Vehicle Crush Measurements Using High Resolution Terrestrial LIDAR

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Abstract

Vehicle crush measurements have been typically done using either offset methods or punctual survey methods such as with a total station and photogrammetry. Each of these measurement classes is problematic in that they are tedious and yield a limited number of data points. As such, the rigorous description of vehicle crush is not always achievable. Recent advances in terrestrial LIDAR systems now offer the possibility of generating dense three-dimensional point clouds. The volume of data associated with a single scanning session often approaches one million points. In addition, the LIDAR system records reflectance parameters that are an indicator of the surface characteristics. This is of particular interest since damaged portions of a vehicle will exhibit different reflectance characteristics than those that are in their original state. An examination of a dataset from a sample scanning is presented along with some results illustrating the modelling opportunities that are possible.

Résumé

Les mesures des deformations des vehicules sont typiquement faites emploient soit le method d' offeset en utilisent un total station totale et avec le photogrammetrie. Chaque methods ont des problemes comme un manque de vitesse pour mesuree et tres peu des points dans l'ensemble des donneees. Les amelierorations recentement avec les systemes LIDAR offere maintenant le possibilite de generation d'un ensemble de donnees de haute densite et en trois dimensions. Ces ensemble de donnees peut attaindre un milliarde des points pour un session de balyage simple. En plus, le systeme LIDAR enregistre un valeur de reflectance qui indicque les characteristiques de surface. Cet aspect est tres importante parce que les regions de vehicule deforme ont des characteristique differente des regions d'origin. Un examination d'un ensemble de donnees representatives est presente avec des resultes qui illustre les opportunities de modelisations qui sont possible.

Introduction

Typically measurement of vehicle crush has been completed using a few standard measurement techniques. Most common are offset methods, which utilise a line, offset a known distance from an undamaged portion of the vehicle to create a base line. From this base line, the deformation measured on the damaged vehicle is related to the corresponding exemplar vehicle profile. Punctual survey methods, using, for example, a total station, are also used to measure and quantify the same vehicle deformation. Another measurement method utilised is terrestrial close-range photogrammetry. The end result of each of these measurements is often to apply them in a qualitative description of vehicle damage for use in ΔV calculations. The damage typically derived from these measurement methods can also be used to complement other physical collision scene evidence in momentum calculations. Alternatively, the results can be used to bridge any gaps that may exist in momentum input variables.

In the calculation of the ΔV experienced during a collision, a set number of measurement points along a continuous horizontal plane are usually utilised. In this method of quantifying crush, a limited number of horizontal points are measured. Crush along one horizontal axis and front-end shift or longitudinal bowing in a side impact are measured.

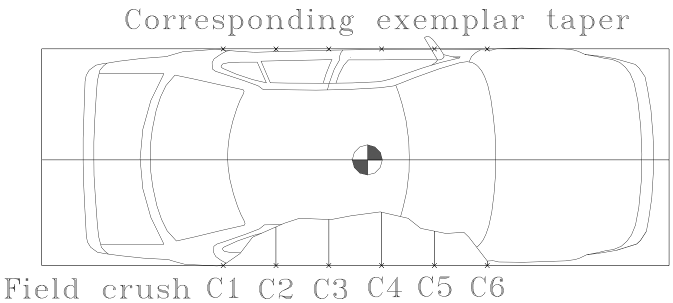

Figure 1. Standard crush measurement

If the maximum point of crush does not fall directly on one of the equidistant crush measurement stations, the nearest crush station is shifted to the location of maximum crush (Tumbas and Smith)[1]. This method is applied along one horizontal plane, usually at the level of maximum deformation, and should be similar both in damage profile and height to the crash test data used to derive a stiffness coefficient for use in a damage analysis. The similarities between crash test results and real-life collisions are not always as correlated as would be desired. Adopting a more detailed method of crush measurement, both during crash testing and on real-life collisions can provide avenues for developing non-linear damage analysis that can make crash test stiffness data accurate over a greater speed and damage profile range (Campbell)[2] (Wolley)[3] (Strother, Kent and Warner)[4].

