

Vehicle motion reconstruction based on EDR/ADR records – simulation research

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Abstract. One of the basic tasks of the accident reconstruction is to define values of parameters of participants of the accident before its actual occurrence. The assessment of correct behaviours is made and the court decides whether the accident participants are guilty or innocent. Therefore, the credibility of specific values is essential. The use of so-called accident recorders – EDR/ADR type of devices, as an alternative compared to classical methods for accidents reconstruction – has become more common over the past years. The paper includes basic notions related to this type of devices, describes potential sources of uncertainty of the car motion reconstruction results, obtained on the basis of their records. Exemplary results of calculations made with simulation methods are presented (but using experimentally verified models). The examples presented confirm their usefulness, however, they also indicate possible significant errors in the motion parameters assessment if simplified devices are used.

1. Introduction

Often a lack of a lot of key information on the course of an event is the essential problem while reconstructing accidents. For more than 60 years in aviation the so-called „black boxes” have been used i.e. devices that continuously record a number of selected parameters for purposes of potential reconstruction of a crash (data characterizing a flight, status of the plane components, also voice, and recently also image from the cockpit). The oldest devices recording quantities that describe motion of vehicles in road transport are tachographs. In 90-ties of 20th century, EDR (Event Data Recorder) devices occurred reminding aerial „black boxes”. Those are special devices meant for the accident reconstruction purposes. They may also be found under another English name: ADR (Accident Data Recorder) or German UDS (Unfalldatenspeicher). Further on in the paper, the acronym ADR shall be used for this type of the device. Potential advantages in using this type of devices seem to be considerably high. First of all, the information resource on the course of the event becomes more extensive. The basic advantage is the fact that here we use the values being measured in real road situation, not the ones assumed by an expert during the hereto analysis. Therefore, the problem of uncertainty of the assumed values of parameters, describing the situation being analysed as well as inadequacies of the analysis effecting from simplifications in applied mathematical models of the vehicle/s motion, their collisions, etc., do not occur. Whenever the „black boxes” records are used, there is also a simplification of the accident reconstruction process. A relevant algorithm for processing recorded parameters of the vehicle motion allows for reconstructing time-spatial relations of the situation that has occurred.



However, range and other specific parameters of the ADR device can affect accident analysis results. In the paper, the author presents examples of simulation research on the influence of selected factors on the outcome of reconstruction. The simulation method and sample calculation results are presented.

2. ADR/EDR Devices

ADRs have been offered for many years. Some of ADRs are vehicle OEM installation, other (e.g. UDS in Europe) are additional systems. Those devices are intended to record quantities that can be useful for forensic experts in identifying the accident/crash sequence and determining its parameters (e.g. initial car velocity, its position on the road). They register selected parameters of a car movement (acceleration, body orientation angles or corresponding to them angular velocities). They can also register driver's activity (e.g. the use of external lighting and other control elements) vehicle crash signature, restraint usage/deployment status, and post-crash data such as the activation of an automatic collision notification system as well as environment conditions (e.g. temperature, moisture). The sphere of activity of these devices (number and type of registered values, time, frequency of registration) varies (see for example [6]). From number of quantities that describe car body motion, we can distinguish two characteristic groups of devices. The simpler ones, named here as ADR2, register car's longitudinal and lateral accelerations and yaw angle only. More advanced devices, named here as ADR1, register also vertical acceleration and two angles (or angular velocities) of a car body - roll and pitch angles.

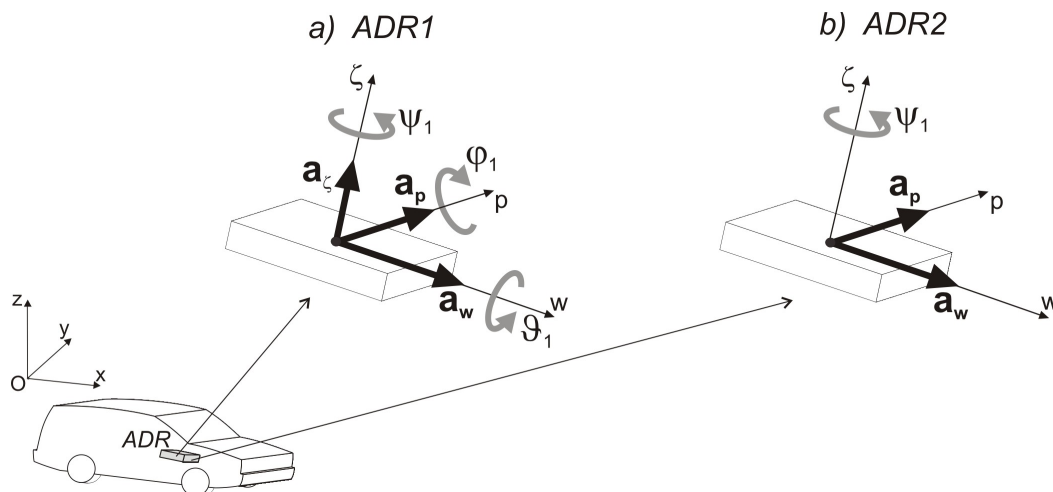


Figure 1. Two types of ADR: ADR1 & ADR2 (w , p , ζ - accelerometer axes: longitudinal, lateral, and “vertical”)

