IMPROVEMENT OF DUMMY POSITIONING AND VEHICLE PARTS DURING A CRASH THROUGH THE INTEGRATION AND FILTERING OF INERTIAL SENSORS

Andrés Aparicio
José Manuel Barrios
Eva Palacios
Arturo Dávila
Jaime López
IDIADA Automotive Technology SA (1)
Spain
Paper Number 09-0372

ABSTRACT

The objective of this paper is to discuss the potential capabilities of inertial sensors for point tracking and the presentation of a new tool which is able to place vehicle and dummy parts in 3D during a crash. This tool can help in the understanding of crash dynamics and optimize restraint system integration as well as CAE correlation.

This paper analyses the uses given to inertial sensors in crash applications, describes the errors obtained and proposes methods to correct them. The use of accelerometer-only based and accelerometer and gyroscope-based platforms is discussed. Recommendations for placement, filtering and calculation methods are given. A tool able to track in 3D the trajectory of a point is presented and the limitations found are commented.

The sled tests carried out to obtain relevant information are presented. Possible applications in current tests and probable new tests exploiting the capabilities of the new tool are suggested.

INTRODUCTION

Accelerometers are the most commonly utilized sensors for crash applications in the automotive industry today. They are installed in order to obtain acceleration, relative speeds and displacement, thus providing invaluable information to aid in the calculation of the most important injury parameters. The specification of their response characteristics is pre-defined and the operation and signal filtering is described by the testing protocols.

Another type of sensor used in crash testing is the gyroscope, although the use of this instrument is not that widely spread in crash testing. The precision data provided by the new damped gyroscope generations is enabling their use in a broader variety of applications. Despite the exceptional performance that these inertial sensors could have, their capabilities are not fully exploited. If errors are minimized and an additional degree of accuracy in the use and calculation is given, they may be used to precisely track the position of any part they are installed and referenced to. Gyroscopes add an important value: they can measure rotation, which can be used as an input to correctly project the signals.

Tracking a moving object's position in time is a big issue, found in a wide variety of applications, including the military, industrial and medical. Nevertheless, and up to date, the most used methodology is 2D tracking of the parts, which only allows tracking of simple movements. In addition to that, tracking requires a huge set up, which is not always possible during a crash: calibrated optics, targets always visible and fixed reference points on the same plane and close to the visual range of the camera. Films obtained by high speed cameras are not capable of providing enough information about dummy parts that stay behind the vehicle's chassis. It is also impossible to determine with precision the amount of intrusion of certain parts of the dummy, such as the head or chest against the airbag, as they are obscured on contact, losing any visual reference available.

METHODOLOGY

The fore mentioned problem can be solved efficiently with an inertial measuring system and its related methodology, consisting of three accelerometers (measuring linear acceleration) and three gyroscopes (measuring angular velocity) orthogonally placed in the dummy and the vehicle. Thanks to this data flow, the required mathematical calculations and the development of special software, we are now able to trace the movement of the dummy with respect to the vehicle.

Euler's Rotational Theorem

According to Euler's Rotational Theorem, any rotation or group of successive rotations may be expressed as one rotation around a single direction or main rotational axle. In this manner, every rotation or group of rotations, found in a three-dimensional space can be specified through the equivalent rotation axle defined by vectors with

three parameters. Generally, these three parameters are called rotational degrees of freedom.

These angles constitute a group of three angular coordinates used to specify the orientation of a reference system of orthogonal axles, generally mobile, respect to another reference system of orthogonal axis, but in this case, fixed.

They are based in describing the way to achieve the final position from the initial one with three rotations, called yaw, pitch and roll. They must be given and calculated in that order, since the final result depends on the order of application.

Coordinate Systems

For this project, three different coordinate systems have been chosen:

- A fixed global system.
- A system referenced to the vehicle.
- A system with origin in the C.G. of head, chest and pelvis of the dummy.

Six parameters describe the location and orientation of a mobile segment relative to the reference segment: three translations (X, Y, Z) and three rotations (yaw, pitch, roll) in the reference point.

