DEPARTAMENTO DE INGENIERÍA CARTOGRÁFICA Y DEL TERRENO

TESIS DOCTORAL

MEJORA DE LOS PROTOCOLOS DE RESCATE Y RECONSTRUCCIÓN DE ACCIDENTES DE TRÁFICO MEDIANTE EL USO DE GEOTECNOLOGÍAS

Programa de Doctorado:

Geotecnologías aplicadas a la Construcción, Energía e Industria.

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INFORME DE LA TESIS DOCTORAL

"**Mejora de los protocolos de rescate y reconstrucción de accidentes de tráfico mediante el uso de geotecnologías**"

presentada por D. Alejandro Morales Sánchez

La Tesis Doctoral presentada por el doctorando D. Alejandro Morales Sánchez reúne todos los requisitos que se le pueden exigir a una Tesis Doctoral, y que a continuación se pasan a detallar:

- El tema presentado por el doctorando en su Tesis Doctoral se enmarca en el campo de la Seguridad y se alinea con una de las iniciativas promovidas por la Dirección General de Tráfico de Visión Cero, mejorando la seguridad vial.

- La metodología y algoritmos desarrollados en la Tesis Doctoral presentan aspectos novedosos en el campo de la fotogrametría y visión computacional que permiten abordar con éxito los objetivos propuestos.

- Por otro lado, hay que reseñar la posible transferencia de tecnología derivada en forma del desarrollo de software y cuya propiedad intelectual, QRescue "Quick Rescue Response in road accidents", ha sido registrada en la Universidad de Salamanca y del que el doctorando es coautor.

- Finalmente, hay que destacar muy especialmente el nivel de producción científica derivado del propio desarrollo de la Tesis Doctoral por parte del Doctorando, el cual permite avalar la calidad y relevancia de la misma. Hay que reseñar la publicación de 3 artículos indexados JCR asociados a la Tesis Doctoral.

Por todo lo anteriormente reseñado, emito un informe con todos mis pronunciamientos favorables, y autorizo su presentación como Tesis Doctoral en el Departamento de Ingeniería Cartográfica y del Terreno de la Universidad de Salamanca.

Ávila, 9 de julio de 2018

LOS DIRECTORES DE LA TESIS DOCTORAL

Fdo. Diego González Aguilera	Fdo. Alfonso Isidro López Díaz

Fdo. Miguel Ángel Gutiérrez García	

LISTADO DE ARTÍCULOS PUBLICADOS

La presente Tesis Doctoral está constituida por un compendio de tres artículos científicos, publicados en revistas internacionales de alto impacto. A continuación, se enumeran estas publicaciones:

1. A new approach to road accident rescue

Alejandro Morales[a], Diego González-Aguilera[b], Alfonso I. López[c], Miguel A. Gutiérrez[c]

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Traffic Injury Prevention, 2016.

DOI: 10.1080/15389588.2015.1062885

2. Energy Analysis of Road Accidents Based on Close-Range Photogrammetry

Alejandro Morales[1], Diego Gonzalez-Aguilera[2,*], Miguel A. Gutiérrez[3] and Alfonso I. López[3]

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Remote Sensing, 2015.

DOI: 10.3390/rs71115161

3. A New Approach to Energy Calculation of Road Accidents against Fixed Small Section Elements Based on Close-Range Photogrammetry

Alejandro Morales[1], Luis Javier Sánchez-Aparicio[2], Diego González-Aguilera[2,*], Miguel A. Gutiérrez[3], Alfonso I. López[3], David Hernández-López[4] and Pablo Rodríguez-Gonzálvez[2,5]

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Remote Sensing, 2017.

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RESUMEN

Los accidentes de tráfico constituyen un gran reto profesional para las Fuerzas y Cuerpos de Seguridad y Equipos de Rescate. Fundamentalmente en dos aspectos: (i) el rescate de víctimas atrapadas y la atención médica en el lugar del accidente; (ii) el análisis y reconstrucción del accidente para determinar la causa del mismo y depurar responsabilidades legales.

Ambos trabajos requieren de una grandísima capacidad de adaptación, ya que las características y circunstancias de cada accidente son únicas, y precisión, puesto que no se pueden cometer errores cuando el tiempo de actuación es limitado. Por todo ello, uno de los aspectos determinantes en este tipo de trabajos es la información. Disponer de ella puede ayudar a tomar decisiones correctas en momentos críticos o evitar que se cometan errores que puedan tener consecuencias fatales.

El rescate de personas atrapadas en un vehículo tras un accidente de tráfico puede resultar muy crítico, complejo y peligroso. Cada accidente de tráfico presenta sus propias complejidades, en lo que a rescate de víctimas atrapadas se refiere. Con el fin de actuar del modo más eficiente y seguro posible, los equipos de rescate y sanitarios siguen unos protocolos de actuación (Morris, 2004) (Sweet, 2011) que son el resultado de muchos años de trabajo y que van siendo actualizados basándose en nuevos conocimientos, herramientas o vehículos.

Los avances en los elementos de seguridad pasiva y los nuevos sistemas de propulsión de los vehículos actuales pueden suponer una complicación o un riesgo para víctimas y rescatadores a la hora de intervenir. Es por ello que, hoy en día, los equipos de rescate requieren de información relativa a los elementos del vehículo que pueden constituir un riesgo o complejidad a la hora de realizar las labores de rescate. El problema radica en que no siempre es posible disponer de dicha información en el lugar del accidente. Del mismo modo, los servicios sanitarios que participan en las labores de rescate carecen de información biosanitaria de las víctimas atrapadas, información que podría ser de gran utilidad en una primera atención médica.

La presente Tesis Doctoral plantea una metodología que permite proporcionar a los equipos de rescate y sanitarios, de forma rápida, sencilla, completa y en el lugar del accidente, toda aquella información que pueda resultar de utilidad para realizar del mejor modo posible las labores de rescate y primera atención médica de las víctimas, permitiendo integrar la metodología propuesta con los protocolos de actuación empleados por los profesionales y de forma que se vean reducidos los tiempos de rescate, se minimicen los riesgos y se salven un mayor número de vidas.

Por otra parte, el estudio y reconstrucción de accidentes de tráfico es una labor muy compleja de la que derivan resultados que pueden tener una grave repercusión legal. Por ello, estos estudios deben realizarse de la forma más precisa y rigurosa posible. Los agentes de tráfico se enfrentan al estudio y reconstrucción de todo tipo de accidentes, normalmente con el hándicap de tener que despejar la vía lo antes posible para reanudar la circulación. Esto les obliga a realizar las mediciones necesarias sobre la escena del accidente antes de que esta se vea alterada. Y cuando este hecho se produce, no es posible volver a realizar mediciones. Todo ello dificulta considerablemente el trabajo e incrementa la posibilidad de cometer errores.

Uno de los aspectos más críticos e importantes a determinar en el estudio de un accidente de tráfico es la velocidad de colisión. La metodología más empleada para el cálculo de esta se fundamenta en el análisis o estudio energético. Los métodos de análisis energético actualmente empleados requieren de la toma de una serie de medidas expeditas tanto en la escena del accidente como en las zonas deformadas de los vehículos. Dichas medidas son realizadas in situ, empleando procedimientos manuales (Carballo, 2005) y sin tener en consideración la geometría original del vehículo, lo que puede provocar una pérdida de precisión y la correspondiente variación en los resultados del método aplicado.

La presente Tesis Doctoral plantea el uso de fotogrametría terrestre y visión computacional para crear modelos fotogramétricos 3D de la escena de un accidente de tráfico y de determinados detalles del mismo, como pueden ser las deformaciones sufridas por los vehículos o las huellas de frenada, de modo que constituyan una base documental rigurosa y precisa que pueda ser utilizada en cualquier momento para realizar un análisis energético preciso que responda a la demanda requerida en los informes periciales.

Con el objetivo de que la metodología propuesta pueda ser aplicable por los agentes de tráfico, se ha tenido en consideración que estos no poseen conocimientos de fotogrametría, que no disponen de herramientas fotogramétricas de precisión y que deben trabajar de forma rápida y precisa. Esto nos ha llevado a proponer una solución de bajo coste complementada con herramientas software que asistan a los agentes.

Se ha podido constatar que la aplicación de los diferentes métodos de análisis energético empleados en la estimación de la velocidad de colisión sobre los modelos fotogramétricos 3D proporcionan unos resultados más precisos que la aplicación de los métodos tradicionales, gracias a la precisión métrica y a la consideración de la geometría original de los vehículos en las deformaciones.