In most cases of the devices, their operational rule is as follows: all quantities are monitored on the ongoing basis. Recording on a hard memory disk commences only at the moment of collision occurrence. Since that moment, a history is recorded from a few up to several seconds backwards with frequency ranking between a few and up to several dozens of Hz. Then, a collision phase is recorded. Often that recording is saved with much higher frequency than for the motion phase before the collision (even 1kHz). It usually lasts a few hundred milliseconds. In many devices, a post-collision phase is also saved (several seconds up to even a few minutes) with a frequency as for the pre-collision phase or much lower. Some devices are equipped in GPS receiver allowing for localization of the place of the accident and for sending automatic information about it to relevant services [6, 7].

In general, there are a few potential sources of uncertainty in motion reconstruction using the ADR records. The reconstruction error (understood as a difference between values of parameters, describing vehicle motion and that have been defined based on ADR records, and accurate values of the

parameters) is the function of errors effecting from ADR general characteristics, measuring and recording apparatus errors, and errors resulting from the processing of recorded quantities. The notion of ADR general characteristics may mean e.g. a number and type of quantities being recorded (e.g. recording of one, two, or three components of the car body's acceleration, recording of quantities describing angular position of the vehicle in a form of angles or angular velocities, etc.), frequency of ADR records, reference system in which the motion-describing quantities are recorded – e.g. whether it is a levelled system or not. Also inappropriate positioning of the device inside the vehicle (e.g. erroneous directions of accelerations measurement) can be mentioned in this group of errors. The scope of error, described as the measuring and recording apparatus error includes all inaccuracies resulting from own errors of the quantities-recording sensors, from properties of the measuring and recording system, and errors that have occurred while reading the recorded quantities. Processing error is the error effecting from methods of integration and differentiation of recorded quantities.

This paper shall focus on the first source out of those mentioned. It will be first of all presented how in ADR2 type of device omission of assessment of certain quantities, defining vehicle kinematics, affects uncertainty of the vehicle motion reconstruction.

3. Simulation method of research

General diagram of simulation method of research is presented on Fig. 2. First, car motion simulation is performed (for a given vehicle in a defined traffic situation). The simulation results are treated as „accurate”. On the basis of those results, recordings of ADR device are simulated (recognizing a specific character of the device – see ADR general characteristics). Using the „recordings”, and by applying devised processing algorithms, a reconstruction of the earlier simulated motion is performed. A comparison of a simulation process of a given quantity and a process obtained basing on ADR recording is the foundation for assessment of a potential error in car motion reconstruction by using such device. A difference between a value, defined using ADR (ADR1 or ADR2), and that defined in the motion simulation research was treated as the error.

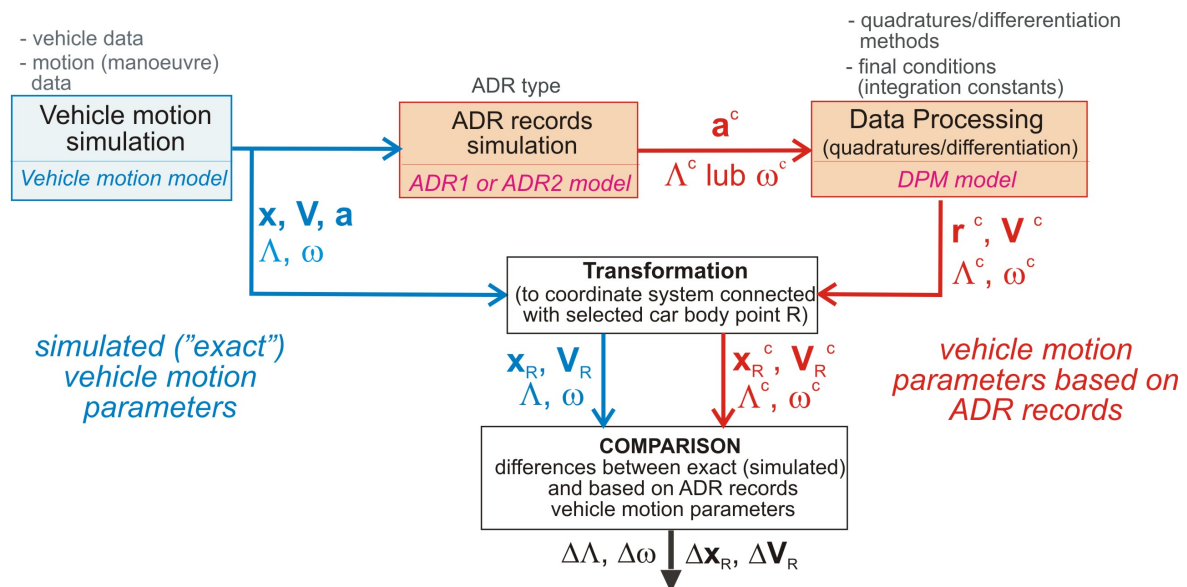


Figure 2. Motion reconstruction accuracy assessment method based on ADR devices records.