Rotations:

- Yaw – rotation around X axis
- Pitch – rotation around Y axis
- Roll – rotation around Z axis

Translations:

- Longitudinal (X) – Direction of the vehicle.
- Lateral (Y) – In direction of Y axis of the vehicle.
- Vertical – In direction of the Z axis of the vehicle.

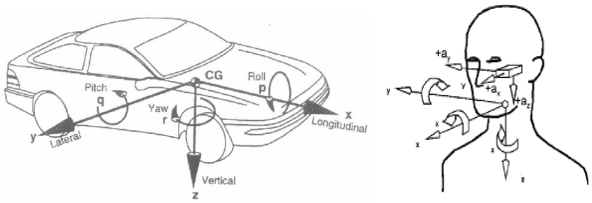


Figure 1. Coordinate Systems.

Calculation Sequence

In figure 2 we find the calculation sequence developed in this project, designed specifically to measure the dummy's global kinematics during a frontal crash. From this methodology, special software was programmed for *Diadem 10.1*, capable of calculating automatically the necessary operations.

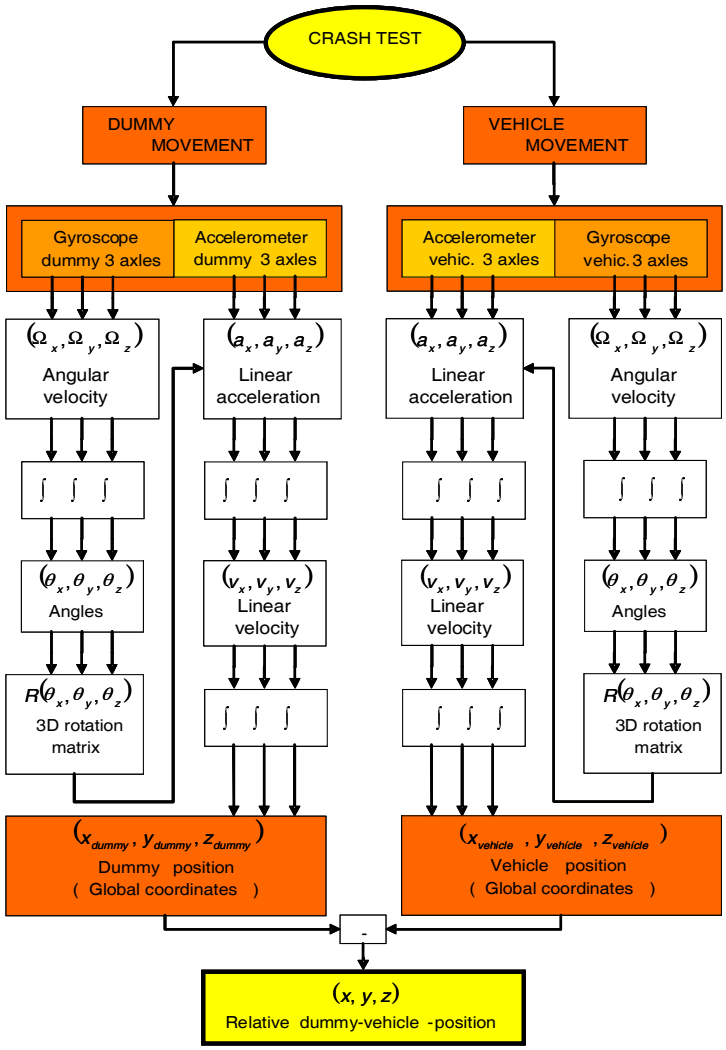


Figure 2. Calculation sequence.

First, the different angular components for the dummy (given by the corresponding three-axial gyroscope) are integrated with respect to time, obtaining the Euler angles. From these angles, a rotational 3D matrix is generated, from the local to the global system, which will be directly multiplied by the different acceleration components (obtained from the accelerometers located in the C.G. of each of the dummy's parts). As a result, a matrix with the acceleration components given as global coordinates is obtained.