Conventional damage measurements during collision investigations, more commonly in side impacts, also look at interior intrusion as well as exterior crush. Transferring a coordinate system to the interior of a damaged vehicle that can properly link crush and intrusion can also be problematic. Collecting enough intrusion points in a severely damaged vehicle and trying to quantify their 3D deflections also provides a daunting challenge with most measurement techniques. In these instances, finding a measurement method that collects dense point clouds of both the exterior and portions of a vehicle's interior would offer potential solutions to each of these difficulties.

What is LIDAR?

A laser is the most common method used to increase the density of the 3D measurement points to the level of being considered a point cloud. A **L**ight **A**mplified by the **E**mission of **R**adiation (LASER) system employs clearly defined light pulses that can be directed to a target while maintaining a consistent pulse field and unit strength. Using a laser as a coordinate measurement tool requires that the time for the pulse to travel from the laser to the object and to return the laser be known.

$$\text{Distance} = (TF * SL) / 2 \quad (1)$$

where:
TF = Time of flight
SL = Speed of light

In addition, scanner mirror deflection angles must also be recorded to complete the vector definition in a 3D polar coordinate frame.

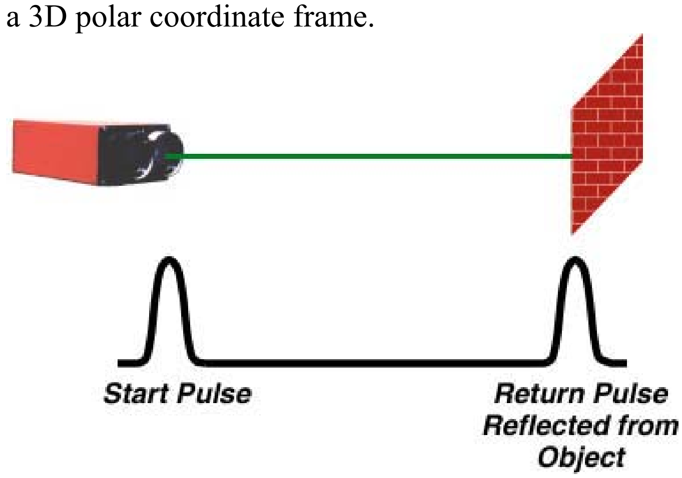

Figure 2. LASER measurement method

Incorporating the distance measurement with horizontal and vertical angle results in a 3D Cartesian coordinate vector. This is the same measurement method employed in a total station. Semi- or fully-automating this process by rotating the horizontal and/or vertical angles by a predefined amount results in a point cloud if the angle variations are minute enough.

$$\text{Laser coordinates} \Rightarrow X,Y,Z \quad (2)$$

LIght **D**etection and **R**anging (LIDAR) technology uses that same distance and angle measurements as a Laser system to derive 3D coordinates from collected data with an important addition. An intensity value is attached to each data point.

$$\text{LIDAR coordinates} = X,Y,Z,\mathbf{i} \qquad \mathbf{(3)}$$

This intensity value is a numeric representation of the reflectance of the measured point. Surfaces of different materials and surfaces with changes in angle will result in different intensity values, creating an identifier to attach to the point coordinate. The importance of this intensity value will be examined throughout the remainder of this paper.

ILIRS-3D LIDAR Scanner

While many LIDAR devices from different manufacturers exist, a dataset collected with the Optech Inc. ILIRS-3D LIDAR scanner will be shown.

Figure 3. ILIRS-3D LIDAR Scanner

This scanner has a range resolution of 1 cm. at 800 m. and can sample 2000 points per second. It is evident that at this sample rate an extremely high number of points can be collected in a short period of time. The light pulse must be reflected back off of a visible surface (the light does not penetrate surfaces) to result in a recorded point. On a vehicle, the number of unique points recorded with LIDAR can easily approach 1 million.