a, V, ω, r, Λ – components vectors (respectively): acceleration, velocity, angular velocity, position, angles

3.1. Vehicle motion model

The program ZL3DSYM [5], which had been made available by its author, was applied for car motion simulation computations. The program uses a complex car motion model. The model corresponds to a passenger car with front independent suspension and rear dependent one. It has 14 degrees of freedom: 6 describing a motion of the car body solid (3 movements of the centre point of the mass and 3 angles of the car body solid), 4 angles of driving wheels, 4 coordinates describing relative motions of the suspension. The model includes non-linear characteristics of suspension elasticity and dumping as well as tires. The tire shear forces model includes influence of the wheel centre velocity, normal road reaction, wheel camber angle, king-pin inclination, caster, and toe-in angles. The ZL3DSYM program has been successfully experimentally verified. A detailed description can be found e.g. in [5].

3.2. Model of ADR device records

A full description of a position and kinematics of the device against the car body and the distance are required to formulate a model of records from ADR device. The diagram has been illustrated on Fig. 3.

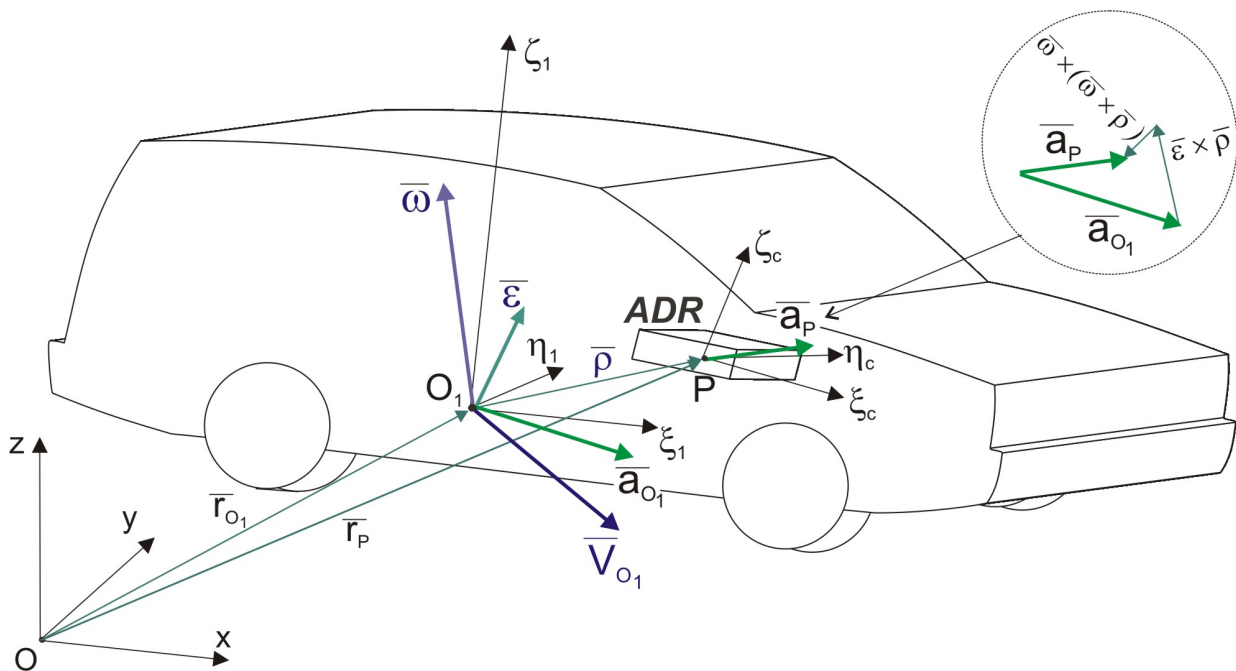


Figure 3. The model of the kinematics of the movement of the vehicle equipped with a ADR device fixed at point P (r – translatory location; V – translatory movement velocity; a – translatory movement acceleration; ω – angular velocity; ε – angular acceleration)

The movement of the vehicle body is treated as a combination of the translatory movement of the centre of the mass of the body $O1$ and the spherical movement of the body against point $O1$. Thus we consider a movement having 6 degrees of freedom (3 displacements and 3 rotations). Fig. 3 presents the assumed coordinate systems.

The following main co-ordinate systems were chosen:

$Oxyz$ – the inertial system fixed with the road; the Ox and the Oy axis are horizontal, the vertical Oz axis is orientated upwards;

$O1\xi_1\eta_1\zeta_1$ – the non-inertial system fixed with the car body; the axes $O1\xi_1$, $O1\eta_1$, $O1\zeta_1$ are the main central axes of inertia of the car body;

$P\xi_c\eta_c\zeta_c$ – the non-inertial system fixed with ADR device, the $P\xi_c$, $P\eta_c$ and $P\zeta_c$ axis are ADR transducers axis (respectively: longitudinal, lateral and “vertical” axis).