By integrating the matrix components, the linear velocity is obtained and after a second integration the dummy's position with respect to the origin in global coordinates is calculated.

Parallel to this activities, the analogous calculus for the vehicle will be made (accelerometers and gyros located in the car) and will finally be subtracted from the dummy's position, giving then the relative dummy position respecting the vehicle.

Frontal Crash Analysis for 2D Modelling

Data from a frontal crash test were used during the first displacement analysis. The crash had a frontal configuration (Frontal impact 40% ODB 64 km/h), with a 40% offset, impacting on the left side of the car (left hand drive car). Crash speed was designated at $64^{\pm 1}$ km/h, having a real impact speed of 63.68 km/h. The available 2D methodology was used to analyze its deficiencies. In this phase of the project, dummy kinematics were studied with the 2D macro (rotation in Y, accelerations in X and Z axes).

In the next figure, two instants of the frontal crash are presented with a superposed X-Z graph (for the driver) obtained via the 2D methodology. Good results are obtained until the 125th millisecond, when the trajectory graph falls abruptly, due to car rotation (not considered in 2D methodology) and some other factors (integration in time).

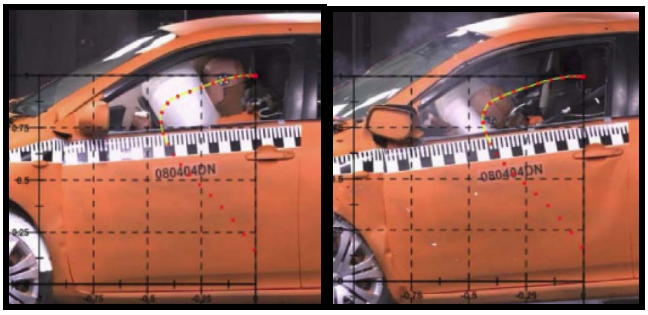


Figure 3. 2D kinematics.

Car Reference Selection

The graph in figure 4 reflects the importance of wisely choosing the X acceleration reference point in the car. Until now, the B pillar driver's side had been the reference point for calculations made for dummies both in the driver and passenger side. Nevertheless, this study demonstrates that the ideal place for reference is the B pillar on the side closest to the dummy whose kinematical data are to be analyzed.

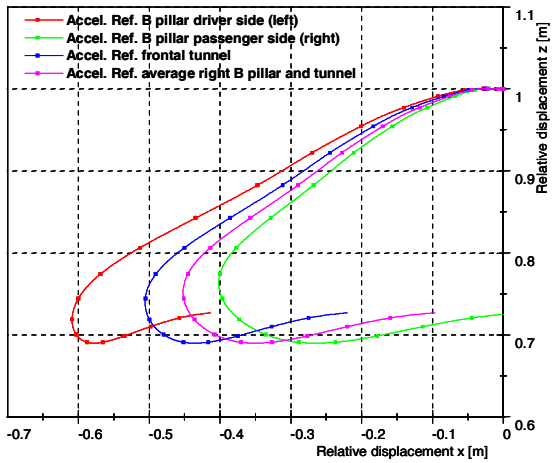


Figure 4. Relative head displacements of the dummy for different vehicle parts.

We can observe the results from the relative head displacement study in a car during a frontal crash test, taking as an acceleration reference for the car, different parts where accelerometers have been installed. There are accelerometers located in: B pillar opposite side (red line), B pillar dummy side (green line), frontal tunnel (blue line) and arithmetical average between frontal tunnel and B pillar dummy side (pink line).

After superposing the lines with the static measurement (figure 5) of the dummy's contour (passenger side), seat and dashboard; before (blue contour) and after (red contour) the crash, we prove that the B pillar closest to the dummy should be the X reference point in the car.

