determine n components of the position and orientation of the moving object at each point of its trajectory, by solving the direct position problem for the proposed mechanism (Fig. 1a) by using coordinates of the platform points and the lengths of at least 6 wires, obtained from encoders [3, 4].

The design goal was to obtain light and cost-effective apparatus for spatial displacement measuring of a car wheel with respect to the car body during motion and at the test rig. The apparatus should be easy to install in a space between the wheel carrier and car chassis. The measurement should be possible for the wheel motion with maximal velocity up to 1 m/s.

The following methods are currently used to measure spatial displacement of the car wheel.

1. 6DOF serial type manipulator (e.g. RV3 Datron) guided by the wheel hub [8]. Pros: indoor and outdoor tests possible; easy installation; sufficient performance, continuous and fast acquisition. Cons: poor dynamic response due to mass, compliance and backlashes of serial structure; high price, can be mounted to the wheel only from outside.
2. Hand-guided manipulator (e.g. Romer Sigma Arm) for measuring coordinates of selected points on the object [7]. Pros: great performance. Cons: indoor use only; high price; discrete and elaborate acquisition;
3. Optical system guided by the wheel hub (e.g. laser tracking [1]). Pros: non-contact measurement; indoor and outdoor tests possible; great static and dynamic performance; continuous and fast acquisition. Cons: high price; not all coordinates of the spatial displacement can be measured; limited workspace, sensitive to environment.
4. Wire-based platform mechanism installed from outside of the car wheel. Pros: easy installation; great performance; continuous and fast acquisition. Cons: indoor use only.

Although the wire-based mechanisms were already used in this application, their real potential is not fully utilized. A novel approach adopted by the authors takes advantage of flexibility in choosing positions of miniature sensors, making it possible to install the apparatus in the wheel cavity and to take the continuous and reliable measurements during the car motion.

Minimum moving inertia, sufficient workspace, backlash-free structure makes wire-based platform mechanism well suited for measuring the car wheel displacement, even during its dynamic response (up to a few Hz). Jeong et al. [6] developed a parallel wire mechanism with six wires for pose measurement purposes. The reported accuracy was about 0.05 mm and 0.1 deg for translation and orientation respectively, what is quite sufficient for the car wheel measurements.

This paper is organized as follows. Section 2 summarizes solving the forward position problem of an equivalent mechanism model with 6DOF, together with analyses of work space limitations and error propagation in a measurement system. This material is thoroughly described in [4, 5]. Some design details of the proposed device in application for measuring of spatial displacement of the wheel knuckle of 5-link suspension mechanism, used in passenger cars, is described in Section 3. Performance of the latest prototype of the wire-based tracker was evaluated on a test rig, where two other measuring devices were used for comparison purposes, in Section 4. Finally, concluding remarks are given in Section 5.

2. Kinematics of 6DOF platform mechanism with wire legs

2.1. Assumptions for kinematic analysis

Kinematic and mobility analysis of the considered platform mechanism is thoroughly described in [5]. Some general definitions are repeated in this chapter for better introduction of the reader. Main assumptions for the kinematic analysis of the mechanism presented in Fig.1, are the following:

I. platforms A and B are rigid;
II. wires are inextensible;
III. there is no wire sack, owing to pretension by few N force;
IV. the proposed mechanism is described by 6DOF, low inertia and negligible net reaction force, therefore it does not influence the measured object characteristics;
V. wires are not interfering with an environment and themselves;
VI. each wire link is modeled as a leg with length $l_i (i = 1, 2 \ldots n)$ and spherical joints at the ends, Fig. 1a;
VII. the joints are ideal;
VIII. lack of friction and backlashes in wire-pulley system, Fig. 1b;
IX. the mechanism working space is without singularities.

2.2. Forward position problem

In forward position problem of a parallel mechanism, its configuration coordinates are given, here the wire lengths, together with constant dimensions of the mechanism. Its pose, described by Cartesian coordinates, is to be determined, what for spatial structures is often a difficult problem in comparison to the serial manipulators [8].

The object (end-effector) spatial positions and displacements (trajectory) can be determined on the basis of p poses described by position vectors ($\boldsymbol{o}_j^c$) and orientation matrices ($\boldsymbol{R}_j^c$), for $j = 1, 2 \ldots p$. Orientation of the reference systems can be determined using different sets of three orientation angles. Roll (γ) – pitch (θ) – yaw (δ) convention was chosen here [3, 4, 7].

Unknown poses of the end-effector can be computed using known poses ($\boldsymbol{o}_j^{ba}$, $\boldsymbol{R}_j^{ba}$) of the measuring platform B with respect to base platform A, where the measuring platform (B, Fig. 1a) is fixed to the end-effector (C, Fig. 1a). The mechanism Cartesian coordinates are grouped together in the following vector:

$$\boldsymbol{k} = [o_x^{ba}\ o_y^{ba}\ o_z^{ba}\ \gamma^{ba}\ \theta^{ba}\ \delta^{ba}]^T \tag{1}$$

In order to determine the measuring platform pose, the following data should be given:

1. constant coordinates of the points $\boldsymbol{a}_i$i $\boldsymbol{b}_i^b$ (i =1, 2...n) on the both platforms (it yields 36 numbers for the most general case and n = 6);
2. constant positions ($\boldsymbol{o}^a$,$\boldsymbol{o}^{cb}$) and orientations ($\boldsymbol{R}^a$, $\boldsymbol{R}^{cb}$) of local platform systems with respect to measured object and base reference system (it yields 12 numbers for the most general case);
3. variable lengths (l_i) of n-wires/legs.