The description of vectors (notation in matrix form "T" means transposition):

$\bar{r}_{O_I} \equiv \mathbf{x}_{O_I} = [x_{O_I}, y_{O_I}, z_{O_I}]^T$ - the position of the centre of the mass of the car body O_I in the inertial $Oxyz$ system;

$\bar{r}_P \equiv \mathbf{x}_P = [x_P, y_P, z_P]^T$ - the position of point P in the inertial $Oxyz$ system;

$\bar{\rho} \equiv \mathbf{\rho} = [\xi_P, \eta_P, \zeta_P]^T$ - the position of point P in the $O_I \xi_I \eta_I \zeta_I$ system;

$\bar{\omega} \equiv \mathbf{\omega} = [\dot{\psi}_I, \dot{\phi}_I, \dot{\vartheta}_I]^T$ - angular velocity;

$\bar{V}_{O_I} \equiv \dot{\mathbf{x}}_{O_I} = [\dot{x}_{O_I}, \dot{y}_{O_I}, \dot{z}_{O_I}]^T$ - the velocity of point O_I ;

$\bar{a}_{O_I} \equiv \ddot{\mathbf{x}}_{O_I} = [\ddot{x}_{O_I}, \ddot{y}_{O_I}, \ddot{z}_{O_I}]^T$ - the acceleration of point O_I ;

$\bar{a}_P \equiv \ddot{\mathbf{x}}_P = [\ddot{x}_P, \ddot{y}_P, \ddot{z}_P]^T$ - the acceleration of point P .

The kinematics of point P is described as follows (P is fixed with the vehicle body, A – the rotation matrix):

$$\text{position:} \quad \mathbf{x}_P = \mathbf{x}_{O_I} + A \cdot \mathbf{\rho} \quad (1)$$

$$\text{velocity:} \quad \dot{\mathbf{x}}_P = \dot{\mathbf{x}}_{O_I} + \dot{A} \cdot \mathbf{\rho} \quad (2)$$

$$\text{acceleration:} \quad \ddot{\mathbf{x}}_P = \ddot{\mathbf{x}}_{O_I} + \ddot{A} \cdot \mathbf{\rho} \quad (3)$$

The rotation matrix A has the form:

$$A = \begin{bmatrix} \cos \psi_I \cdot \cos \phi_I & \cos \psi_I \cdot \sin \phi_I \cdot \sin \vartheta_I - \sin \psi_I \cdot \cos \vartheta_I & \cos \psi_I \cdot \sin \phi_I \cdot \cos \vartheta_I + \sin \psi_I \cdot \sin \vartheta_I \\ \sin \psi_I \cdot \cos \phi_I & \sin \psi_I \cdot \sin \phi_I \cdot \sin \vartheta_I + \cos \psi_I \cdot \cos \vartheta_I & \sin \psi_I \cdot \sin \phi_I \cdot \cos \vartheta_I - \cos \psi_I \cdot \sin \vartheta_I \\ -\sin \phi_I & \cos \phi_I \cdot \sin \vartheta_I & \cos \phi_I \cdot \cos \vartheta_I \end{bmatrix} \quad (4)$$

where angles ψ_I , ϕ_I , ϑ_I describe spherical motion of the vehicle body against the pole O_I (known as “quasi-Euler” angles):

- the yaw angle ψ_I (rotation around the axis $O_I \zeta_I$),
- the pitch angle ϕ_I (rotation around the axis $O_I \eta_I$),
- the roll angle ϑ_I (rotation around the axis $O_I \xi_I$).

The succession of rotations corresponds to the succession of their description (see also Fig. 4).

The transformation of the system $O_I \xi_I \eta_I \zeta_I$ to the system $O_I x_I y_I z_I$ is described by the relation:

$$[x_I, y_I, z_I]^T = A \cdot [\xi_I, \eta_I, \zeta_I]^T \quad (5)$$

The transformation in the opposite direction (from $O_I x_I y_I z_I$ to $O_I \xi_I \eta_I \zeta_I$) is described by the inverse matrix A^{-1} , where:

$$A^{-1} = A^T \quad (6)$$

which is derived from their mutual orthogonality.

The position of the sensors ADR is defined by the point of fixing P and the axes of the system $P \xi_c \eta_c \zeta_c$, fixed with the device. The $P \xi_c \eta_c \zeta_c$ system is obtained from the $O_I \xi_I \eta_I \zeta_I$ system by translation by a vector $\bar{\rho}$ and rotation described by matrix C . Analogical rotations to the ones describing the angular position of the car body in relation to the road (the yaw ψ_I , the pitch ϕ_I , the roll ϑ_I) have been taken, but in the opposite sequence: the ADR roll ϑ_c (rotation around the longitudinal axis ξ_c), the ADR pitch ϕ_c (rotation around the lateral axis η_c), the ADR yaw ψ_c (rotation around the “vertical” axis ζ_c) – see Fig. 4. Such a sequence of rotations has been taken because of the ease of levelling the sensors (orientated in relation to the vehicle). Their introduction enables any angular positioning of ADR in relation to the body. This in turn enables to account for the related errors of the readings of the ADR sensors.