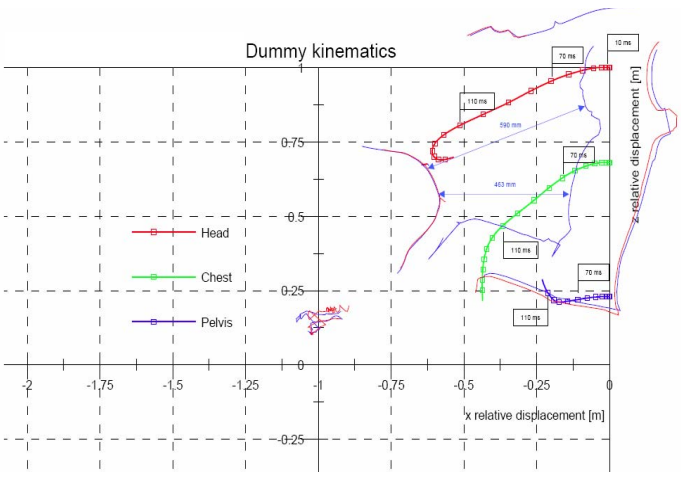


Figure 5. 2D head, chest and pelvis kinematics superposed to the static measurement.

SLED TEST WITH DUMMY ROTATION

Objective

The objective of this test was to determine the precision of the followed 3D methodology. Due to the fact that frontal crash tests are not completely linear, as they include a slight dummy and vehicle rotation, the established method is to be validated using a sled test adapted to the purpose.

After evaluating a series of alternative tests, a rotation in the dummy was forced by putting the seat with a 30º angle with respect to the longitudinal forward direction, as shown in the next figure.

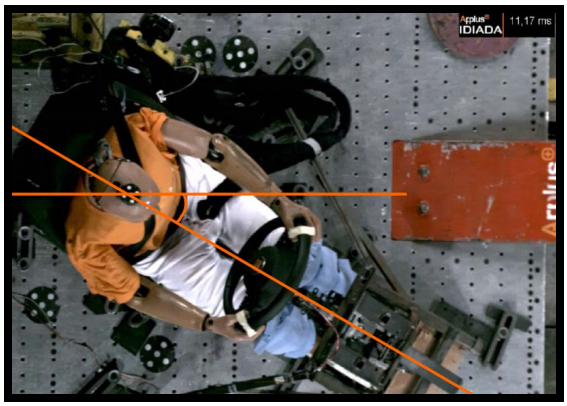
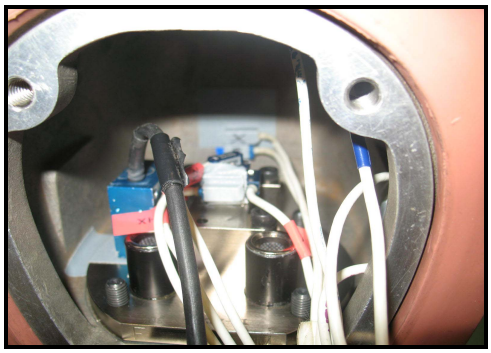


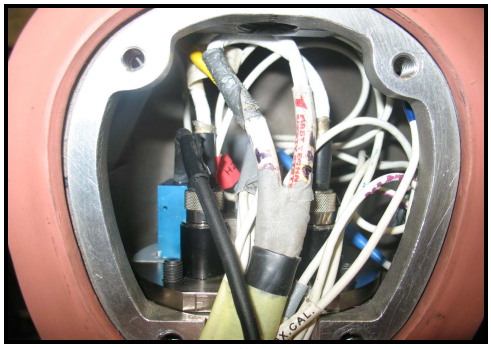
Figure 6. Dummy and seat placement for sled test.