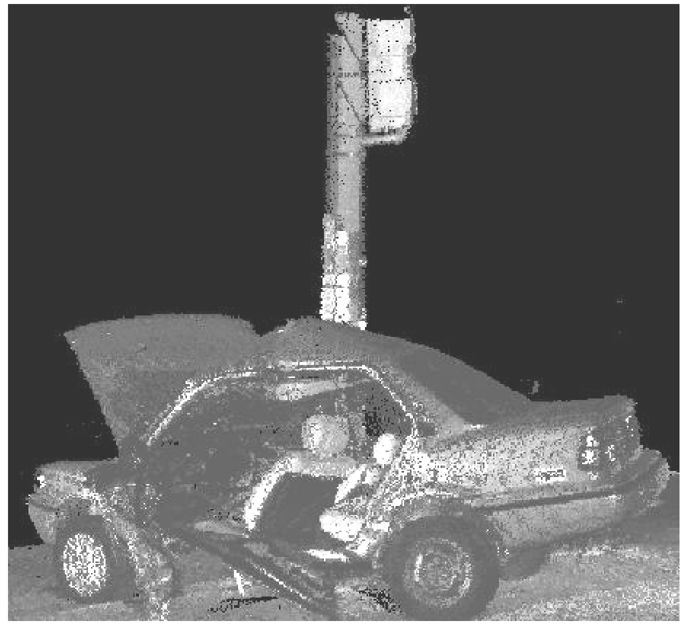

Figure 4a. Visual representation of LIDAR results.

Figure 4b. Visual representation of LIDAR results.

This data set illustrated here is from a late model Ford Tempo that struck a traffic light standard with its right side. The car is still engaged with the pole and has partially bowed around the pole. Over 3 million points were recorded from 5 separate LIDAR stations around the vehicle. After merging common points from the 5 stations, there were over 1 million unique points. The visual representation of the LIDAR recorded data resembles a grainy picture in part due to the density of the points and in part due to the image intensity value. It is this image intensity that can be used to distinguish between metal and glass, damaged and undamaged portions of metal and to match damaged to exemplar vehicles.

Finding conjugate points between damaged and undamaged vehicle datasets

In matching damaged to exemplar vehicles to derive crush, an undamaged portion of the damaged vehicle needs to be found to match to the exemplar vehicle. Rather than examining each of the 1 millions points, a smaller and more manageable group of points with certain features is selected for matching. In this method of matching, an interest operator is used to evaluate a group of points for the following characteristics:

Distinctness – the point(s) should be different from neighbouring points.
Invariance – the selected points as well as the selected position should be invariant with respect to the expected geometric and radiometric distortions.
Reliability – the selected points should be expected to appear in the other datasets.
Uniqueness – distinctness represents the local separability of points, whereas uniqueness evaluated the global separability.
Interpretability – the selected points should be able to allow evaluation for edges, corners, blobs or other simple but labelled features (Förstner)[5](Lemmens)[6] .

In Equation 4, the interest operator evaluates the eigenvalues and eigenvectors of the selected points using the normalised image gradients, or intensity values. If the selected points have met the above characteristics then the result should yield characteristic eigenvalues and eigenvectors.

$$\begin{bmatrix} \sum \mathrm{gx}^2 & \sum \mathrm{gx\,gy} \\ \sum \mathrm{gy\,gx} & \sum \mathrm{gy}^2 \end{bmatrix} \tag{4}$$

The resulting values are then used to identify the conjugate points in another LIDAR data set. In this case, it is finding the same undamaged portion on a damaged and exemplar vehicle to orient them to complete crush measurements. The eigenvalues and eigenvectors are calculated for a group of points on an exemplar vehicle that also satisfies the above criteria. A window that is the same size or contains the same number of points as the original selection evaluated in the interest operator is placed on the damaged vehicle in approximately the same location. The points are then evaluated in the same manner to compare for likeness to find the conjugate points. If the set of points being compared does not have sufficiently high similarity then the selection window is shifted in one direction to evaluate a new group of points on the damaged vehicle. The new group of points need not be all new. A slight shift in the selection area will result in a few points being discarded from the interest operator and a few new ones being introduced on the opposite side of the shift. The eigenvalues and eigenvectors should be found to have high similarity between the selected points on each of the datasets. This implies that a set of conjugate points have been found between both datasets.