The matrix C has the form:

$$C = \begin{bmatrix} \cos\psi_c \cdot \cos\varphi_c & -\sin\psi_c \cdot \cos\varphi_c & \sin\varphi_c \\ \cos\psi_c \cdot \sin\varphi_c \cdot \sin\vartheta_c + \sin\psi_c \cdot \cos\vartheta_c & -\sin\psi_c \cdot \sin\varphi_c \cdot \sin\vartheta_c + \cos\psi_c \cdot \cos\vartheta_c & -\cos\varphi_c \cdot \sin\vartheta_c \\ -\cos\psi_c \cdot \sin\varphi_c \cdot \cos\vartheta_c + \sin\psi_c \cdot \sin\vartheta_c & \sin\psi_c \cdot \sin\varphi_c \cdot \cos\vartheta_c + \cos\psi_c \cdot \sin\vartheta_c & \cos\varphi_c \cdot \cos\vartheta_c \end{bmatrix} \quad (7)$$

The transformations from the system $P\xi_c\eta_c\zeta_c$ to the system $O_I\xi_I\eta_I\zeta_I$ have the form:

$$[\xi_I, \eta_I, \zeta_I]^T = C \cdot [\xi_c, \eta_c, \zeta_c]^T \quad (8)$$

The opposite transformation (from $O_I\xi_I\eta_I\zeta_I$ to $P\xi_c\eta_c\zeta_c$) is described by the inverse matrix C^{-1} , orthogonal against C :

$$C^{-1} = C^T \quad (9)$$

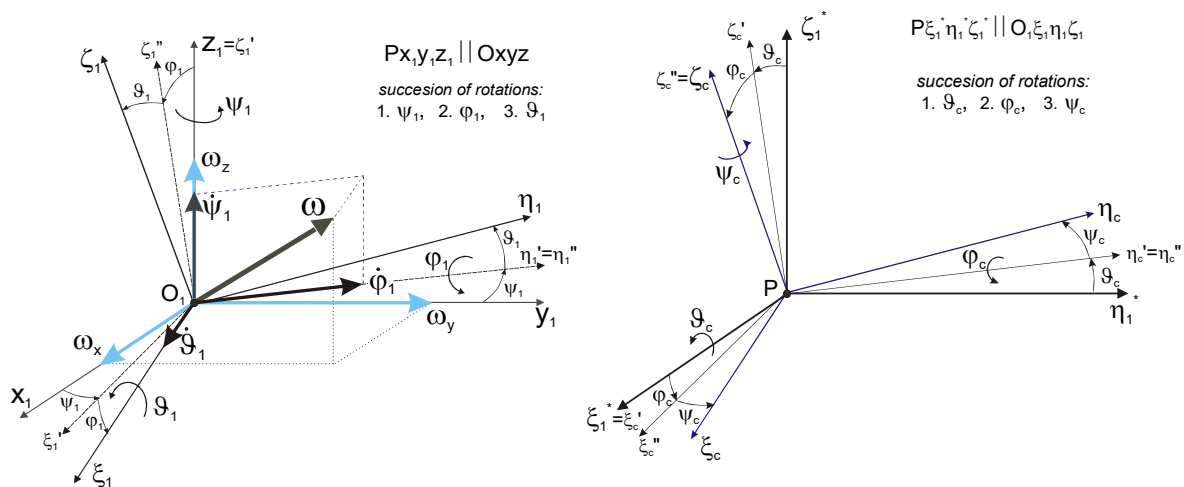


Figure 4. The angular positioning of the coordinate systems: $O_I\xi_I\eta_I\zeta_I$ in relation to $Oxyz$ and $P\xi_c\eta_c\zeta_c$ in relation to $O_I\xi_I\eta_I\zeta_I$

The inertial acceleration sensors show the value proportional to the sum of the components in the direction of the activity of the sensor: the force of inertia and the force of gravity. The sensor's indication is the sum of the components in the direction of the activity of the sensor of the real acceleration and the acceleration of gravity. Accepting that, in general the acceleration sensor is three-axial, that is:

$$\mathbf{a}^c = [a_w^c, a_p^c, a_z^c]^T \quad (10)$$

we obtain the general vector relation for the readings of the sensor

$$\mathbf{a}^c = \mathbf{a}_{Pc} - \mathbf{g}_c \quad (11)$$

where

$$\mathbf{a}_{Pc} = [a_{P\xi_c}, a_{P\eta_c}, a_{P\zeta_c}]^T = C^{-1} \cdot \mathbf{a}_P = C^{-1} \cdot A^{-1} \cdot \ddot{\mathbf{x}}_P \quad (12)$$

$$\mathbf{g}_c = [g_{\xi_c}, g_{\eta_c}, g_{\zeta_c}]^T = C^{-1} \cdot \mathbf{g}_\xi = C^{-1} \cdot A^{-1} \cdot \mathbf{g} \quad (13)$$

and $\mathbf{g}=[0, 0, -g]^T$ – the vector of acceleration of gravity.

$\mathbf{a}_{Pc}$ and $\mathbf{g}_c$ represent the acceleration of point P and the acceleration of gravity, accordingly, described in the $P\xi_c\eta_c\zeta_c$ system.

The presented description assumes no own errors of the sensors. The model, relevant for the indications describing angular position (angles or angular velocities), is also prepared. Its formal description is available in [1, 2, 3].