Dummy Instrumentation

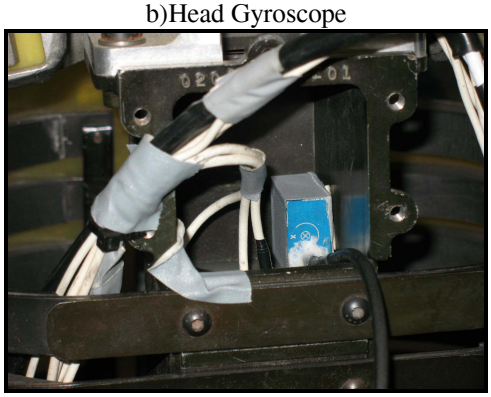
In the next figure, the final dummy instrumentation can be observed inside the head, chest and pelvis (accelerometers and three-axial gyroscope IES 3103-3600).



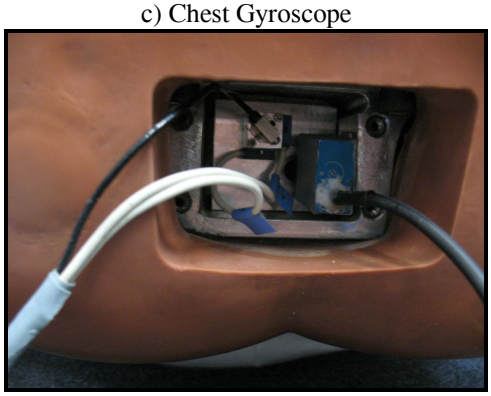
a) Accelerometers



b)Head Gyroscope



c) Chest Gyroscope



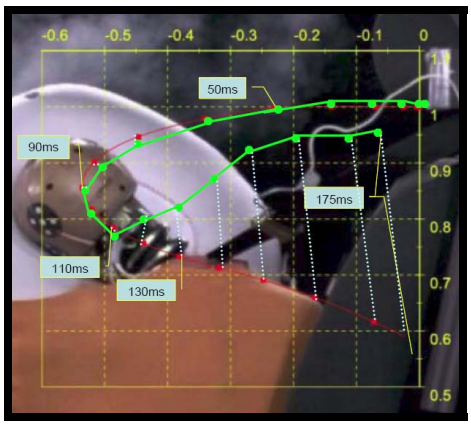
d) Pelvis Gyroscope

Figure 7. Dummy instrumentation.

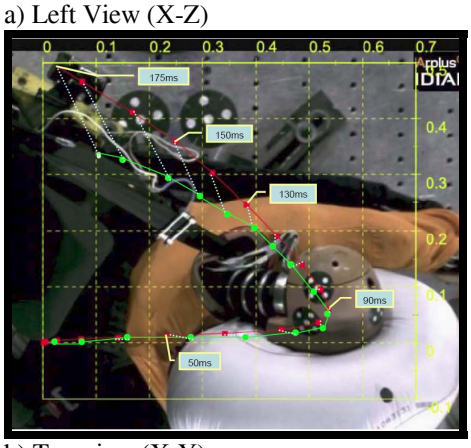
Test Results

<u>Visual Tracking vs. Calculated Trajectory</u> – To estimate the exactitude and liability of the methodology developed during the course of this study, the calculated position graphs have been superimposed (on the same scale) to the films captured during the test. In figure 8, the calculated projections (a) X-Z and (b) X-Y of the head path (red lines) can be seen, superposed in a picture taken in the instant of greatest X displacement of the head (t= 90ms.).

From the available videos, (a) left side camera and (b) top view camera, an estimation of the real C.G of the head is made (green lines) during the entire duration of the test. Note that, due to the nature of the test and equipment, it is very difficult to make a visual tracking of the chest and pelvis.



a) Left View (X-Z)



b) Top view (X-Y)

Figure 8. Head path comparison (red line: real path; green line: calculated).

Shown next is a chart that shows all the data obtained, including the estimated error (ε_X, $\varepsilon_{X'}$,ε_Y, ε_Z) from the video analysis. Up to the 120th ms, the methodology would give a position error of less than 15% in all cases, which, although improvable, is considered satisfactory. In fact, as shown in the chart, up to the 120th ms the average of all errors taken every 10 ms is in all cases, less than 7%.