Las metodologías derivadas de las líneas de investigación abordadas en esta Tesis Doctoral han permitido aumentar la información disponible y con ello mejorar los procesos, haciendo más objetiva, precisa y fiable la información resultante. Todos los estudios realizados en esta Tesis Doctoral se han validado en diferentes escenarios reales y simulados en los que han participado profesionales.

ABSTRACT

Traffic accidents constitute a great professional challenge for both Security Forces and Rescue Teams. That challenge is mainly reflected in two aspects: (i) rescue of victims who are caught up and medical attention at the accident location; (ii) analysis and reconstruction of the accident to determine the cause of the accident and debug legal responsibilities.

Both jobs require a great capacity to adapt to the situation, since the characteristics and circumstances of each accident are unique; and precision, due to the fact that mistakes can not be made when the action time is limited. Therefore, one of the determining factors in the successful accomplishment of this type of task is information. Having adequate information can help professionals make the right decisions at critical times or prevent mistakes that can have fatal consequences.

The rescue of people trapped in a vehicle after a car crash can be very critical, complex and dangerous. Each traffic accident displays its own complexities, as far as the rescue of trapped victims is concerned. In order to act in the most efficient and safest possible way, rescue and sanitary teams follow some protocols of action (Morris, 2004) (Sweet, 2011) which are the result of many years of work. These protocols are always under an update process that is based on new knowledge, tools or vehicles.

Advances in passive safety elements and new propulsion systems of current vehicles can be an added difficulty or a risk for victims and rescuers when intervening. That is the reason why nowadays rescue teams require information regarding the elements of the vehicle that may constitute a risk or a complexity when carrying out rescue task. The problem is that it is not always possible to have this information at the accident site. In the same way, the health services that participate in the rescue task lack bio-sanitary information on trapped victims, information that could be very useful in the first medical assistance.

This Doctoral Thesis proposes a methodology that allows to provide the rescue and health teams with any information that may be useful to perform the best possible rescue task and first medical assistance of the victims in a quick, easy, complete and on site way. By means of this proposal, an integration of the suggested methodology with the action protocols used by professionals will be accomplished. As a consequence, rescue times would be reduced, risks would be minimized and a greater number of lives would be saved.

On the other hand, the study and reconstruction of traffic accidents is a very complex task and results derived from it can have a serious legal repercussion. Therefore, these studies must be carried out in the most precise and rigorous possible way. Traffic agents face the study and reconstruction of all types of accidents, usually with the handicap of having to clear the road as soon as possible to resume traffic. This forces them to make the necessary measurements on the accident scene before it is altered. And when this happens, it is not possible to take measurements again. All this makes the work considerably more difficult and increases the possibility of making mistakes.

One of the most critical and important aspects to determine in the study of a traffic accident is the speed of collision. The most used methodology for the calculation of it is based on the energy analysis or study. The energy analysis methods currently employed require the taking of a series of expedited measures both at the accident scene and in the deformed areas of the vehicles. These measurements are carried out in situ, using manual procedures (Carballo, 2005), and without taking into consideration the original geometry of the vehicle. This circumstances can cause a loss of precision and the corresponding variation in the results of the applied method.

This Doctoral Thesis proposes the use of terrestrial photogrammetry and computational vision to create 3D photogrammetric models, both of the scene of a traffic accident and of certain details from it, such as deformations suffered by vehicles or braking traces. Therefore, they constitute a rigorous and precise documentary base that can be used at any time to carry out an accurate energy analysis that responds to the demand required in expert reports.

With the aim of enabling the proposed methodology to be applied by traffic agents, it has been taken into consideration that they do not have sufficient photogrammetry knowledge, that they do not have precision photogrammetric tools and that they must work quickly and accurately. This scenario has led us to propose a low-cost solution complemented with software tools that assist agents.

It has been found that the application of the different methods of energy analysis used in the estimation of the collision speed on 3D photogrammetric models, provide with more accurate results than the application of traditional methods, thanks to the metric precision and the consideration of the original geometry of the vehicles in the deformations.

The methodologies derived from the research lines addressed in this Doctoral Thesis have allowed to increase the information available and thereby improve the processes, making the resulting information more objective, accurate and reliable. All the studies carried out in this Doctoral Thesis have been validated in different real and simulated scenarios in which professionals have been involved.

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Con la finalización de esta Tesis Doctoral se cumple uno de los objetivos más costosos y deseados de mi vida académica, el cual no habría sido posible lograr sin la inestimable ayuda de numerosas personas.

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CONTENIDO

CAPÍTULO I

INTRODUCCIÓN

1. INTRODUCCIÓN

En los últimos años se ha producido una gran evolución en los vehículos, fundamentalmente en lo que a seguridad se refiere, pero también en los sistemas de propulsión empleados. Los vehículos actuales se encuentran dotados de un gran número de elementos de seguridad activa y pasiva. Los primeros están destinados a evitar que se produzca un accidente (e.g. ABS (Anti-lock Braking System), ESP (Electronic Stability Programme), avisador de cambio involuntario de carril, etc.), mientras que los segundos se encargan de reducir las consecuencias, sobre todo para las víctimas, en caso de que este se produzca (e.g. airbag, pretensores de cinturón, estructuras de deformación programada, refuerzos del habitáculo, etc.). Así mismo, y con el fin de reducir las emisiones contaminantes o incrementar la autonomía, se están comercializando cada vez más los vehículos impulsados por motores híbridos, eléctricos o mediante GLP (Gas Licuado del Petróleo).

Todos estos avances en la industria del automóvil van encaminados a reducir la tasa de mortalidad en accidentes de tráfico y a minimizar la contaminación medioambiental. Pero al mismo tiempo exigen, en caso de que se produzca un accidente, una nueva forma de trabajar por parte de las Fuerzas y Cuerpos de Seguridad y Equipos de Rescate, ya que estos nuevos elementos pueden complicar las labores de rescate y dificultar la reconstrucción del mismo. Es por ello que, con los vehículos actuales, se debe hacer frente de una forma mucho más eficiente a las labores de rescate y reconstrucción.

El complejo proceso de rescate de víctimas atrapadas tras un accidente de tráfico requiere de una rápida y eficaz intervención por parte de los equipos de rescate. Tal y como se ha comentado anteriormente, los avances en seguridad pasiva y los nuevos elementos de propulsión de los vehículos actuales pueden suponer un grave riesgo o dificultad para los rescatadores y víctimas atrapadas. Así, por ejemplo, la activación de un airbag o de un pretensor de cinturón, o el corte de un botellín de alta presión durante las labores de rescate, puede suponer un grave riesgo. Del mismo modo, el uso de baterías de alto voltaje (en torno a los 400 voltios) en vehículos híbridos y eléctricos exige de ciertos conocimientos y elevadas medidas de seguridad a la hora de intervenir en un accidente, puesto que este tipo de baterías pueden suponer el riesgo de morir electrocutado.

Por todo ello, resulta fundamental para los equipos de rescate disponer, en el lugar del accidente, de toda la información posible relativa a la existencia y ubicación de los elementos de seguridad que puedan constituir un riesgo o una complejidad para víctimas y rescatadores (e.g. ubicación de los airbags, pretensores, baterias, refuerzos, etc.). Esta información resulta de gran ayuda en la toma de decisiones y en la forma de proceder de los equipos de rescate.

Del mismo modo, la posibilidad de disponer de cierta información biosaniaria sobre las personas que han resultado heridas puede resultar de gran utilidad para los servicios médicos actuantes a la hora de tomar ciertas decisiones en la primera atención que se les presta en el lugar del accidente. Si los ocupantes habituales de un vehículo deciden proporcionar cierta información biosanitaria (e.g. grupo sanguíneo, alergias a medicamentos, enfermedades crónicas, etc.), de utilidad en caso de una atención urgente, y con total garantía de que esta es tratada de forma confidencial y cumpliendo con la normativa legal correspondiente, sería posible proporcionar dicha información a los servicios médicos en el lugar del accidente.

Debemos tener en cuenta que en situaciones críticas la rapidez en la intervención y toma de decisiones es fundamental debido al poco tiempo del que se dispone. Hay estudios que afirman que los 60 minutos (Golden Hour) posteriores al accidente resultan críticos con respecto a la atención médica para mantener viva a una víctima (Sukegawa & Sekino, 2011). Otros estudios (Sánchez-Mangas, García-Ferrrer, de Juan, & Arroyo, 2010) mantienen que una reducción de 10 minutos en el tiempo de respuesta médica puede reducir en un tercio la probabilidad de muerte. Por ello, toda la información de la que se pueda disponer, que ayude en esa toma de decisiones, es de vital importancia.