3.3. Data processing model (DPM)

The purpose of the car motion reconstruction is to reconstruct a time history of vehicle's velocity and its motion trajectory. Procedures of numerical integration (quadratures) of recorded accelerations (and possible angular velocities) and differentiation are used for that purpose. The diagram of proceeding in case of the body angles records in ADR device has been presented on Fig. 5. First of all, if possible (this is the case of ADR1 type of devices), the recorded accelerations are adjusted by gravity acceleration components being sensed by the sensors. Further on, the accelerations are transformed into inertial reference system (related to the road). In this form, they are integrated twice, which allows for defining velocities and positions. Computations are usually made „backwards”, which means from the last moment for which vehicle position and its velocity to the start are known. Knowing the ADR's position in a vehicle, the results obtained are transformable to any point of the vehicle's body.

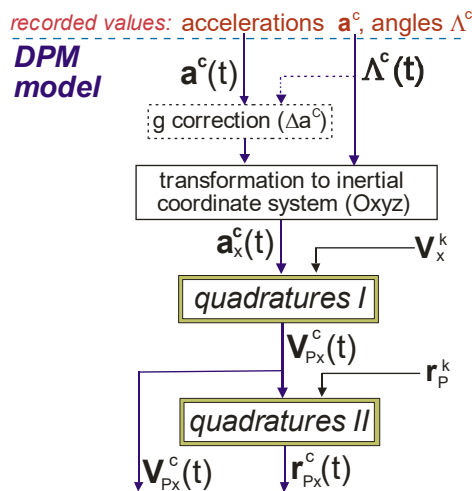


Figure 5. Block diagram of data elaboration. a_x , V_x , r_x - vectors of acceleration, velocity and position in the earth-fixed coordinate system $Oxyz$; V^k , r^k - final value of velocity and position; index P - denotes the value for point P in which ADR is fixed

$$a^c : \begin{cases} a_w^c, a_p^c, a_z^c \\ a_w^c, a_p^c \end{cases} ; \Lambda^c : \begin{cases} \psi_l^c, \phi_l^c, \theta_l^c \\ \psi_l^c \end{cases} \quad \begin{matrix} \text{- ADR1} \\ \text{- ADR2} \end{matrix}$$

A set of: the motion simulation program ZL3DSYM plus ADR mathematical model (plus DPM model) has been experimentally verified. A comparative assessment has been made for a few characteristic tests (straight-line braking, traffic lane-change maneuvers, and turn entering maneuver). Examples are presented in [2, 3]. They indicate a good compliance between the experiment and the simulation.

4. Exemplary results

4.1. Example description and reference to previous works

In previous works (e.g. [1, 2, 3, 4]) there was confirmed that, in the case of simplified ADR2 devices, it is possible that the reconstruction results are significantly different from the actual vehicle motion (in such a way that the correct assessment can not be made). There is pointed out the influence of many factors on the possible difference (kind and time of maneuver, ADR2 position in the car, method of quadrature, recording frequency, road irregularities).

In this paper an example showing influence of the macroprofile of the road is presented. The example concerns lane change maneuver performed by passenger car (mass ca. 1450kg, wheelbase ca. 2,5m) with velocity of about 100km/h. In the next subsections there are shown time histories of simulated ADR recordings and reconstructed on their basis histories of vehicle velocity and trajectory (for vehicle center of mass).

4.2. Maneuver performed on horizontal road surface

Fig. 6a-d show selected curves plotted in result of the test and representing the records of quantities important from the point of view of the reconstruction of vehicle motion, i.e. time histories of longitudinal a_w^c , lateral a_p^c and "vertical" a_z^c accelerations (Fig. 6a-c) and time histories of pitch angle

φ_l , and roll angle $\mathcal{G}_l$ (Fig. 6d). In the acceleration graphs, components of the acceleration of gravity $\Delta a_w^c, \Delta a_p^c, \Delta a_\zeta^c$, captured by the acceleration transducers used, have been plotted.

Fig. 6e-f present results of the processing of data shown in Fig. 6a-d, i.e. six quantities ($a_w^c, a_p^c, a_\zeta^c, \psi_l$ – not shown, $\varphi_l, \mathcal{G}_l$) for ADR1 and three quantities (a_w^c, a_p^c, ψ_l) for ADR2. The velocity and trajectory was reconstructed for the period under consideration, in the order from the final instant to the initial instant. Fig. 6e shows the time history of the vehicle velocity (or more precisely, of the velocity of the point O_l). Fig. 6f shows the reconstructed trajectories of point O_l for both the ADR units.

It can be seen that in the case of the ADR1 device, the reconstructed time-histories practically coincide with the accurate ones. In the case of ADR2, there are differences. The error in the initial velocity is small and amounts to approx. 0,2%. However, the trajectories differ significantly. The error in the assessment of the lateral position is approx. 0,4 m (11,4% vs. 3,5m - the total lateral displacement of the vehicle during the maneuver).