The number of input data to the problem can be reduced by using a special geometry (i.e. planar platforms) of the mechanism.

Lengths ($l_i = \|\boldsymbol{l}_i\|$) of n-wires compose the mechanism configuration coordinates vector:

$$\boldsymbol{q} = [l_1 l_2 \ldots l_n]^T \tag{2}$$

The wire vector can be expressed by a function of three orientation parameters ($\boldsymbol{R}^{ba}$), and three components of the position vector ($\boldsymbol{o}^{ba}$) of platform B with respect to platform A, in the following manner [2, 4]:

$$\boldsymbol{l}_i = \boldsymbol{R}^{ba}\boldsymbol{b}_i^b + \boldsymbol{o}^{ba} - \boldsymbol{a}_i; \quad i = 1, 2...n; \quad n \geq 6 \tag{3}$$

where:
$\boldsymbol{b}_i^b$– position vector of the point B_i in reference system fixed to platform B,
$\boldsymbol{o}^{ba}$- position vector of the point o^b in reference system of the platform A.

Forward position problem of the considered parallel platform mechanism is based on a solution of a set of constraints equations, which can be expressed by constant distances between the corresponding points of two platforms, i.e.:

$$\boldsymbol{l}_i^T\boldsymbol{l}_i = l_i^2; \quad i = 1, 2...n; \quad n \geq 6 \tag{4}$$

The set of n nonlinear algebraic constraint equations (4) with 6 unknowns (1) is solved for each p point of the trajectory using an effective iterative routine based on Newton-Gauss method [5]. In the case of an overdetermined system (when $n > 6$), the solution is found in a least square sense, what can reduce the solution uncertainty under data with noise (from measurements) [9].

The object (end-effector) pose can be determined for given solution of (4) by using the following spatial transformations for position and orientation, respectively:

$$\boldsymbol{o}_j^c = \boldsymbol{R}^a(\boldsymbol{R}^{cb}\boldsymbol{o}^{cb} + \boldsymbol{o}_j^{ba}) + \boldsymbol{o}^a; \quad j = 1, 2...p \tag{5}$$

$$\boldsymbol{R}_j^c = \boldsymbol{R}^{cb}\boldsymbol{R}_j^{ba}\boldsymbol{R}^a; \quad j = 1, 2...p \tag{6}$$

2.3. Inverse position problem

The mechanism pose, described by Cartesian coordinates (1), are known in the inverse position problem, together with constant dimensions of the mechanism [8]. Its configuration coordinates (2) can be determined in straightforward manner by transforming (5) and (6) to obtain $\boldsymbol{o}_j^{ba}$ and $\boldsymbol{R}_j^{ba}$ for each point of the trajectory (j = 1, 2... p).

2.4. Mechanism workspace limitations

Workspace of the considered platform mechanism must suit to the workspace of the measured object. The following factors limiting the mechanism workspace are described below.

a) Permissible range of wire's lengths

Reading of the measuring wires length is correct only when the wires are in tension and without collisions. It is assumed that length of each measuring wire is bounded by:

$$l_{i,min} < l_i < l_{i,max}; \quad i = 1, 2...n; \quad n \geq 6 \tag{7}$$

In the case of violation of the lower bound (7), the wire drum (Fig. 1b) can not wind-up more wire and sustain its tension. In the case of violation of the upper bound (7), the wire drum is fully unwound, i.e. the cable has reached its maximal length.

b) Permissible range of wire's angles

The angle α (Fig.1b) of the wire line should be small (e.g. $\alpha \leq 20$ deg) during tracking to minimize friction induced effects.

c) Wires crossing and collisions with environment

In order to consider an interference problem the wires are modeled by a cylindrical surface with known radius (r_i) and axis described by parametric equation of line in space [4].

In order to avoid interference (crossing) between the wires during measurements of the end-effector displacement, the distances between each couple (i and j) of the cables are calculated and verified. The problem of collision of the wires with environment is formulated using the cylinders for description of the suspension rods, and the planes for description of the platforms and other surrounding surfaces. The collision of a cylinder with a plane can be detected by finding the intersection point of the plane with the cylinder axis displaced by the cylinder radius (r_i). If the plane intersects with this axis, then the condition that the intersection point belongs to the plane is verified. If the directional vector of the plane (describing an environment object) is perpendicular to the cylinder axis (cable) and this axis does not lie in the plane, then the cable does not collide with the environment.

d) *Proper conditioning of the measurements*

In order to measure the spatial displacement with the best accuracy, the considered mechanism dimensions and workspace can be optimized to reduce processing errors. The following factors can be treated as influential on the measurement inaccuracy [9]:

- uncertainty of a distance measurement using wire-based sensors (depends on the sensor quality);
- estimation uncertainty of constant dimensions of the platform mechanism (depends on a quality of additional measurements);
- geometrical errors due to idealization of the mechanism model (due to imperfections of the design and prototyping);
- propagation error due to indirect measurement– (depends on a measurement and processing system selection);
- the mechanism compliance, friction and backlashes (depends on design and prototyping quality);
- inertial effects during a dynamic response;
- ambient temperature.