En la actualidad, un gran número de fabricantes de vehículos proporcionan lo que se conoce como Rescue Sheet (RS) (www.rescuesheet.info) para cada uno de los modelos de coche que fabrica. Se trata de una ficha, del tamaño de un A4, en la que aparecen representados de forma gráfica los elementos de seguridad pasiva que puedan suponer un riesgo para víctimas y rescatadores. Pero, a pesar de la existencia de esta, no existe regulación que obligue a llevarla en el vehículo ni mecanismo que garantice la posibilidad de acceder a ella en caso de accidente. Numerosas asociaciones de conductores como ADAC (Allgemeiner Deutscher Automobil Club), RACC (Real Automovil Club de Cataluña) o FIA (Federación Internacional del Automovil) Foundation, recomiendan llevar la RS del vehículo impresa en el parasol del conductor o del acompañante. Pero esta recomendación no garantiza que esté siempre disponible y/o accesible en caso de accidente.

En cuanto a la información biosanitaria de los ocupantes de un vehículo accidentado, en la actualidad no existe ningún sistema que permita acceder a ella en el lugar del accidente o simplemente saber si alguno de los ocupantes es donante de órganos.

Ante esta situación, existe la necesidad de que los servicios de rescate y sanitarios puedan tener acceso en cualquier accidente a la información necesaria para optimizar las labores de rescate.

Con la intención de dar solución a esta necesidad, y tal y como se describe en el **Artículo 1** titulado "*A new approach to road accident rescue*" de esta Tesis Doctoral, se ha desarrollado un sistema que permite proporcionar, tanto a bomberos como a los servicios médicos, de un modo muy rápido y en el lugar del accidente, toda la información necesaria con el objeto de que el proceso de rescate pueda ser lo más rápido, seguro y eficiente posible.

El sistema desarrollado se basa en el uso de códigos QR (ISO/IEC, 2006) en los que se codifica la información para que esta sólo pueda ser leída mediante un software específico instalado en un dispositivo móvil de tipo smartphone o tablet. Con el fin de garantizar el acceso a la información en cualquier situación y tipo de accidente se ha realizado un estudio, tal y como se detalla en el **Artículo 1,** que ha permitido determinar el número, tamaño y resolución óptima de los códigos QR, así como su ubicación en el vehículo. En cuanto a la información codificada en los mismos, detallada en el **Artículo 1**, se ha diseñado una hoja de rescate avanzada (ARS-Advanced Rescue Sheet) que incorpora a la RS convencional cierta información propuesta por especialistas de rescate consultados. La ARS también se complementa con la información biosanitaria de los ocupantes habituales del vehículo que han considerado relevante los especialistas sanitarios consultados.

Con el fin de garantizar la confidencialidad de la información que se maneja, se ha desarrollado una plataforma software compuesta por una App para dispositivos móviles y un servicio web. Desde este último se generan los códigos QR con la información de la ARS codificada. Por otro lado, la App, que debe estar instalada en un dispositivo móvil empleado por los servicios de rescate, es la encargada de leer y decodificar la información contenida en el código QR. De este modo, se garantiza que sólo es posible tener acceso a la información del código QR desde los dispositivos móviles que tengan instalada la App.

La fase posterior al rescate de víctimas atrapadas en un accidente de tráfico suele ser la investigación y reconstrucción del mismo con el fin de identificar las causas que lo provocaron. Esta fase es especialmente importante en aquellos casos en los que resulte necesario dirimir responsabilidades legales. Esta labor, realizada normalmente por los cuerpos y fuerzas de seguridad del estado, suele ser muy compleja debido a la gran cantidad de factores involucrados (e.g. reguladores, técnicos, medico-legales y fisiológicos).

En lo que a causas del origen de accidentes de tráfico se refiere, la velocidad es considerada mundialmente como la primera causa de los mismos, ya sea por excesiva o por inadecuada. En la investigación de accidentes la velocidad es un parámetro determinante, principalmente porque de ella dependen aspectos fundamentales como: la responsabilidad, la legalidad, la percepción, el movimiento de los vehículos, los daños ocasionados, etc. Resulta por tanto fundamental para los investigadores determinar la velocidad a la que se produjo el accidente.

Existen diferentes métodos para calcular la velocidad dependiendo del tipo de accidente. Y se distinguen muchos tipos de accidentes, siendo los choques uno de los más comunes. Se entiende por choque a la colisión entre un vehículo en movimiento y un objeto (u otro vehículo) estático o en movimiento. La metodología más empleada para el cálculo de la velocidad en este tipo de accidentes (choques) se fundamenta en el análisis o estudio energético.

La energía cinética que tiene un vehículo es aquella energía que posee debido a su movimiento y depende, tal y como se extrae de su fórmula ($E_c = \frac{1}{2}mv^2$), de la velocidad y la masa del vehículo ((Arregui-Dalmases, Teijeira, Carmen Rebollo-Soria, Kerrigan, & Crandall, 2011). Así pues, determinar la energía cinética que poseía un vehículo en el momento de la colisión permite calcular la velocidad a la que este circulaba.

El cálculo de la energía cinética requiere, teniendo en consideración el principio de conservación de la energía, determinar las diferentes energías en las que se transforma esta durante el accidente: energía de rozamiento, energía de deformación, energía de desplazamiento, etc. En muchas ocasiones, elementos de seguridad activa como el ABS evitan que se produzcan huellas de frenada, por lo que el análisis de las deformaciones estructurales sufridas por los vehículos tras la colisión, así como el desplazamiento de los mismos, constituyen los factores más importantes a determinar para calcular la energía disipada (Díaz Sánchez & Sánchez Ferragut-Andreu, 2004).

Los métodos actualmente empleados para el cálculo energético se basan en la adquisición de una serie de medidas expeditas tanto en la escena del accidente como en los vehículos accidentados. Las Fuerzas y Cuerpos de Seguridad actuantes realizan una toma de datos exhaustiva en el lugar del accidente. En la actualidad, dichas medidas se realizan mediante procedimientos rudimentarios y empleando una cinta métrica (Carballo et al., 2005). Esto puede provocar una pérdida de precisión ya que esta dependerá de la destreza y habilidad de la persona que realice las mediciones. Además, estas mediciones no pueden ser verificadas posteriormente ya que son tomadas en la escena del accidente y una vez que esta es modificada las características geométricas del mismo cambian.

Con el fin de dar solución a esta problemática, y tal como se describe en el **Artículo 2** de esta Tesis Doctoral "*Energy Analysis of Road Accidents Based on Close-Range Photogrammetry*", se ha desarrollado un método que permite a las fuerzas y cuerpos de seguridad actuantes realizar una reconstrucción métrica precisa del accidente para su posterior análisis energético en cualquier momento. La solución propuesta pasa por el uso de fotogrametría terrestre y visión computacional (Gonzalez-Aguilera et al., 2018) para la creación de una nube de puntos 3D, tanto de la escena del accidente (360º), como de elementos concretos de esta (deformaciones sufridas por los vehículos, huellas de frenada, etc.), con el fin de que estos puedan ser evaluados para realizar un análisis energético preciso del mismo que responda a la demanda requerida en los informes periciales.

En comparación con el resto de técnicas geomáticas, la fotogrametría terrestre junto con la visión computacional es la solución más económica y fácilmente implementable que permite obtener resultados de alta calidad. Además, puesto que la información recabada en el lugar del accidente se compone de imágenes fotográficas, la captura de datos fotogramétricos sirve también como documentación gráfica de la escena del mismo, aportando tanto información cuantitativa como cualitativa.

Aunque la aplicación de este tipo de tecnologías no invasivas y de bajo coste permiten obtener muy buenos resultados, no podemos perder de vista al usuario final (e.g.

Fuerzas y Cuerpos de Seguridad actuantes y peritos) que las va a utilizar, y que debe encontrar en ellas una solución sencilla, eficiente y que mejore los protocolos tradicionales. Para ello, se ha propuesto en esta Tesis Doctoral que los equipos empleados para la captura de imágenes sean pequeños y económicos. Es decir, que puedan emplearse cámaras digitales no métricas, del tipo de las de un smartphone, ya que se trata de una tecnología que es accesible a todo el mundo. Además, el proceso de captura debe ser lo más rápido posible, ya que en ese tipo de situaciones el tiempo es una prioridad y los métodos tradicionales son lentos y costosos. Por último, el proceso no debe requerir de conocimientos fotogramétricos, para que pueda ser realizado por cualquier agente.