Transformation of the datasets

Once a group of conjugate points have been identified between the 2 datasets, one set of selected points must be transformed to match the other conjugate points in coordinates and orientation. This requires a shift in the x,y,z axes as well as φ,ω,κ rotations about each of these axes.

$$\begin{aligned} X &= ax + by - cz + e \\ Y &= ay - bx - dz + f \\ Z &= az + cx + dy + g \end{aligned} \tag{5}$$

where $(X,Y,Z)_i$ are represent point **i** on the exemplar vehicle and $(x,y,z)_i$ are the corresponding point **i** on the damaged vehicle.

$$\begin{bmatrix} x & y & -z & 0 & 1 & 0 & 0 \\ y & -x & 0 & -z & 0 & 1 & 0 \\ z & 0 & x & y & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \\ g \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (6)$$

$$x = (A^t PA)^{-1} A^t P w \qquad (7)$$

where:

x – Parameter vector

A – Design matrix

w – Misclosure vector

P – Statistical weight matrix (for 3-D Datum definition)

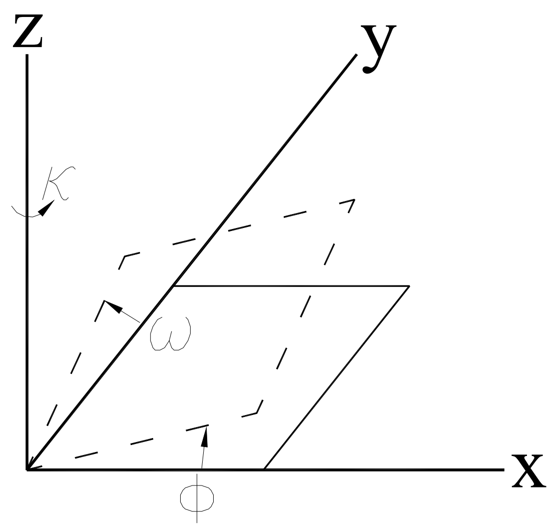

Figure 5. Non-linear parameter equivalence.

$$k = \sqrt{(a^2 + b^2)} \qquad (8)$$

$$\kappa = \arctan(-b/a) \qquad (9)$$

$$\phi = \arctan(c/k) \qquad (10)$$

$$\omega = \arctan(d/k) \qquad (11)$$

$$e' = e + \delta e \qquad (12)$$

$$f' = f + \delta f \qquad (13)$$

$$g' = g + \delta g \qquad (14)$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = k\, R_z(\kappa) R_x(\omega) Ry(\phi) \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} e' \\ f' \\ g' \end{bmatrix} \qquad (15)$$

Equations 8-14 establish non-linear parameter equivalence and Equation 15 is the final calculation of a non-linear 3D similarity least-squares transformation with k set to 1 to maintain the original scale. The result is that the damaged vehicle has been positioned and oriented with the best fit of the points identified in the image operator. At this point, detailed deformation comparison and crush analysis between the two vehicles can begin.

Applications of results

The volume of data made possible through this type of analysis allows for current collision analysis to be completed with much greater detail as well as development of new practices. As outlined earlier, the current practice when completing a crush analysis on a vehicle is to look at deformation of a very limited number of points on the vehicle along the two horizontal planes and usually one vertical height. What is then not applied is the deformation in the vertical (Z) plane. This has in past been partly due to the magnitude of vertical deformation being smaller in magnitude in relation to the horizontal deformation and the complexity of creating a field measurement method for recording this information. The results of this LIDAR dataset make that a mute issue, allowing for the development of a 3D displacement vector field.

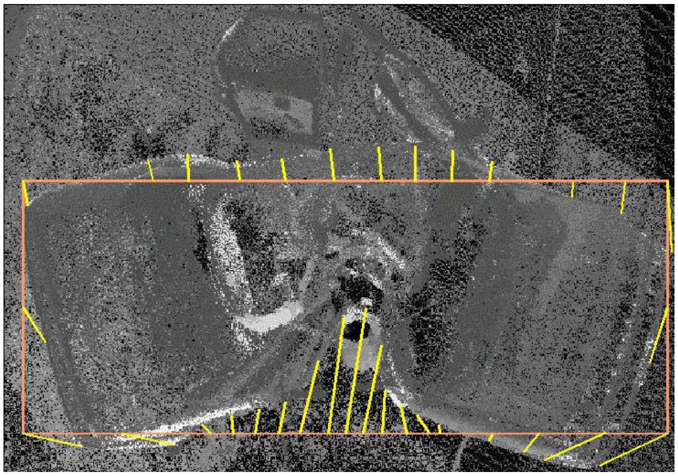

Figure 6a. Simplified 3D vector field, overhead view.