During the mechanism design process an uncertainty analysis was carried out to estimate an influence of the sensors noise on the position and orientation measurements of the given object [5]. It was assumed that:

- signals from sensors are disturbed by independent normal random process with zero mean value and constant variance;
- geometrical errors of the wire-legs are much less than main dimensions of the platform mechanism;
- linear error propagation theory can be used to solve the problem [9].

A relationship between increments of the wire lengths and changes of the platform position and orientation is written down using the first order kinematics [8, 10]:

$$\boldsymbol{H}\,\delta\boldsymbol{q} = \delta\boldsymbol{k} \tag{8}$$

where:

$\boldsymbol{H}$ – means an (pseudo-) inverse ($\boldsymbol{H} = \boldsymbol{J}^{-1}$) of the mechanism Jacobian ($\boldsymbol{J}$) matrix [8];

$\delta \boldsymbol{q} = [\delta l_1\ \delta l_2\ \ldots\ \delta l_n]^T$ – vector of increments of the wire lengths;

$\delta \boldsymbol{k} = [\delta o_x^{ba}\ \delta o_y^{ba}\ \delta o_z^{ba}\ \delta\gamma^{ba}\ \delta\theta^{ba}\ \delta\delta^{ba}]^T$ – vector of spatial displacement increments.

The mechanism Jacobian matrix depends on its configuration and can be derived by differentiating the constraint equations (4) with respect to time. The parallel mechanism Jacobian matrix can be defined as [10]:

$$\boldsymbol{J}_{n\times 6} = [\widehat{\boldsymbol{l}}_1\ \widehat{\boldsymbol{l}}_2\ \ldots\ \widehat{\boldsymbol{l}}_n]^T \tag{9}$$

where each column of the matrix means a unit spatial vector of i-th wire-leg [4], defines as:

$$\widehat{\boldsymbol{l}}_i = [\hat{\boldsymbol{l}}_i^T\ \ ((\boldsymbol{o}^c - \boldsymbol{b}_i) \times \hat{\boldsymbol{l}}_i)^T]^T \tag{10}$$

There exist a unique inverse of the Jacobian matrix if the mechanism is regular (n= 6) and has a nonsingular configuration. For redundant sensors (n > 6) a pseudo-inverse can be determined with its specific features [9].

Confidence intervals for the measured spatial displacement (1) can be estimated assuming intervals of standard deviation (e.g. in the range of $\pm 3\sigma$) for each wire sensor and using the linear error propagation principle [9]. The output variance depends on a sum of input variances scaled by the system influence coefficients. For the considered measurement system it can be defined by the following formula [5]:

$$\sigma k_i^c = \pm \sqrt{\sum_{j=1}^{n} \sum_{i=1}^{6} (\boldsymbol{H}_{i,j}\, \sigma q_j)^2} \tag{11}$$

In order to reduce the measurement uncertainty (11) the matrix $\boldsymbol{H}$ (8) should be well conditioned, i.e. with low condition number [4]. Good conditioning can be achieved by proper selection of the mechanism dimensions and operation in a workspace distant from singularities. Eq. 8 can be used also during a calibration process of the considered measuring system to reduce systematic errors [2].

3. Application for measuring of spatial displacement of the wheel knuckle

The considered wire-based mechanism (Fig. 1) is adapted to the so-called elastokinematical measurements of the wheel guiding mechanism used in automobiles [4, 5]. The measurements are used to determine some changes in the position and orientation of the wheel-knuckle system with respect to the car body, caused by the changes of the wheel load during a selected maneuver. Initial tests were carried out on the so-called 5-link suspension mechanism for guiding front-driven wheels of VW Passat B6, Fig. 2. The suspension mechanism was installed in a test rig to simplify a preliminary stage of the tracking mechanism verification. The following reference systems are presented in Fig. 2: $\{oxyz\}$ base – car body; $\{o^a x^a y^a z^a\}$ fixed platform – car body; $\{o^c x^c y^c z^c\}$ measured object (wheel knuckle) with center in the wheel center point.

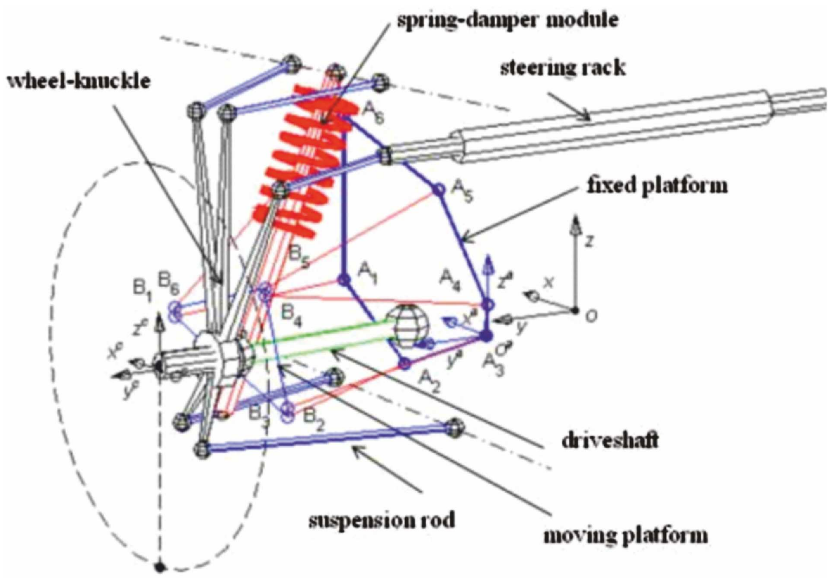

Fig. 2. Perspective view of: (i) 5-link suspension mechanism for guiding a front, driven wheel of VW Passat B6 and (ii) wire-base platform mechanism installed between the wheel knuckle and car chassis