Por todo esto, se propone la creación de una serie de modelos en nubes de puntos 3D de la escena del accidente y del propio vehículo empleando fotogrametría terrestre y visión computacional a partir de un conjunto de imágenes 2D adquiridas con cámaras digitales convencionales por usuarios no expertos. De este modo, las fotografías pueden ser tomadas por un agente utilizando, por ejemplo, la cámara de un smartphone de un modo sencillo. Para guiar a los agentes en el proceso de toma de fotografías 2D se han elaborado dos protocolos de captura: (i) Un protocolo de "*toma paralela*" para reconstrucciones detalladas en áreas específicas del vehículo (como las zonas deformadas por la colisión) o de la escena (como marcas de derrape); (ii) un protocolo de "*toma convergente*" para la reconstrucción de nubes de puntos 3D de 360º (como la escena completa del accidente). Ambos protocolos permiten la captura de las imágenes en un breve periodo de tiempo. A partir de dichas fotografías y mediante un software Open Source desarrollado y abierto a la Comunidad Científica internacional (Gonzalez-Aguilera et al., 2018), se generan de forma automática las nubes de puntos 3D fotogramétricas, las cuales poseen una resolución y precisión adecuadas para ser utilizadas por otras herramientas software que permitan realizar un análisis energético preciso del accidente. Así, por ejemplo, es posible integrar un modelo de puntos 3D detallado con el análisis dinámico de los parámetros del accidente mediante la creación de un mapa de deformaciones sufridas en el vehículo, lo que resulta de gran utilidad a la hora de aplicar métodos de análisis energético basados en las deformaciones estructurales sufridas por los vehículos.

La metodología desarrollada ha sido evaluada en un accidente, concretamente una colisión entre dos vehículos, simulado en las instalaciones de la Academia de Seguridad Pública de Extremadura (APEX). Para dicha evaluación se tomaron imágenes 2D del accidente y se generaron las nubes de puntos 3D sobre las que se realizaron las mediciones para aplicar diferentes métodos de análisis energético que permitieron mejorar la estimación de la velocidad de colisión respecto a los métodos tradicionales.

Así mismo, esta metodología ha sido probada con éxito por los agentes de la Policía Local de Salamanca para el análisis de diversos accidentes de tráfico de cierta gravedad ocurridos en la ciudad de Salamanca. Fruto de esta colaboración han surgido nuevas necesidades propuestas por la propia Policía Local, como la de poder integrar los análisis energéticos dentro de la misma herramienta de reconstrucción 3D, así como incorporar en el análisis energético otra tipología de accidentes bastante habitual y no considerada hasta ahora según la iniciativa European Road Assessment (EuroRAP): los impactos frontales o frontolaterales contra elementos rígidos de pequeña sección, ya sean elementos naturales (e.g. arboles) o artificiales (e.g. postes, señales).

Con el fin de atender estas demandas, se ha continuado esta línea de investigación, tal y como se describe en el **Artículo 3** de esta Tesis Doctoral "*A New Approach to Energy Calculation of Road Accidents against Fixed Small Section Elements Based on Close-Range Photogrammetry*", introduciendo novedades en el método fotogramétrico empleado para generar el modelo de puntos 3D. Concretamente en dos de las fases: extracción y matching de características y orientación y autocalibración de las imágenes, lo que ha permitido adaptarse a otras tipologías de accidentes.

Estos impactos contra elementos fijos se caracterizan por que provocan una mayor deformación en la zona de contacto contra el elemento rígido, que a su vez es muy reducida en extensión. Este hecho supone que los modelos matemático-lineales (Campbell, 1974) (McHenry, 1975) tradicionalmente empleados para el análisis energético basado en las deformaciones sufridas por los vehículos en colisiones contra elementos rígidos puedan llegar a introducir errores de hasta el 30% ((Díaz Sánchez & Sánchez Ferragut-Andreu, 2004) por lo que, en lugar de estos, deben aplicarse otros métodos de análisis energéticos específicos para este tipo de impactos como el de Wood (Wood, Doody, & Mooney, 1993).

La aplicación de este método requiere medir la deformación máxima sufrida por el vehículo, algo que mediante técnicas de medición manual no siempre resulta sencillo ni preciso, puesto que debe determinarse visualmente el punto de máxima deformación de la carrocería, y su medición se debe realizar con respecto a una línea paralela al frontal del vehículo que representa el emplazamiento original de la carrocería antes del impacto. Del mismo modo, requiere determinar la deformación media sufrida en la zona deformada a partir de un mínimo de 2 medidas equidistantes y un máximo de 6. Esto último, al igual que en el caso anterior, resulta complicado y poco preciso si la medición se realiza de forma manual, puesto que se realizan desde una línea imaginaria. En ambas mediciones existe una simplificación de la geometría deformada ya que las medidas se toman desde la línea imaginaria de referencia. Esto puede provocar que se introduzcan errores en las mediciones y que por tanto los resultados no sean todo lo precisos que deberían.

Para dar solución a este problema, tal y como se describe en el **Artículo 3** de esta Tesis Doctoral, se ha desarrollado una herramienta software (CRASHMAP) que permite a los agentes realizar las mediciones para obtener la deformación máxima y media de la zona afectada a partir del modelo de puntos 3D fotogramétrico creado, de modo que el punto de máxima deformación pueda ser determinado con total precisión a partir de un histograma de deformaciones. Además, mediante la herramienta desarrollada, es posible obtener la deformación media no sólo a partir de un máximo de 6 medidas equidistantes, sino de tantas como resolución tenga el modelo 3D generado. Del mismo modo, si se dispone de un modelo de puntos 3D del vehículo original antes de sufrir las deformaciones, será posible comparar ambos modelos para considerar la geometría original del vehículo y conseguir que las medidas sean más precisas.

Tal y como se ha indicado anteriormente, con el objetivo de asistir a los investigadores en el análisis energético de los accidentes y mejorar la oferta de productos software comerciales de reconstrucción que se basan en la simulación del mismo en 3D y obvian el análisis energético apoyado en modelos 3D, se ha desarrollado un sistema software (CRASHMAP) que facilita la creación y análisis de los modelos fotogramétricos en 3D.

Finalmente, se ha analizado el error cometido al aplicar los métodos de cálculo energético en base a medidas expeditas y manuales, que no siempre son sencillas de realizar, y donde existe una simplificación de la geometría deformada a la hora de realizar las mediciones frente a la medición basada en las nubes de puntos 3D fotogramétricas mediante la herramienta software CRASHMAP, que tiene en cuenta la geometría original de los vehículos y por tanto proporciona una mayor precisión. La metodología desarrollada ha sido evaluada en un accidente real, concretamente una colisión frontal de un vehículo contra el poste de acero de una marquesina publicitaria, obteniéndose resultados de estimación de la velocidad que mejoran la calidad y eliminan la subjetividad de los métodos tradicionales.

1.1. Estructura de la Tesis Doctoral

Esta Tesis Doctoral se presenta de acuerdo con la regulación vigente para programas de doctorado de la Universidad de Salamanca, siendo objeto de transferencia científica, a través de tres artículos publicados en revistas científicas internacionales de alto impacto.

Se estructura en cuatro capítulos, acordes al desarrollo de las labores de investigación llevadas a cabo para la materialización de los objetivos fijados, y dos anexos que complementan la memoria con información y documentación de interés, tal y como se describe a continuación:

Capítulo I. Introducción: Proporciona una visión general del marco en el que se desarrolla la presente Tesis Doctoral, así como una presentación de las tecnologías empleadas durante su desarrollo. Finaliza con una descripción de la estructura del presente documento.

Capítulo II. Hipótesis de trabajo y objetivos: Describe los planteamientos de partida y los objetivos que han motivado el desarrollo de las líneas de investigación seguidas en esta Tesis Doctoral.

Capítulo III. Artículos publicados: Contiene, por cada una de las publicaciones realizadas, un resumen descriptivo y el contenido íntegro de la misma. Las publicaciones contenidas en este apartado son:

"A new approach to road accident rescue"

"Energy Analysis of Road Accidents Based on Close-Range Photogrammetry"

"A New Approach to Energy Calculation of Road Accidents against Fixed Small Section Elements Based on Close-Range Photogrammetry"

Capítulo IV. Conclusiones y perspectivas futuras: En este capítulo se describen las conclusiones y resultados alcanzados con el desarrollo de esta Tesis Doctoral, y se ponen de manifiesto las líneas de trabajo derivadas de la misma y que podrán dar continuidad a este trabajo.

Anexo I. **Indexación y factor de impacto de las publicaciones**: Proporciona información referente a parámetros de calidad de las revistas científicas donde han sido publicados los artículos.

Anexo II. **Software**: Recoge información y documentación relacionada con los registros de la propiedad intelectual relativos al software desarrollado en la presente Tesis Doctoral.