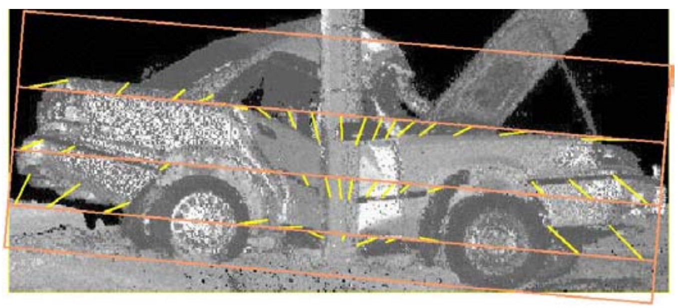

Figure 6b. Simplified 3D vector field, side view.

Utilising a 3D displacement vector, a more detailed method of quantifying the energy used in bowing a vehicle, like the bowing that is evident in the vehicle in Figure 6a. The side view of the displacement vector has been simplified for easier viewing to 3 vertical levels. As well as the horizontal shifts that were evident in Figure 6a, a vertical shift is also evident when the Figure 6b side view is examined. Having this volume of detail makes it possible to quantify vertical shifts at individual locations on the vehicle.

Allowing for measurement of displacement along the vertical as well as the horizontal plane makes possible the derivation of a 3D -ΔV equation to be used in place of the current 2D -ΔV equation.

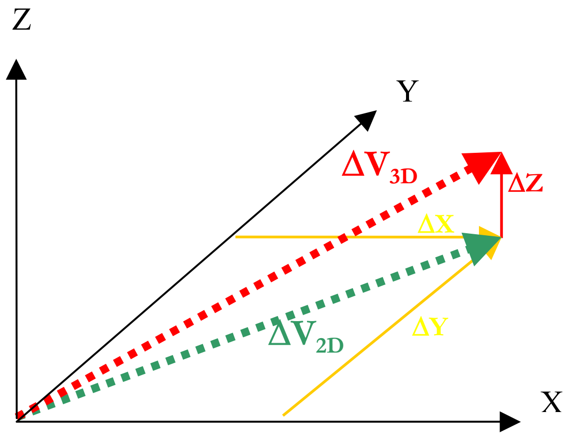

Figure 6. Proposed ΔV_{3D}.

This level of detail also opens the door to non-linear deformation models that can be used to equate detailed damage measurements from crash test results to real-life collisions. With a validated non-linear deformation model even lower speed and/or extremely high speed collisions could be compared with crash test results of some other form of baseline data.

Another source of information that this paper has not addressed yet is the high detail interior vehicle point data that is also usually unavailable. Only points which are visible to the LIDAR scanning unit are able to be measured but with proper planning some if not most of a vehicle's interior may be recorded if desired. In the LIDAR data shown in Figure 4a. a large portion of the vehicle's interior was modeled since both driver's side doors were removed. Depending on the detail required in each case, the top of a properly supported vehicle can be removed to allow LIDAR scanning to be completed from one or more elevated positions.

Future enhancements.

While the model for matching detailed LIDAR scans of damaged and exemplar vehicles for damage analysis has been developed, there are still areas to improve in this method. Future enhancements will include the semi- or fullautomation of the exemplar to damaged vehicle orientation process. This will include algorithms that require less user intervention to select both the exemplar and damaged vehicle point groups to be used in the interest operator. This combined with the proposed development of $\Delta\mathbf{V}_{3D}$ and non-linear deformation models will result in a very robust damage measurement tool available to the field of collision investigation and vehicle crashworthiness.

Conclusions

In addition to being the source of high density 3D point cloud data, LIDAR data collection has proven itself as a useful tool to collect accurate point cloud data in high volume within a short period of time. Also available through LIDAR scanning is the intensity value of each recorded point to give more identifying details about individual points as well as point groups. Using an interest operator with the available intensity values, a method of relating a damaged vehicle to an exemplar vehicle has been developed. Once the conjugate points are identified between the LIDAR datasets and the damaged vehicle has been transformed to the exemplar vehicle datum using least-squares, detailed true 3D damage analysis is now possible. As the availability of LIDAR scanning equipment and/or services improves, prices will decrease and this will help to bridge some of the data gaps that have historically plagued collision investigators everywhere.

Acknowledgements

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