The design goal was to obtain an apparatus that represents a good compromise between expected accuracy and expense. The device should be easy to install in a space (wheel cavity) between the wheel carrier and car chassis, Fig. 2. The measuring mechanism can not interfere with the suspension rods, spring-damper module, steering rack, driveshaft, etc. The tracking system should be described by low inertia, what is crucial during car outdoor tests. The mechanism position workspace is described by an ellipsoid with ca. 100 (along x), 50 (y) and 150 (z) mm radii and position accuracy below ±0.5 mm. Its orientation workspace is described by ca. ±40 deg for z axis and ca. ±10 deg for the remaining axes with the desired accuracy below ±0.1 deg. The measurements should be possible for the wheel motion with maximal velocity up to 1 m/s along z axis and rotational velocity up to 1 rad/s about z axis (wheel bounce and steer motions).

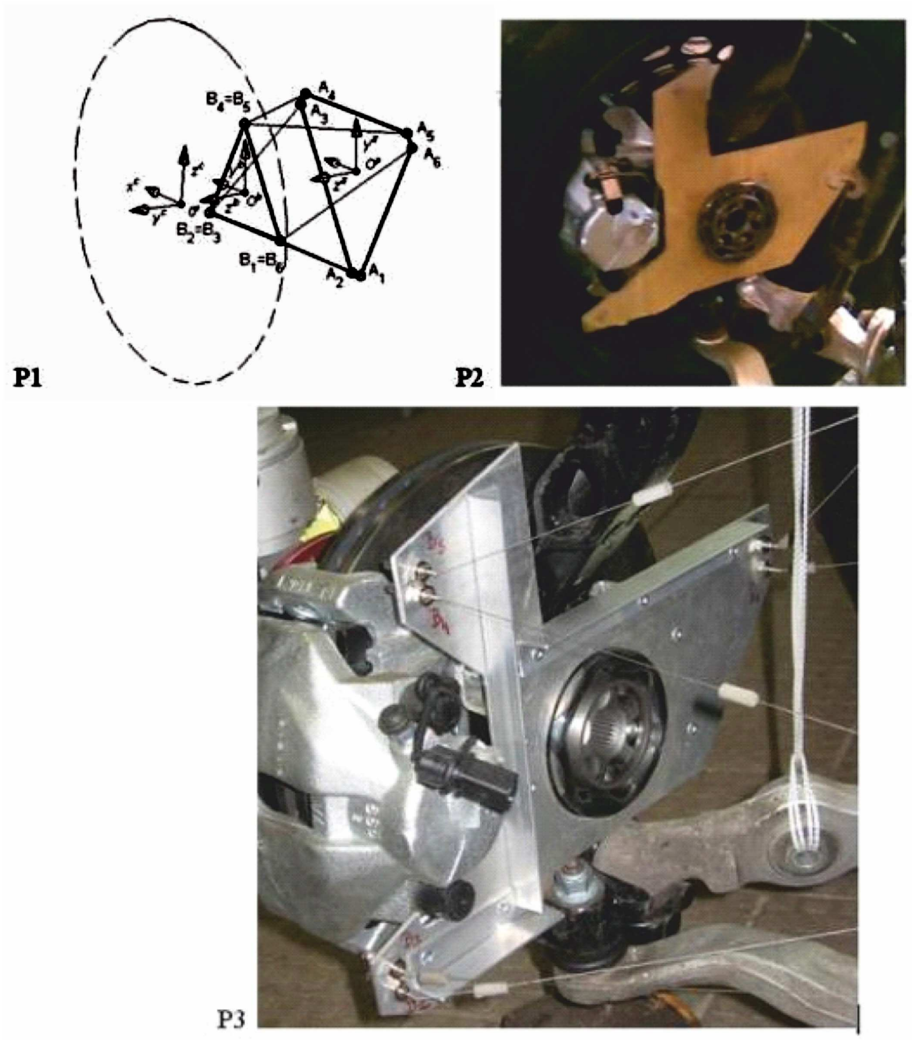

Fig. 3. Views of the first three prototypes of the moving platform attached to the wheel knuckle

Three prototypes of the mechanism platforms were investigated during different project phases [3, 4, 5]. The first prototype (P1 in Fig. 3) was purely virtual at conceptual phase. Main dimensions of the mechanism were assumed and checked with respect to the workspace limitations. The measuring platforms are assumed to be planar, what simplifies building prototypes and dimensioning. The second prototype (P2 in Fig. 3) was physically installed in a real environment. The moving platform included attachment points to the wheel knuckle and geometrical interferences, like brake caliper and CV-joint. The last–third prototype (P3 in Fig. 3) of the moving platform was made of aluminum sheet, enforced with angle bars for increased stiffness.

Fixed platform was made as a plate of Plexiglas for the test stand application. Locations of the points on fixed and moving planar platforms are presented in Fig. 4.