CAPÍTULO II

HIPÓTESIS DE TRABAJO Y OBJETIVOS

2. HIPÓTESIS DE TRABAJO Y OBJETIVOS

2.1. HIPÓTESIS DE TRABAJO

Para la consecución de los objetivos de la presente Tesis Doctoral se establecen, a priori, las siguientes hipótesis de trabajo:

- El tiempo de actuación es un factor crítico en el rescate de personas atrapadas en accidentes de tráfico.
- Los protocolos de rescate de personas atrapadas en un accidente de tráfico empleados por los servicios de emergencias requieren del conocimiento de cierta información del vehículo accidentado para trabajar de forma óptima y evitar riesgos.
- Disponer de información biosanitaria de una víctima en un accidente de tráfico puede contribuir a mejorar su atención inicial en el lugar del accidente.
- Los métodos de análisis energético constituyen una herramienta válida para estimar la velocidad de colisión en los choques frontales contra elementos rígidos.
- El análisis de un accidente de tráfico para determinar la velocidad de colisión debe ser todo lo preciso posible puesto que de él pueden derivarse graves responsabilidades.
- Las técnicas fotogramétricas de corto alcance constituyen un método óptimo y no invasivo para la modelización geométrica de accidentes de tráfico mediante la creación de nubes de puntos 3D.

2.2. OBJETIVOS

El propósito de esta Tesis Doctoral consiste en el cumplimiento de un objetivo general y un conjunto de objetivos específicos, que a continuación se detallan.

2.2.1. Objetivo General

Solucionar, mediante herramientas tecnológicas de rápida respuesta y alta fiabilidad, las necesidades demandadas por las Fuerzas y Cuerpos de Seguridad actuantes en los accidentes de tráfico en relación a la asistencia informativa en el rescate de víctimas atrapadas y a la investigación de accidentes en lo relativo al análisis energético.

2.2.2. Objetivos Específicos

Para cumplir este objetivo general se plantean diversos objetivos y sub-objetivos específicos:

1. Optimizar el proceso de obtención de información necesaria para que los servicios de rescate y sanitarios puedan actuar del modo más seguro y eficiente posible en un accidente de tráfico con víctimas atrapadas.

    - Implementar un sistema software que permita la generación de una hoja de rescate avanzada concreta para cada vehículo y ocupantes habituales y su codificación en un código QR, así como la decodificación de la misma mediante la lectura del código desde un dispositivo móvil.

    - Analizar el número, tamaño y ubicación en el vehículo de los códigos QR necesarios con el objetivo de que puedan ser leídos en cualquier tipo de accidentes.

2. Desarrollar un método sencillo, rápido de aplicar, de bajo coste y no intrusivo con los elementos de la escena del accidente, que permita a las Fuerzas y Cuerpos de Seguridad actuantes realizar una reconstrucción métrica precisa del accidente para su posterior análisis energético en cualquier momento.

    - Validar el uso de fotogrametría terrestre y visión computacional para la creación de nubes de puntos 3D tanto de la escena del accidente como de elementos concretos del mismo, aplicando sobre ellos diferentes métodos de análisis energético.

    - Contrastar la validez del uso de los modelos fotogramétricos 3D respecto a los métodos tradicionales.

    - Validar la fiabilidad y posibilidades del método fotogramétrico en diferentes tipos de colisiones.

    - Analizar si el método propuesto puede aportar ventajas en determinados tipos de accidente con respecto a los métodos tradicionales.

    - Implementar una herramienta software que complemente el método fotogramétrico y que permita la creación de las nubes de puntos 3D, la toma de medidas precisas sobre dichas nubes y la aplicación de forma automática los diferentes métodos de cálculo energético en función del tipo de accidente.

Capítulo III

ARTÍCULOS PUBLICADOS

3. ARTÍCULOS PUBLICADOS

3.1. Un nuevo enfoque para el rescate en accidentes de tráfico

La publicación científica recogida en este apartado representa el primer hito establecido en la hoja de ruta de la línea de investigación. En ella se describe una nueva metodología para la asistencia a los equipos de rescate y sanitarios que intervienen en el extracción y atención de víctimas atrapadas en accidentes de tráfico. Dicha metodología permite a los equipos de rescate y sanitarios mejorar la seguridad y eficacia de las intervenciones, asi como reducir los tiempos de respuesta en el escenario del accidente gracias a la integración de la misma en sus protocolos de actuación.

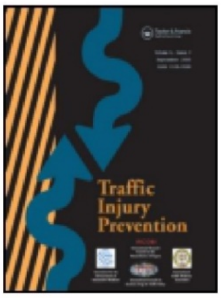
La metodología desarrollada permite obtener información crítica y relevante de cara a la extracción de las víctimas y a una primera atención médica. Concretamente, es información relativa a elementos de seguridad pasiva o elementos del sistema de propulsión del vehículo que puedan suponer un riesgo o complicación a la hora de descarcelar a la víctima, así como información biosanitaria útil relativa a las víctimas que puede ser de gran utilidad en una primera intervención médica.

Toda esta información, que puede ser considerada de gran utilidad, se ha extraido de una serie de entrevistas mantenidas con los especialistas más destacados a nivel nacional (Cuenca, Toledo, Tarragona, Toledo, Valladolid y Ávila).

La metodología se basa en el uso de códigos QR que almacenan la información codificada en su interior de forma que esta pueda ser leída mediante un disposivo móvil con una aplicación específicamente desarrollada y que garantiza la confidencialidad de la información contenida en el código QR. El número y características de los códigos QR necesarios y el emplazamiento de estos en el vehículo ha sido determinado mediante un profundo análisis sobre diferentes vehículos accidentados.

La concepción de la metodología se concreta en el desarrollo de un sistema informático compuesto por dos herramientas software. La primera, denominada *aWebRescue*, es una aplicación web que permite al usuario codificar toda la información relevante de cara al rescate, relativa a su vehículo y a los ocupantes habituales del mismo, en un código QR. La segunda, denominada *tagForRescue*, es una aplicación para dispositivos móviles capaz de decodificar la información contenida en los códigos QR generados por *aWebRescue* y mostarla de forma gráfica. Esta aplicación utiliza una base de datos local que garantiza el acceso a la información de forma inmediata y en cualquier lugar.

La metodología desarrollada ha sido validada a través de diferentes simulacros de rescate de víctimas atrapadas en vehículos ejecutados junto con el Cuerpo de Bomberos de la ciudad de Ávila (España). Estos simulacros han permitido comparar los tiempos de rescate. Se ha concluido que la metodología propuesta permite mejorar los tiempos de respuesta de los protocolos de actuación empleados por los equipos de rescate, de media un 14%. Del mismo modo, se ha podido demostrar que se mejora la seguridad de víctimas e intervinientes.



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A new approach to road accident rescue

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TECHNICAL NOTE

A new approach to road accident rescue

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ABSTRACT

Objective: This article develops and validates a new methodology and tool for rescue assistance in traffic accidents, with the aim of improving its efficiency and safety in the evacuation of people, reducing the number of victims in road accidents.

Method: Different tests supported by professionals and experts have been designed under different circumstances and with different categories of damaged vehicles coming from real accidents and simulated trapped victims in order to calibrate and refine the proposed methodology and tool.

Results: To validate this new approach, a tool called *App_Rescue* has been developed. This tool is based on the use of a computer system that allows an efficient access to the technical information of the vehicle and sanitary information of the common passengers. The time spent during rescue using the standard protocol and the proposed method was compared.

Conclusion: This rescue assistance system allows us to make vital information accessible in posttrauma care services, improving the effectiveness of interventions by the emergency services, reducing the rescue time and therefore minimizing the consequences involved and the number of victims. This could often mean saving lives. In the different simulated rescue operations, the rescue time has been reduced an average of 14%.

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rescue time; road accident rescue; rescue sheet; QR code; golden hour; firefighters; health care services

Introduction

If passengers survive a road accident, the time taken to extricate them is, in most cases, vital for their survival. Sánchez-Mangas et al. (2010) analyzed to what extent a reduction in the time interval between a road accident and the arrival of the emergency services to the accident scene is related to a lower probability of death. Their results suggest that a 10-min reduction in medical response time can be statistically associated with an average decrease in the probability of death by one third, on both motorways and conventional roads. In fact, the well-known golden hour that encloses the 60 min after the road accident is critical with regard to health care to keep a victim alive (Sukegawa and Sekino 2011).