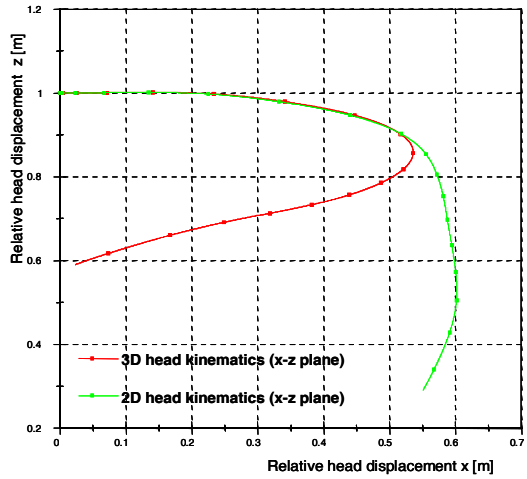
Table 1.
Estimated error

	HEAD										
	Calculated movement			Real movement				Error			
t (s)	x	y	z	x	x'	y	z	ε_x (%)	$\varepsilon_{x'}$ (%)	ε_y (%)	ε_z (%)
0,000	0,000	0,000	1,000	0,000	0,000	0,000	1,000	0,000	0,000	0,000	0,000
0,010	0,004	0,002	1,000	0,004	0,004	0,002	1,001	7,036	7,036	2,050	0,087
0,020	0,026	0,004	1,000	0,025	0,030	0,004	1,001	2,494	14,589	0,395	0,083
0,030	0,071	0,006	1,000	0,071	0,078	0,006	1,001	0,062	9,031	6,560	0,074
0,040	0,140	0,009	1,001	0,160	0,140	0,010	1,001	12,197	0,346	7,059	0,027
0,050	0,233	0,013	0,997	0,274	0,225	0,012	0,997	14,959	3,675	5,672	0,035
0,060	0,341	0,018	0,979	0,375	0,340	0,018	0,970	9,062	0,299	0,432	0,921
0,070	0,447	0,025	0,946	0,466	0,449	0,022	0,930	3,970	0,442	13,499	1,756
0,080	0,517	0,038	0,902	0,521	0,509	0,033	0,887	0,818	1,520	14,534	1,639
0,090	0,536	0,060	0,856	0,535	0,535	0,055	0,852	0,135	0,135	9,435	0,457
0,100	0,521	0,095	0,817	0,510	0,521	0,095	0,810	2,105	0,051	0,154	0,923
0,110	0,487	0,140	0,785	0,460	0,486	0,140	0,765	5,786	0,045	0,130	2,588
0,120	0,439	0,191	0,756	0,430	0,439	0,170	0,800	2,047	0,046	12,297	5,450
0,130	0,382	0,246	0,733	0,395	0,381	0,210	0,820	3,347	0,204	17,129	10,601
0,140	0,319	0,303	0,713	0,340	0,320	0,225	0,870	6,323	0,468	34,702	18,080
0,150	0,249	0,359	0,691	0,290	0,270	0,260	0,930	14,306	7,959	38,111	25,717
0,160	0,167	0,412	0,660	0,233	0,199	0,290	0,948	28,337	15,882	41,960	30,366
0,170	0,073	0,465	0,617	0,150	0,120	0,325	0,948	51,417	39,272	43,211	34,958
0,175	0,023	0,494	0,590	0,109	0,070	0,338	0,955	78,788	66,969	46,200	38,200

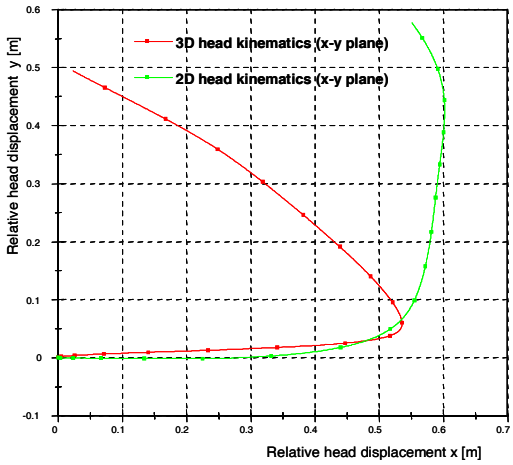
Displacement in X is considered valid until the 150th ms, as the error is still underneath the 15% mark.