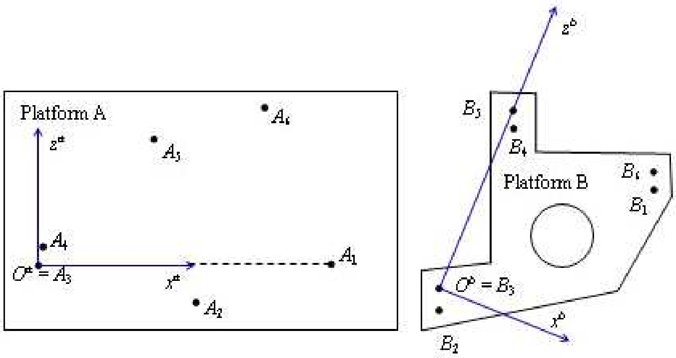

Fig. 4. Locations of wire points and reference systems on (a) fixed and (b) moving planar platforms

The joint coordinates were estimated in local reference systems (Fig. 4) using a portable coordinate measurement machine Arm 2000 Sigma [7], which is an operator-guided serial structure with 6 revolutes (infinite rotation) and spherical contact probe. This 6R arm is pretty accurate (±0.025 mm for length measurements) and task flexible owing to 3-rd order redundancy. Determined coordinates of the joints on fixed and moving platforms are given in Tab. 1.

Table 1.

Joint coordinates of fixed and moving platforms of tracking device (P3)

	[*xyz*] [mm]		[*xyz*] [mm]
A_1	[412.8 0 0]	B_1	[271.7 0 175.9]
A_2	[232.7 0 -93.9]	B_2	[4.0 0 -12.3]
A_3	[0 0 0]	B_3	[0 0 0]
A_4	[1.3 0 50.2]	B_4	[3.7 0 176.2]
A_5	[147.3 0 198.8]	B_5	[0 0 187.7]
A_6	[421.6 0 257.9]	B_6	[267.9 0 190.1]

Besides two platforms, 6 miniature (40×40×58mm) draw-wire sensors were installed at test rig, Fig. 5. Specifications of the available sensors are the following: measuring range up to 1000 mm (for 4 sensors) and 2000 mm (2 sensors); accuracy ±0.1%; max draw velocity up to 0.8 m/s.

4. Verification of the latest prototype

The latest prototype (P3) of the 6DOF wire-based tracking device was verified on the basis on experiments on the test rig with the 5-link suspension mechanism, Fig. 5. The suspension mechanism was installed without the spring-damper module, which was substituted by a screw-rod system. Changing length of this rod enables realization of the wheel bounce motion (compression and rebound). Installed rack and pinion system enables independent excitation of the wheel turn (left and right).

In order to evaluate a performance of the wire-based platform, two other measuring devices are used for comparison purposes. The first one is 6R arm described in the previous chapter. This operator-guided device is for measuring coordinates of points on the object in separate poses. Necessary transformations from the coordinates to the object position and orientation are described in [7]. The second device used for tracking is a commercial 6DOF serial type manipulator (RV3 Datron) guided by the wheel hub [8], Fig.5. It enables continuous measurement, but only of 5 components of the wheel pose. Additionally, the available RV3 is quite heavy and had some backlashes in the joints.

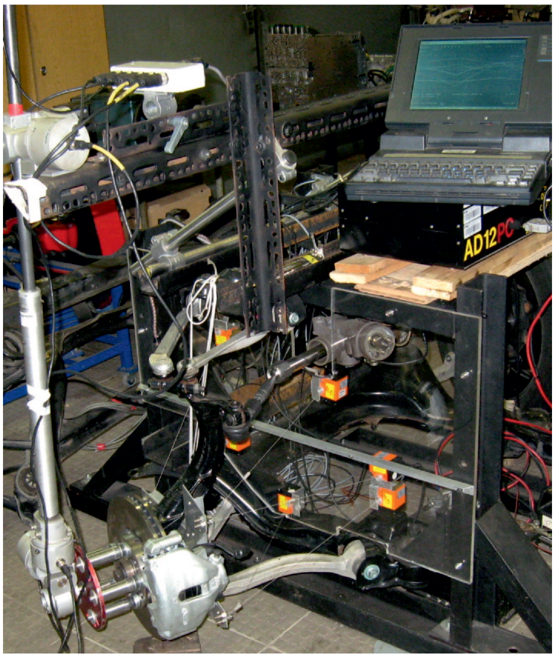

Fig. 5. Photo of the test rig with 5-link suspension mechanism with 6DOF wire-based mechanism and 6DOF serial type manipulator (RV3), both guided by the wheel hub

Verification of the wire-based mechanism was carried out on the basis on the following test emulating a pure bounce motion of the car wheel. The wheel was moved, changing in a quasi-static fashion the rod-screw length, from the design position (1) to full compression stroke (2), then again to the design position (1), and next to full rebound stroke (3) and return to the beginning, i.e. position (1). The car steering (rack) system was fixed in straight ahead position during this test.

Changes of the wire's lengths ($l_1 \ldots\ l_6$), acquired from the sensor's encoders and scaled next, are presented as a function of the wheel bounce coordinate (z_c) in Fig. 6. The enclosed results from 3 measurements are described by satisfactory repeatability. Exemplary changes of the lengths for this test exhibit wires l_3,l_4,l_5 andl_6, which should be monotonic in a wide range and without any hysteresis. The response of wire $l_1$is not satisfactory due to only ca. 3 mm range and non-monotonic fashion. This can negatively influence the measurement accuracy. Even worse response can be noticed for wire l_2. There appears a clear hysteresis and discontinuity. Other conditions for the workspace limitations, like permissible wire angles and collision-free trajectory, were fulfilled without reservation.