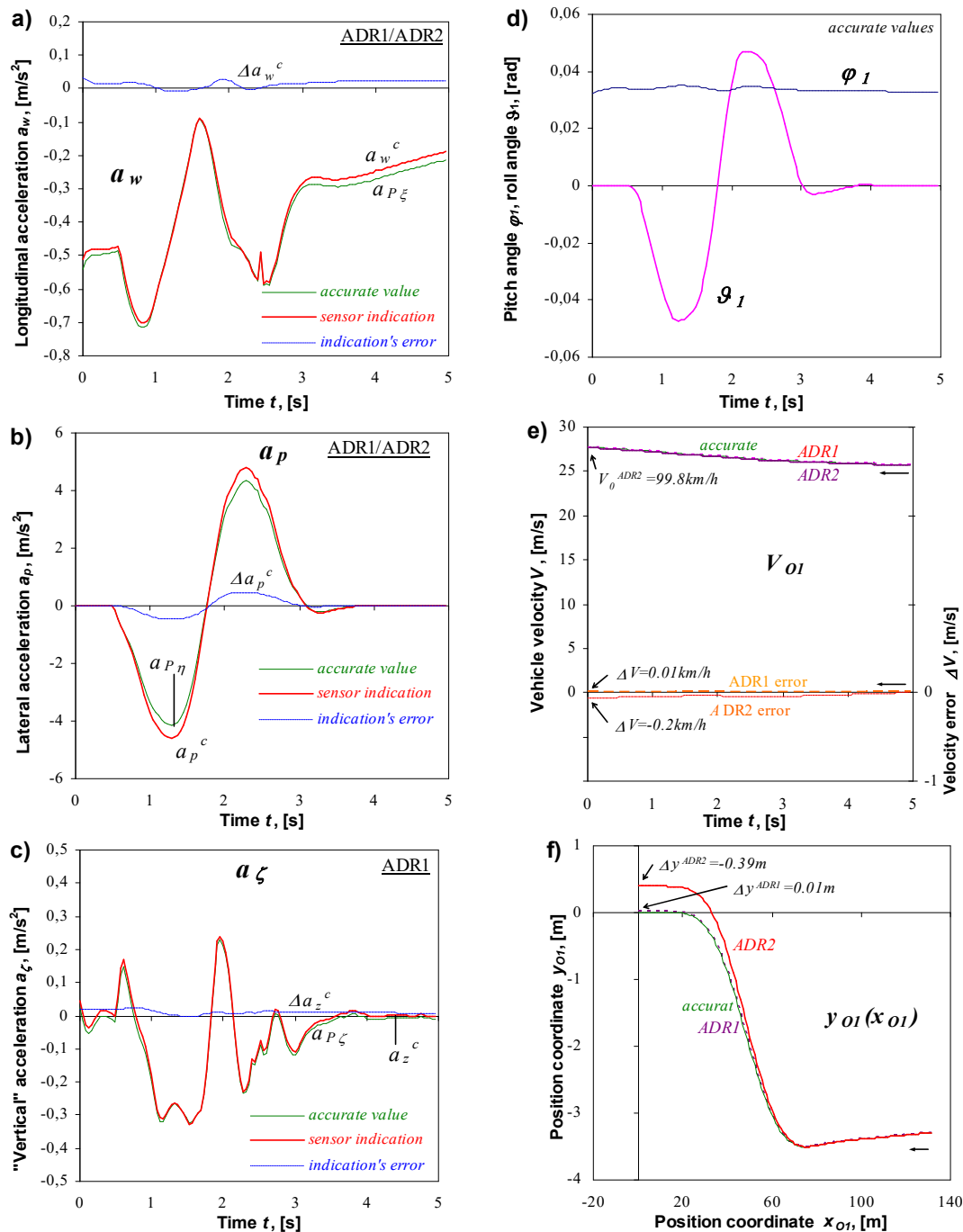


Figure 6. Lane change maneuver performed by passenger car, horizontal road surface. Time histories of ADR recordings (a, b, c, d) and reconstructed vehicle velocity(e) and vehicle C.G. trajectory (f)

4.3. Maneuver performed on road surface with lateral inclination

Fig. 7 shows in analogous form simulation results obtained for maneuver performed on the road with lateral inclination (5% on right). Here, in the case of reconstruction, only the results for the ADR2 device are limited (for ADR1 the results coincide as before with the exact result). On the other hand, the results of reconstruction are presented in two variants: without and with the correction of the