2D vs. 3D Comparison

The results obtained through the 3D methodology developed in this project and the results that would have been obtained following the original 2D methodology (considering only angular velocity in Y and accelerations in X and Z) were compared. As presented in figure 9, after the 80th ms, 2D simplification (green lines) would not have been valid, as the tendency lines fall abruptly.



a) X-Z



b) X-Y

Figure 9. Head trajectory from 2D methodology.

It is worth mentioning that the advantages of the 3D methodology reside in the fact that it allows the representation of the trajectory of the different parts of the dummy in a 3D space, not just in the bi-dimensional projections. In figure 10 we can appreciate the 3D representation of the global

dummy kinematics during the 30º test, for the head (red line), chest (green line) and pelvis (blue line).

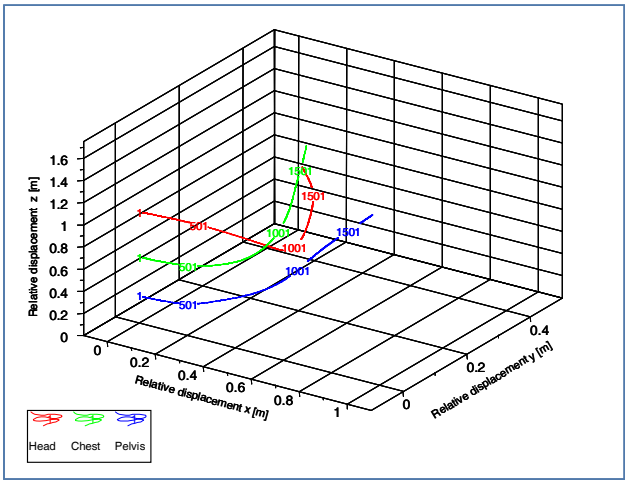


Figure 10. Global Dummy Kinematics.

The test concluded at a mere 49,59 km/h against the sled decelerators from the planned 50 ± 1 km/h. The angle was 30º from the centreline and the airbag was triggered at 17 ms.

ALTERNATIVE SOLUTIONS

There are a number of alternative solutions to obtain these data during crash testing. For this project, the tests included a 2D analysis, which used data obtained from accelerometers and gyroscopes. These accelerometers were installed in the B pillars, the central tunnel and the arithmetical average between the tunnel and B pillar. A gyroscope was used to measure rotation around the Y axis.

For the proposed 3D test, a setup of 3 accelerometers and 3 tri-axial gyroscopes were used. The recalled information was analyzed and good results were obtained.

One of the proposed alternative methods, instead of making use of tri-axial accelerometers and gyroscopes, is to use 2 tri-axial accelerometers in the same test. This setup has to be orthogonal, so that no axles end up aligned in the same plane as another one. This assures the consecution of 6 different acceleration pulses, each one in a specific direction, using (Equation 1) for solution.

$$\mathbf{a}(P_s) = \mathbf{a}(O_s) + \boldsymbol{\alpha}^s \wedge \overline{\mathbf{OP}} + \left|\boldsymbol{\Omega}^s \wedge \left(\boldsymbol{\Omega}^s \wedge \overline{\mathbf{OP}}\right)\right. \quad (1).$$

Using this procedure, any combination of points would be enough to solve the problem, as in the end, there are 6 unknowns: 3 $\boldsymbol{\Omega}$ and 3 $\boldsymbol{\Omega}'$ (derivatives), having a total of three equations.

Until now, a triple tri-axial accelerometer setup has been tested and the $\boldsymbol{\Omega}$ and its derivative have been calculated via iterative methods. This setup faces a number of problems, such as convergence, sensitivity to signal filtering, etc. Every time iteration is made, an approximate result is obtained and when deriving, some signal noise is generated. This noise is the cause that the convergence is low for the system.