The lengths of the wires were also measured in positions 1, 2 and 3 using 6R arm in order to verify the sensor's responses. The obtained results are added as a three discrete points in each subplot of Fig. 6. Results from 6R arm confirm well readouts from the wire sensors. This kind of measurements can be carried out for calibration of the wire sensors.

The wire lengths obtained from the wire sensors are used as input data for solving the direct position problem of the wire-based platform mechanism in order to estimate poses of the wheel knuckle. The determined coordinates of the wheel position and orientation are presented in Figs. 7, 8 and 9 as functions (on vertical axes) of the wheel bounce coordinate (z^c). The same coordinates, but determined on the basis of measurements using RV3 and 6R arm, are added to the graphs for comparison. Lateral displacement (y^c in Fig. 7) of the wheel center is roughly the same for the three devices. In characteristics of the wheel longitudinal displacement (x^c in Fig. 7), which changes in a range of ca. 5 mm, more details are noticeable. The wire-based tracker and RV3 exhibit hysteresis loops with the backbone values converging to the points (no 1, 2 and 3) determined using 6R arm. It is not quite obvious, whether this hysteresis does result from characteristics of the measured mechanism or the measuring devices.

Similar tendency appears in the characteristics of the wheel orientation angles, i.e.: δ^c, γ^c (Fig. 8) and θ^c (Fig. 9). The last angle was not measured by RV3 (5 component device). All angles change in a small range of ca. ±1 deg. Therefore, some discrepancies between the results from three devices

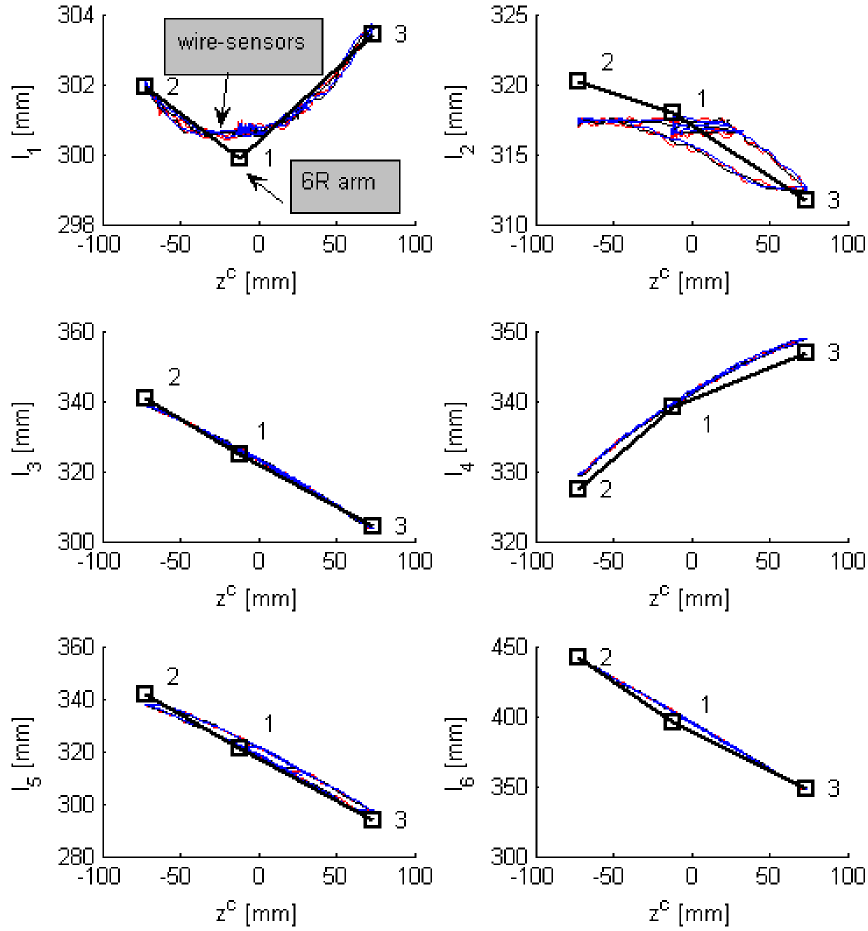

Fig. 6. Changes of wire's lengths ($l_1 \ldots l_6$) as function of the wheel bounce coordinate (z^c), obtained from measurements no1 (3 repetitions) using wire-sensors and 6R arm

are noticeable. Characteristics of δ^c angle is especially interesting. Results from wire-platform are close to the ones from 6R arm, but RV3 exhibit different tendency (probably due to the specimen wear).