Due to the advances concerning safety in vehicles and the different propulsion systems, it is becoming increasingly necessary to have relevant information to perform quick and safe rescue of trapped victims. The new security elements of vehicles entail risk and difficulty when victims are trapped inside and they have to be extricated, so technical information about vehicles and their passengers could be crucial in order to optimize the rescue process. Although there are some studies about new extrication techniques, such as those by Wik et al. (2004) for frontal and side crashes and, more recently, specific measures for emergency rescue teams (Yu 2013) to ensure the safety of rescuers in secondary rear-end accidents, the possibilities offered by the new technologies have not been fully harnessed by emergency services as a support tool in traffic accident interventions. Therefore, it seems clear that the rescue time depends directly on the knowledge of certain information.

In order to reduce rescue time, the Allgemeiner Deutscher Automobil Club (ADAC) proposed the creation of a rescue sheet (RS) in 2009. It is a standardized record at the European level with technical information and security systems of the vehicle provided by the manufacturers, which must be considered by firefighters when performing rescue operations in order to reduce their response times. This sheet is the size of an A4, and it transforms all of the basic technical information into a graphical framework (that allows quick interpretation). Complementary to this, this sheet uses several colors and graphical symbols in order to represent the different security elements.

There is a gap in this context because the information provided by the paper-based RS is not easily accessible and the information provided is limited. In particular, the ADAC proposal is that drivers download and print the RS of their car on an A4 sheet and place it on the sun visor of the driver's seat. They must also place a sticker on the windshield indicating that the car carries the RS. Thus, in case of an accident firefighters know that the vehicle contains the RS and will try to locate the sun visor. Therefore, the analogic format and the location (inside the vehicle) of the proposed ADAC's RS often prevent its access. In addition, this sheet (which is printed on paper) can be lost or

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/gcpi.

deteriorate. On the other hand, the proposed rescue sheet does not consider all of the relevant information (technical and biomedical) needed, which in many cases can be important.

Based on these gaps, we consider that better access and knowledge of certain information in road accidents could contribute to minimize rescue time and thus save lives. Focused on reducing the rescue time in traffic accidents, the present article aims to solve these drawbacks—that is to improve the accessibility and the quality of the information provided. For the former, quick response codes (hereafter QR) placed on strategic areas of the car were designed. Scientific studies using QR in this industry are not very common. Some authors such as Moharil et al. (2012) have used QR to provide an efficient approach to automatic number plate recognition but not for accessing RSs. For the latter, advanced technical information on the vehicle and biomedical information on the common occupants could be useful in supporting the rescue.

This article has been organized as follows: the following section describes the experiments designed to address the access to information and the reduction in rescue time. The next section presents the different tools developed and the experimental results conducted on several simulated cases in order to validate the new rescue approach and thus the reduction in time. The following section discusses the significance of our discovery, discussing how it accepts, rejects, or expands on existing discoveries. The article ends with future perspectives on the new approach proposed in the field of road safety.

Methods

In order to fill the gap noted in the Introduction, 2 different hypotheses have been taken into account:

Hypothesis 1: Analyze the format and location of the RS proposed by ADAC (sun visor of the driver's seat) in order to determine its suitability to guarantee the best accessibility. To this end, a study using 204 crashed vehicles provided by MAPFRE insurance company was carried out with the aim of finding out about the degree of accessibility. After this study, it seems clear that the access to information could be improved.

Hypothesis 2: Determine whether the information provided by the paper-based RS is enough for emergency services and, if not, how it could be improved. Firefighters from different communities in Spain (Cuenca, Tarragona, Toledo, Valladolid, and Avila), the Spanish Traffic Accidents Rescue Professional Association, and medical services specialist in road accidents were consulted. As a result of the feedback provided, relevant and useful technical and biomedical information was proposed to complement the RS.

Based on the hypotheses above and with the aim of minimizing rescue time, a computer system was developed to provide efficient access to technical information on the vehicle and sanitary information on the common passengers. Mobiles devices such as tablets or smartphones were used to yield better usability. To access information, QR codes were used because these codes provide quick access to information even when they are damaged, providing a clear advantage versus the paper-based RS. Despite the QR codes' simplicity, 3 key aspects have been analyzed for QR codes in order to optimize and calibrate the performance of the proposed system:

- The first aspect (Test 1) was to determine the minimum number of QR codes needed per vehicle and where they should be placed. These properties are key, because the QR codes give access to the information, taking to read at least one code (regardless of the accident conditions). For this reason a wide set of photos (437 photos in 142 interventions), taken by Avila's Firefighters, have been analyzed. In addition, 204 vehicles, provided by MAPFRE, were used to evaluate the optimum locations where the QR code could be placed. In all simulated situations, the least damaged areas were analyzed as well as the least affected zones, depending on the type of accident (frontal, lateral, spill, rear, etc.).
- The second aspect was to design a way of encoding the information enclosed by the QR code, establishing a numerical format that optimizes the storage capacity and the response time and avoiding that this information was accessible for other QR-based applications. (This aspect did not require a specific test.)
- The third aspect (Test 2) was to analyze its readability under real situations. To this end, several tests were performed after the accident and in nonideal situations (e.g. poor lighting conditions, partial loss of the QR code, etc.). This second test was used to determine the optimum properties of these codes, considering the ISO/IEC 18004:2006 guidelines:
  - The QR code size and the maximum distance from which this code can be read.
  - The resolution or number of readable points in the QR code. This determines the amount of storable data. Higher resolution implies more difficulty in reading.
  - Redundancy: The ability to restore information when the QR code is damaged. There are 4 classification levels (L, M, Q, and H) that include different restoration levels; for level H (the highest level), 30% of the information can be restored.

Finally the robustness and efficiency of the proposed approach was performed with a third test (Test 3) based on 8 drills (simulated accidents) designed in collaboration with firefighters and MAPFRE insurance company. To ensure objectivity in the results, 4 groups were established within the 8 drills, establishing 2 comparative studies: standard rescue vs. new rescue approach. In each one, 2 modern vehicles (less than 8 years old) were used with similar properties: (1) category; (2) number of doors; (3) similar damage; (4) final position; (5) security elements (airbags, protection sidebar, structural reinforcements, pretensioners, etc.); and (6) number of victims.

Results

The main result of our study has been the development of a computer system (Figure 1), *App_Rescue*, that improves accessibility and quality of information in road accident rescue. This system involves the development of 2 different modules: the first one, called *aWebRescue*, is a web application that allows the user to generate and print QR codes, including advanced technical information on the vehicle and sanitary information on the

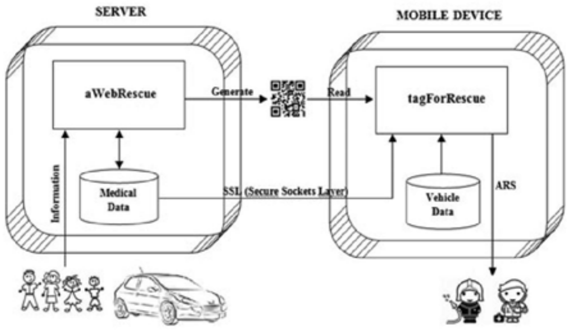

Figure 1. General diagram of the computer system, *App_Rescue*.

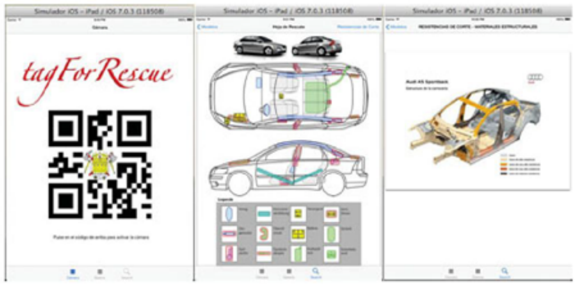

Figure 2. *tagForRescue* tool for reading and accessing RS and ARS information.

common passengers. The second component, called *tagForRescue*, is an application for smartphones and tablet devices that can only be used by emergency services.

The information provided by the computer system to emergency services is a key element to guarantee speed and reliability inroadaccident rescue. For this reason, and after Hypothesis 2 described previously, we found that there is technical and biomedical information that is not currently being shown by the paper-based RS to rescue services that couldbe useful to reduce rescue time and thus improve safety. In particular, the following information has been added to the RS:

- The type of fuel used by the vehicle.
- A 3D model of the vehicle chassis, including the manufacturing materials (e.g., steel, aluminum, magnesium, etc.) and their shear strengths.
- Additional security elements of the vehicle (e.g., armored windows, antiroll bars, panoramic roof, etc.).
- Relevant health information for the usual occupants to cover a first medical intervention. Specifically: blood type, chronic illnesses, medications, treatments, and allergies.

Based on this information we have created an *advanced rescue sheet* (hereafter ARS).