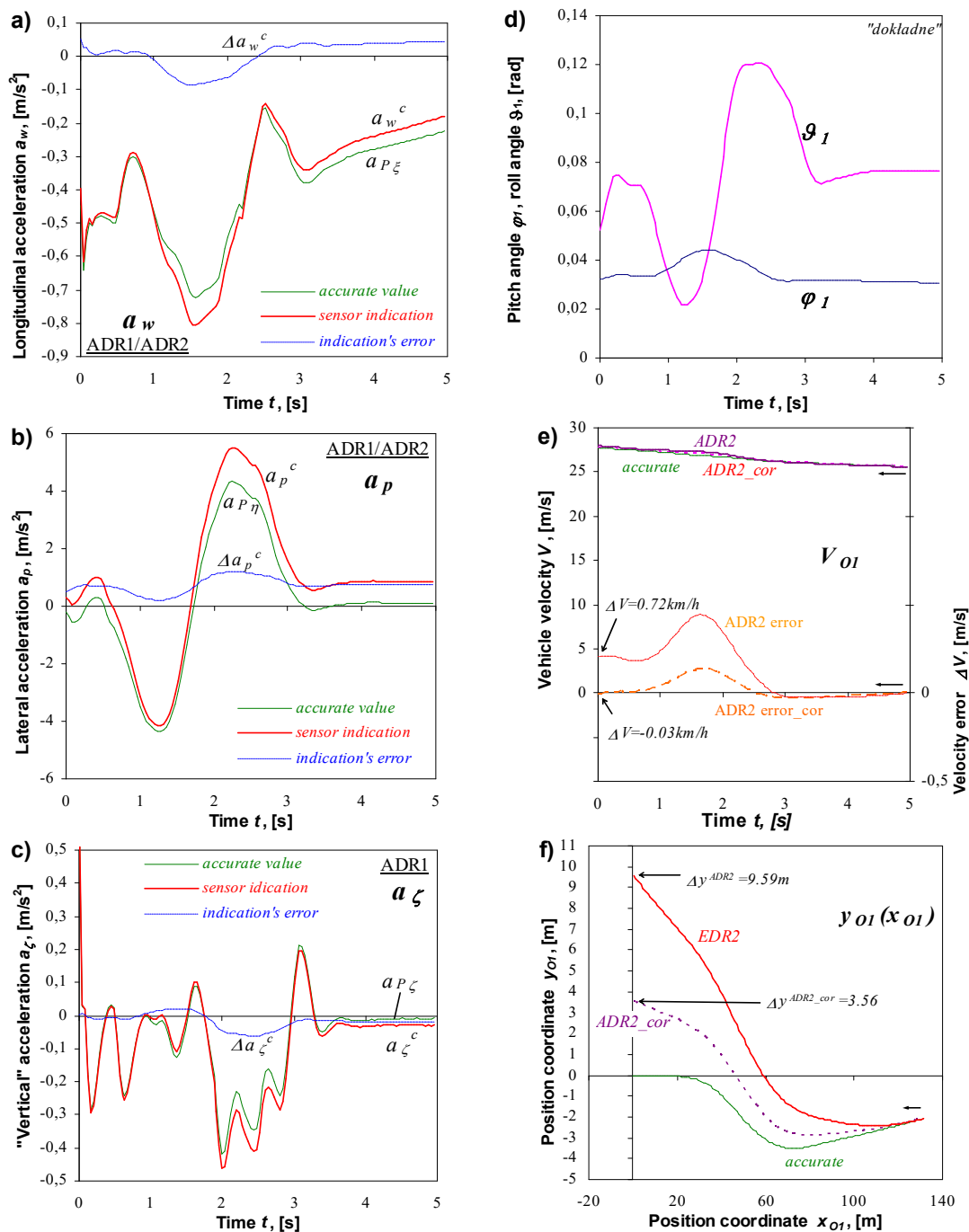


Figure 7. Lane change maneuver performed by passenger car, laterally inclined road surface (inclination 5% on right side). Time histories of ADR recordings (a, b, c, d) and reconstructed vehicle velocity(e) and vehicle C.G. trajectory (f)

acceleration sensors' indications. This correction consists in taking into account in the acceleration courses the values resulting from the inclination of the road.

For vehicle velocity reconstruction, there are no significant changes compared to the horizontal road surface (although the error here is slightly larger if we do not correct the road inclination). In the case of reconstruction of the vehicle C. G. trajectory, if we do not make a correction of the road inclination, the error is very large. It reaches over 9,5 m in the lateral direction. It means a completely different

position of the vehicle on the road than in "reality". The introduction of the correction of accelerations resulting from the lateral road cant significantly improves the result. However, the error in the lateral position assessment is still very large (about 3,5 m). It can be concluded that the correction of the inclination of the road improves the accuracy of the reconstruction, but not always sufficient. It reveals the effect, which is that the inclination of the road, in addition to generating an additional component of the acceleration (which we remove by the previously described correction) changes the angular position of the vehicle relative to the road surface. The "additional" longitudinal and lateral inclination of the car body (to the road surface) appears.

5. Conclusion

Solutions of ADR/EDR devices being offered nowadays on the automotive market, differ at number of quantities being recorded. Author of this paper has focused his attention on assessment of the impact of simplifications applied therein, described in the main body of this paper, on uncertainty of values of the key parameters, defining the vehicle motion (velocity, motion trajectory). Problems such as those related to e.g. measuring and recording apparatus applied in the devices have not been considered.

The experimentally verified simulation method has been used here for research purposes. On the basis of exemplary tests (dynamic lane-change maneuver), it has been illustrated that the simplifications applied in "black boxes" solutions (ADR2 type of devices), may lead to significant errors in motion reconstruction. This mostly refers to the car motion trajectory reconstruction. Also, a result that considerably differs from the real one is a possibility in case of velocity reconstruction. The basic reason for it is that ADR2-type of devices does not provide information about angles of the car body solid's orientation: about the pitch angle and the roll angle. In case of ADR1-type of devices, which collect such information, no essential reconstruction errors have been found.

A wider scope of research results, confirming the above statements and delivering more detailed information can be found e.g. in works [1, 2, 3, 4].

6. References

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