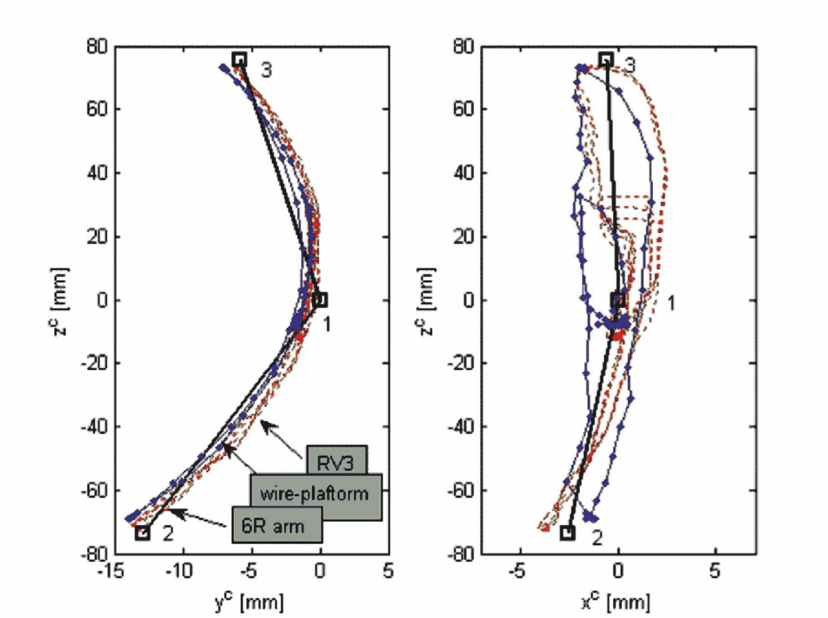

Fig. 7. Changes of y^c and x^c coordinate of the wheel center as function of the wheel bounce coordinate (z^c), obtained from measurements (3 repetitions) using wire-sensors, 6R arm and RV3 manipulator

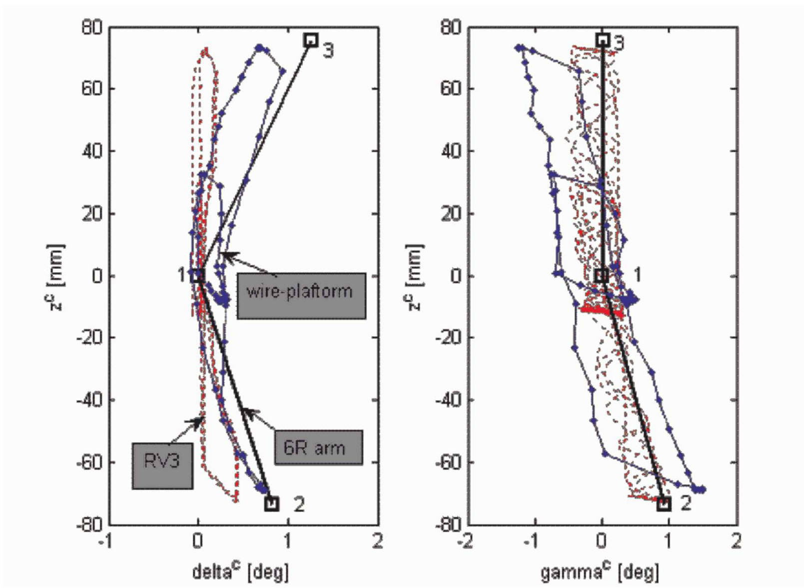

Fig. 8. Changes of the wheel knuckle orientation angles (δ^c, γ^c) as a function of the wheel bounce coordinate (z^c), obtained from measurements (3 repetitions) using wire-sensors, 6R arm and RV3 manipulator

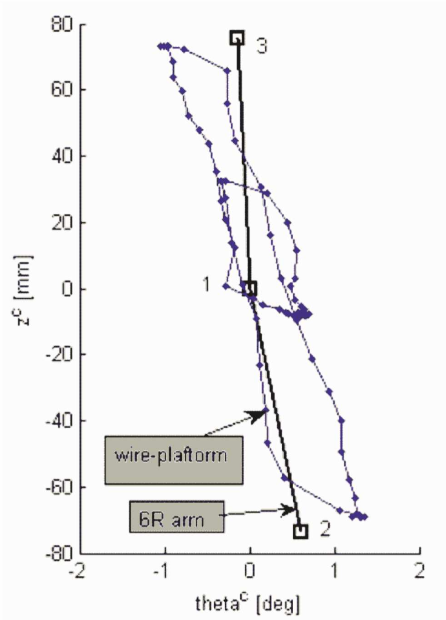

Fig. 9. Changes of the third orientation angle (θ^c) of the wheel knuckle as a function of the wheel bounce coordinate (z^c), obtained from measurements (3 repetitions) using wire-sensors and 6R arm

Table 2.

Comparison of estimated uncertainties of the wheel knuckle coordinates using the considered measurement devices

No	Coordinates of wheel knuckle position and orientation	Required range	6R arm Romer	RV3 Datron	6DOF wire-based tracker (P3)
1	x^c [mm]	< ± 0.2	± 0.2	±1	±2
2	y^c [mm]	< ± 0.2	± 0.2	±0.5	±1
3	z^c [mm]	< ± 0.5	± 0.2	±1	±2
4	γ^c [deg]	< ± 0.1	± 0.05	± 0.2	± 0.4
5	γ^c [deg]	< ± 0.1	± 0.05	± 0.2	± 0.3
6	θ^c [deg]	< ± 0.2	± 0.05	Not available	± 0.4

5. Conclusions and future works

Performance of the developed 6DOF wire-based mechanism for tracking the wheel knuckle was verified on the basis of measurements on a test rig, using also two other commercial measuring devices (ca. 10 times more expensive) for comparison purposes.

The results obtained by using different measurement devices exhibited some discrepancies. A part of the characteristics demonstrated a wide hysteresis in readouts of wire-based mechanism and RV3. The origin of this hysteresis is not quite obvious. It can result from characteristics of the measured suspension mechanism or the measuring devices. The third measuring device, i.e. 6R arm, was assumed to be the most accurate. Unfortunately, only discrete measurements were made in three points of the trajectory. Therefore, only a backbone of the characteristics with hysteresis was checked.