Regarding Hypothesis 1, a computer system with 2 different tools was developed (Figure 1):

- *aWebRescue*: A Web application programmed in PHP that allows drivers to generate and print their own QR codes encoding the ARS. Its friendly and ease-to-use interface is supported by a database that contains advanced technical information on the vehicle and sanitary information on the common passengers. The database connection is made through a safety protocol that guarantees data security and complies with the Spanish Organic Law on Data Protection (LOPD, 15/1999) . The information stored in the QR code that generates the application is also encoded by a numerical system, thus ensuring that personal information cannot be read by third-party apps. The open source library "PHP QR Code" was used to generate QR codes.
- *tagForRescue*: An app developed for smartphones and tablet devices and guarantees robustness, speed, and reliability in accessing advanced vehicle technical information and sanitary information on the passengers. This app was developed using object-oriented programming techniques and a model–view–controller architectural pattern for implementing the user interface. In particular, *tagForRescue* has been created for IOS and Android operating systems using XCode IDE and Studio 1.0 IDE, respectively. It makes use of 2 databases: a local database from which the technical information on the vehicle is obtained and a remote database from which the relevant health information on the common occupants is obtained. Thanks to the local database, minimal access (no Internet connection) to technical information is guaranteed. The connection to the remote database is done following a secure protocol to ensure confidentiality and data protection.

The application *tagForRescue* provides the following features to the user (Figure 2):

- By scanning the QR code using the camera of the mobile device: The application extracts numerical data from the QR code and makes a query to the local database and another query to the remote database in order to obtain health information on the common occupants. This advanced information (ARS) is shown structured in different screens, making management of the app easier.
- By reading a QR code from a picture stored on a mobile device: This option was designed in case the police or a witness arrived at the scene before emergency services. They could photograph the QR code and send it to emergency services. The application is able to read the code from a picture and performs the sequence of steps described in the previous option.
- By manually accessing the RS (without reading the QR code) from the brand and model of the vehicle or by a car model search system: This option is intended for the case in which it is not possible to read any of the vehicle's QR codes.

As mentioned in the Methods section, the number, location, encoding, and readability of QR codes are crucial factors for success with the computer system proposed. The following paragraphs describe in detail the different parameters proposed for these factors.

Based on the results of the first test (Test 1), the ideal number of QR codes to be used is 3, and the most suitable places to put them are as follows (Figure 3):

- The top corner of the windscreen (opposite to the cap of the fuel tank side), which is laminated and even when it cracks it does not break.
- Inside the protective door of the fuel tank, which protects the code when overturned.
- Next the rear plate.

Figure 3. Strategic QR codes' location in the vehicle: door of the fuel tank (top left), top corner of the windscreen (right) and next to the rear plate (bottom left).

The second test (Test 2) evaluated the possibility of incorporating different QR code types (size, resolution, and redundancy). The different sizes used were 5 cm wide (to be read from up to 1.5 m), 3.5 cm wide (with a reading distance of 0.85 m), and 2.5 cm wide (to be read from up to 0.50 m). Considering density as the variable, different QR codes were tested with the following values: 21 rows × 21 columns (QR-1), 25 rows × 25 columns (QR-2), and 41 rows × 41 columns (QR-6). Regarding the redundancy, all of the QR codes tested had an H class redundancy (allowing a high rate of correct reading if the QR code is damaged).

The codes were placed into 3 different positions:

- The first QR code was placed on the windshield (top corner), considering a total of 75 samples (damaged cars with different degrees of windshield fracture; Figure 3). These samples were distributed in 3 groups: (1) day samples (with natural lighting conditions); (2) sunset samples (with poorer lighting conditions); and (3) night samples (complemented with the use of a lantern, similar to those used by rescue professionals).

  As a result of the 75 different samples (Table 1), the best solution, with success rates of 88% (during the day and at sunset) and 83% (at night), seems to be the QR code with a 5-cm-wide, QR-2 density of points (25 rows × 25 columns) and H class.
- The second QR code was located at the back of the vehicle (next to the rear registration plate) in 37 rear-end accident vehicles with different degrees of damage.

As shown in Table 1, the best results were obtained from the QR-2 density of points, with a size of 5 cm wide and a level of redundancy of H. The identification was successful in 29 of the 37 cases. In the 8 remaining vehicles, the reading was not possible due to their level of damage.

The third QR code was placed inside the fuel tank door in 51 side-damaged cars. In this case, only 1 of the 51 tested vehicles had lost the fuel tank door, so the reading was successful in 98% of cases.

After Test 2 was conducted, it was confirmed that the most suitable features for reading the QR codes are a QR-2 density of points (25 rows × 25 columns), a size of 5 cm wide, and a level of redundancy of H. Likewise, it was confirmed that reading at least one of the 3 QR codes was possible in all of the analyzed crashed vehicles.

Finally, Test 3 allowed us to check the efficiency, robustness, and reliability of the computer system with regard to rescue time. To this end, vehicles of different brands and categories (ranging from compact utility cars to the largest executive cars, classic sedans, 4-wheel drive vehicles, and family cars) were analyzed with the tools proposed and compared with the standard protocol. Specifically, the following vehicle models were tested: Toyota Yaris, Peugeot 207, Volkswagen Golf, Seat Leon, Nissan Qashqai, Volkswagen Tiguan, Audi A4, and BMW 3 Series.

All rescues were carried out by the same team of firefighters, including 1 in charge of coordination and command and 5 effective rescuers. In addition, all tests were performed at the same time of day and with the same set of tools, so issues such as visibility, team experience, or fatigue of the members was not an influencing factor of final results.

Before starting the drills, a meeting was held to explain the operation of the developed system to the firefighters (location of the codes and the management of the *tagForRescue* application on an IPad 2). In order to make the drills as realistic as possible, firefighters were not allowed to see the conditions of the vehicles and were not guided on how to proceed with the rescues before the drills began.

In all case studies, the same procedure was followed. Firstly, the position of the vehicle was determined (complete rollover, side dump on all 4 wheels, etc.). Then, the number of trapped victims and the type of trapping was determined. Afterwards, the QR codes were generated with *aWebRescue* according to the parameters established in Tests 1 and 2 and fixed to the vehicles. Subsequently, the vehicle was placed in the chosen position and the simulated victims (firefighters) was introduced into the car. All vehicles were from real accidents, allowing the tests to be as reliable as possible.

Finally, firefighters performed the rescue while a witness timed and controlled the tasks taken by each firefighter at each different rescue stage.

In order to conduct a comparative study between the time spent on a standard rescue (protocol without RS) and the proposed one (*tagforRescue* protocol with ARS), 4 groups were established within the 8 drills. Each group includes 2 vehicles with very similar characteristics involved in the same type of accident.

- The first drill was performed with a Toyota Yaris (year 2010) and a Peugeot 207 (year 2008), both 3-door versions and from rollover accidents. A rollover accident with a conscious single victim (the driver) was simulated without trapped limbs. In both cases the extraction was performed by the tailgate of the vehicle.
- Both vehicles had a driver airbag, passenger airbag, side and curtain airbags, door reinforcing structures, and seat belt pretensioners. The Peugeot 207 had column reinforcements at the base and the top of the A-pillar, and the pillar and B-pillar ring were central, whereas the Toyota did not. Additionally, the Toyota Yaris had knee and head airbags, whereas the Peugeot 207 did not.
- The second drill was performed with a Volkswagen Golf VI (year 2009) and a Seat Leon (year 2010), both 5-door

Table 1. Satisfactory results (%) for the reading of QR codes with different densities and sizes, placed at the top corner of the windscreen and next to the rear plate.

	QR-1			QR-2			QR-6		
	5 cm	3.5 cm	2.5 cm	5 cm	3.5 cm	2.5 cm	5 cm	3.5 cm	2.5 cm
				Top corner of the windscreen					
Morning	68	73	83	64	72	88	57	60	71
Sunset	65	71	81	65	71	87	56	59	69
Night	68	73	83	64	72	88	57	60	71
				Next to the rear plate					
Morning	62	70	76	62	73	78	57	62	70
Sunset	57	65	70	57	70	76	57	59	68
Night	62	70	76	62	73	78	57	62	70

versions and from side impact collisions on the passenger side, being overturned onto the driver's side. A driver's side overturned accident with a conscious single victim (the driver) was simulated without trapped limbs. In both cases the extrication was performed by removing the vehicle's roof.