In 1975, Padgaonkar et al. developed a new method using nine accelerometers placed on a mount, which has the form of a rectangular Cartesian coordinate system. There were two accelerometers at the end of each axis, normal to that axis, and three at the origin. Having this 3-2-2-2 arrangement, the equations become algebraic, thus eliminating the need for integration.

People at Robert A. Denton, Inc. have created a female dummy head that allows an array of up to 15 accelerometers. This head, the one of a Hybrid III 5th percentile female, has been developed using the 9-accelerometer model, accounting now for top, front, left, rear and a C.G. mount inside the device.

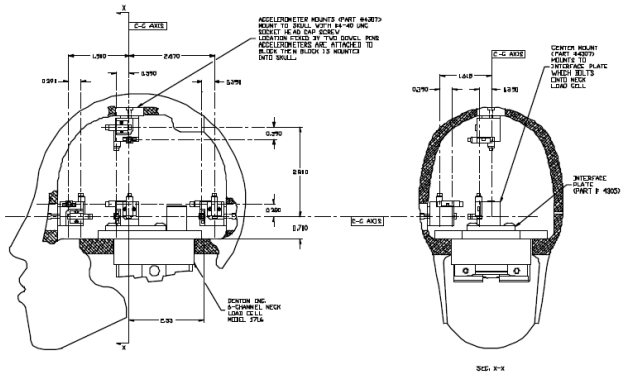


Figure 11. Robert A. Denton's dummy head array.

Padgaonkar et al. (1975) showed that this 3-2-2-2 scheme presents a significant advantage over the six accelerometer scheme in that the calculation of angular acceleration at any time point is independent of previous measurements, avoiding the possibility of errors accumulating over time.

The 3-2-2-2 array concept has been widely used and there has been considerable work done to develop techniques for the compensation and calibration of the array.

Some other techniques for measuring rigid body acceleration have been developed. These include measuring the angular velocity directly, using magneto-hydrodynamic sensors and an array of nine accelerometers divided in three tri-axial groups. However, these improved techniques are

more costly and require more data acquisition channels.

Whichever the case may be, it is difficult to obtain reliable data. Unreliable data is obtained because of:

- Accelerometer integration errors.
- Accelerometer alignment.
- The systems (as a whole) are used to find peak accelerations, not rotation.
- We look for trajectory, so the error accumulates and shows the wrong data (second derivates and much iteration).

CONCLUSIONS

The initial tests conducted using 2D and 3D models have shown an important improvement in movement tracking and trajectory calculation. Nevertheless, more testing and model improvements need to be made. An important part of the future steps is the trial of 1 tri-axial accelerometer plus 3 pairs of 2 single axle accelerometers setup. This setup will serve as a comparison array to aid the other tests in selecting the most precise testing setup.

Signal managing is another issue, as noise generated through integration and iteration may create large errors that may lead to incorrect data management and use. These errors must be quantified and corrected, so as to have the knowledge on how integration and sensor positioning have an influence on the result.

The general purpose of these tests is to obtain a reliable and robust methodology and equipment that leads to a better understanding and modelling of passenger behaviour during an accident. All the tests and their respective results must develop into a precise, yet practical instrument system for dummy monitoring.

REFERENCES

[1] Palacios Bazán, Eva María. 2008. "Desarrollo de una Metodología que Permita Determinar la Cinemática Global de Dummy durante el Ensayo de Choque Frontal".

[2] Padgaonkar, A.J., Krieger, K.W. and King, A.I. 1975. "Measurement of angular acceleration of a rigid body using linear accelerometers", Journal of Applied Mechanics, 552-556

[3] Robert A. Denton, Inc. 2002. "Model 4263 Small Female Head Accelerometer Array".

[4] Anderson, Robert .W. G. 2000. "A study on the biomechanics of axonal injury".