A comparison of estimated uncertainties of the wheel knuckle coordinates, obtained using the wire-based tracker, 6R arm and RV3 is enclosed in Tab.2. The design requirements about accuracy of the wire-based tracker were not fully achieved at this stage of the project. Both linear and angular coordinates of the wheel knuckle need to be determined with lower uncertainty to make the proposed mechanism useful for the defined application. The identified imperfections of the actual design will be improved in a next prototype by including:

- changes in position of the wire sensors no1 and 2, in order to increase their work range;
- the wire sensor no2 need to be changed (after inspection);
- one additional (7th) wire sensor will be used, to take advantage of redundant measurements.

Successive experiments are planed both on the test stand, and in dynamic outdoor conditions, finally.

Manuscript received by Editorial Board, September 21, 2010;
final version, February 25, 2011.

REFERENCES

[1] Andrade-Cetto J.: *A Wire-Based Active Tracker*. IEEE Transactions on Robotics, vol. 24, no. 3, pp. 642-651, 2008.

[2] Eusebio E., et al.: *Characterization of a Cable-Based Parallel Mechanism for Measurement Purposes#*. Mechanics Based Design of Structures and Machines, Volume 38, Issue 1, pp. 25-49, January 2010.

[3] Góra M., Knapczyk J., Maniowski M.: *Analiza położeń i przemieszczeń mechanizmu przestrzennego przy wykorzystaniu pomiarów czujnikami linkowymi*. XX Konferencja Naukowo-Dydaktyczna TMM, Zielona Góra, 2006.

[4] Góra M., Knapczyk J., Maniowski M.: *Estimation of platform pose and displacement of parallel mechanism using wire-based sensors*. The Archive of Mechanical Engineering, Vol. 54, No 4, p. 365-389, 2007.

[5] Góra M.: *Analiza kinematyczna wielowahaczowych mechanizmów zawieszeń samochodów.* Praca doktorska, Wydział Mechaniczny, Politechnika Krakowska, 2010.

[6] Jeong J.W., Kim S.H., Kwak Y.K.: *Kinematics and workspace analysis of a parallel wire mechanism for measuring a robot pose.* Mechanism and Machine Theory, vol.34, pp.825-841, 1999.

[7] Knapczyk J., Maniowski M.: *Methods of geometric parameters estimation of a mechanism model based on point coordinates measurements*. The Archive of Mechanical Engineering, Vol. 60, 2009.

[8] Morecki A., Knapczyk J., Kędzior K.: *Teoria mechanizmów i manipulatorów*, WNT Warszawa, 2002.

[9] Thomas F., et al.: *Uncertainty model and singularities of 3-2-1 wire-based tracking systems*. Advances in Robot Kinematics, pp. 107-116, Kluwer Academic Publisher, 2002.

[10] Verhoeven R., Hiller M., Tadokoro S.: *Workspace, stiffness, singularities and classification of tendon-driven Stewart platforms*. Advances in Robot Kinematics: Analysis and Control. Kluwer Academic Publ. 1998.

Weryfikacja mechanizmu platformowego o 6 stopniach swobody z czujnikami linkowymi do pomiaru przemieszczeń przestrzennych

S t r e s z c z e n i e

W pracy przestawiono wyniki weryfikacji eksperymentalnej opracowanego mechanizmu platformowego z czujnikami linkowymi, przeznaczonego do wyznaczania położenia lub przemieszczenia obiektu w przestrzeni. Potrzeba rozwiązanie takiego zadania istnieje wielu dziedzinach. Autorzy podjęli próbę zastosowania mechanizmu linkowego do mierzenia pozycji i orientacji koła samochodu względem nadwozia.

Postawione wymagania konstrukcyjne obejmują m.in.: korzystny stosunek ceny aparatury do dokładności pomiaru; możliwość zainstalowania mechanizmu we wnęce koła; możliwość badań w warunkach dynamicznych podczas testów drogowych samochodu. Zdefiniowane wymagania może spełnić mechanizm o strukturze równoległej i 6 stopniach swobody, składający się z dwóch sztywnych platform połączonych ze sobą co najmniej sześcioma linkami czujników do pomiaru odległości. Sprężyny w czujnikach gwarantują odpowiedni naciąg linek, który uzasadnia opis kinematyczny linki jako łącznika o zmiennej długości i zakończonego sferycznymi przegubami.

Platforma stała jest związana z bazą-nadwoziem, a platforma ruchoma jest wodzona przez obiekt-koło, którego trajektoria jest do wyznaczenia. Zmiany pozycji i orientacji platform powodują zmiany długości linek czujników pomiarowych. Rozwiązując zadanie proste manipulatora równoległego wyznacza się szukane położenie koła. Rozłożenie linek musi być odpowiednio dobrane, tak aby nie ograniczać przestrzeni roboczej mechanizmu, np. przez kolizję linek.

Ocenę właściwości wykonanego prototypu mechanizmu linkowego dokonano na podstawie pomiarów na stanowisku z zainstalowanym zawieszeniem, tzw. pięcio-wahaczowym, kół przednich samochodu VW Passat. Do pomiarów wykorzystano także dwa inne urządzenia do wyznaczania położenia zwrotnicy koła. Porównane wyniki potwierdziły postawione założenia, ale wykazały także pewne niedoskonałości, które planuje się poprawić w kolejnym prototypie urządzenia.