- Both vehicles had a driver airbag, passenger airbag, side and curtain airbags, door reinforcing structures, and seat belt pretensioners. The Volkswagen Golf had knee airbags and the Seat Leon did not.
- The third drill was performed with a Nissan Qashqai (year 2010) and a Volkswagen Tiguan (year 2010), both 5-door versions and from multiple-vehicle collisions with front-to-rear crashes. Thus, an accident with serious damage to both the rear and front with 2 victims (the driver and a passenger) was simulated. The driver was unconscious and trapped by the lower limbs. The passenger was conscious and without any trapped limbs. The rescue could not be performed by the tailgate due to the damage to the vehicles so it was carried out by removing the doors and the driver side's central pillar.
- Both vehicles had a driver airbag, passenger airbag, side and curtain airbags, door reinforcing structures, and seat belt pretensioners. The Volkswagen Tiguan had column reinforcements at the A and B pillars, whereas the Nissan Qashqai did not.
- The forth drill was performed with an Audi A4 (year 2010) and a BMW 3 Series E90 (year 2009), both 5-door versions and from front-passenger side collisions. Thus, an accident with serious damage to both the front and passenger side with 2 victims (the driver and a passenger) was simulated. Both victims were conscious and only the passenger was trapped by the lower limbs. The rescue was performed by the side of the vehicles.
- Both vehicles had a driver airbag, passenger airbag, side and curtain airbags, door reinforcing structures, and seat belt pretensioners. The Audi A4 had structural reinforcements in the post, the B-pillar, and the lower horizontal crossbar, whereas the BMW 3 Series E90 did not.

All analyzed drills were timed for each phase and task, for both the standard protocol (without RS) and the proposed one (*tagforRescue* with ARS). Table 2 shows the results for each of the drills.

The total rescue time was reduced by 16.8% using the proposed system in the first rescue, 28.7% in the second, 14.8% in the third, and 13.2% in the fourth. The average rescue time was reduced by 14% by using the proposed system.

Discussion

The importance of the new approach proposed for road accident rescue is that thanks to the information provided, ARS, and the computer system developed, *App-Rescue*, more lives can be saved. In addition, the proposed system solves the problems noted for the paper-based RS, because the information can be accessed more efficiently and quicker in any type of accident. In particular, the ADAC initiative to design a standardized record at the European level called RS has 2 major limitations: (1) a certain lack of technical information on the vehicle and health information on the common occupants and (2) no guarantee effective accessibility under real and complex situations. There

Table 2. Time required to put into practice various task of the rescues using standard and proposed protocols.

	Task	Standard protocol	Proposed protocol
		Toyota Yaris	Peugeot 207
First Rescue	Location and reading QR code	0 s	9 s
	Control and removal of risks	6 min 28 s	2 min 42 s
	Open hole to extrication	2 min 39 s	3 min 2 s
	Victim release	0 s	0 s
	Total time	17 min 25 s	14 min 29 s
		Volkswagen Golf	Seat León
Second Rescue	Location and reading QR code	0 s	12 s
	Control and removal of risks	6 min 52 s	2 min 18 s
	Open hole to extrication	8 min 34 s	3 min 48 s
	Victim release	0 s	0 s
	Total time	21 min 43 s	15 min 29 s
		Volkswagen Tiguan	Nissan Qashqai
Third Rescue	Location and reading QR code	0 s	8 s
	Control and removal of risks	5 min 41 s	2 min 52 s
	Open hole to extrication	10 min 23 s	7 min 50 s
	Victim release	5 min 10 s	3 min 14 s
	Total time	23 min 27 s	19 min 58 s
		Audi A4	BMW Series 3
Fourth Rescue	Location and reading QR code	0 s	9 s
	Control and removal of risks	4 min 10 s	2 min 15 s
	Open hole to extrication	11 min 53 s	8 min 59 s
	Victim release	5 min 56 s	6 min 26 s
	Total time	25 min 12 s	21 min 52 s

are several specific publications for firefighters (Morris 2004; Sweet 2011) that describe protocols, techniques, and tools to be used in rescue work. They focus on information about moving to the accident site, security steps, management of the accident, potential hazards, extrication techniques, etc., but the RS is not considered as a support document. Though these publications represent an essential tool in the specific training of rescue services members in terms of management tools, protocols definition, preparing rescue plans, etc., experience has shown that having specific information on each vehicle and its common occupants on the scene is crucial to ensuring the safety and improves the efficiency of rescue. In this sense, it can be stated that the proposed system works correctly based on the tests performed. The information provided has been useful, reliable, and complete for emergency services. Last but not least, the rescue times achieved with the new system were reduced in all simulated rescues.

Based on the tests and results obtained, we can conclude that the computer system developed constitutes a useful tool for emergency services in road accident rescues. This system is able to provide information to rescue teams that was not available before, in particular, advance technical and medical information about the vehicle and its occupants, which is crucial for saving lives. The information included in the ARS has been proposed by professionals and experts, which supports its usefulness and completeness. In addition, the system has been designed so that the information is easily configurable and accessible. The reliability and response time of the system have been demonstrated in the tests conducted. In all tests the information has been accessed through at least one of the QR codes placed in the vehicle, which means that both the location and the characteristics chosen (size, density, and redundancy) were appropriate. Last but not least, rescue times have been reduced (by 14% on average) in all tests performed, which will contribute to minimizing injury to occupants and save lives.

We would like to emphasize that the proposed information system does not affect standard rescue protocols followed by emergency services; in contrast, it would serve as an important support tool to aid in decision making. Moreover, as Calland (2005) pointed out, a perfect coordination between health services and firefighters in rescues is necessary, and new applications would help improve that coordination.

Implementation of the proposed system is easy, because the use of the application does not require training, and it is low cost, because it would only involve the creation, printing, and placement of QR codes, which can be done by vehicle owners, car dealerships, or Inspección Técnica de Vehículos (ITV) stations.

The following are proposals for the future:

- Adapting the proposed system to larger, heavier, and more complex vehicles (trucks, buses, trains) or even those carrying dangerous goods.
- The use of an electronic tag with a radio frequency identification system to store the encoded information on the vehicle and the occupants, instead of QR codes, or in addition to these. This way it could always be placed in the same location in all vehicles and allow reading simply by approaching the vehicle with the device.
- Developing an expert system for decisions based on the information provided by the current system helps firefighters implement the evacuation protocol and improve the victim's extrication. This could be relevant if the firefighters conduct a 3D scan of the damaged vehicle with a mobile device and based on the theoretical 3D shape of the vehicle and its current form, the system, given the characteristics of the car, may advise regarding the best way to perform the extrication.

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3.2. Análisis energético de los accidentes de tráfico basado en la fotogrametría de corto alcance

La publicación científica recogida en este apartado constituye el segundo hito establecido en la hoja de ruta de la línea de investigación y pretende cumplir con el segundo objetivo específico planteado al inicio de esta Tesis. En ella se plantea una nueva metodología para la asistencia en el análisis energético de los accidentes de tráfico basada en procedimientos fotogramétricos.

Las fuerzas de seguridad encargadas de llevar a cabo un estudio o reconstrucción de un accidente de tráfico aplican, en muchas ocasiones, métodos basados en el análisis energético de las deformaciones sufridas por los vehículos y de los desplazamientos espaciales de estos (Sánchez-Ferragut, et al., 2004) para determinar la velocidad de colisión del vehículo. Estos métodos requieren de la realización de una serie de medidas de la deformación estructural sufrida por el vehículo, entre otras. Estas medidas se realizan siguiendo procedimientos manuales (Carballo et al., 2005) y no siempre resulta posible realizarlas con total precisión. Además, al realizarse in situ, sólo permiten ser tomadas en el momento, ya que suele existir la necesidad de retirar los vehículos accidentados para despejar la vía.

La metodología propuesta supone una herramienta de apoyo que permite a las Fuerzas y Cuerpos de Seguridad mejorar sus actuaciones en aquellos accidentes de tráfico que requieran un análisis energético del mismo. Básicamente, consiste en poder crear mediante herramientas de bajo coste y de forma rápida, sencilla, no invasiva, rigurosa y eficaz, nubes de puntos 3D de la escena original y detalles del accidente. Estas nubes de puntos 3D poseen la calidad suficiente para realizar sobre ellos todo tipo de mediciones con una precisión mayor que con los métodos tradicionales, lo que se traduce en unos resultados más precisos a la hora de aplicar los distintos métodos de análisis energético. Esta forma de trabajar permite a los agentes despejar la vía lo antes posible y crear un modelo documental 3D del accidente sobre el que poder trabajar en cualquier momento con total precisión métrica.

La metodología se basa en el uso de fotogrametría terrestre de corto alcance (Luhmann, Robson, Kyle, & Harley, 2011) para la generación de nubes de puntos 3D de la escena del accidente y de zonas concretas de esta o de los vehículos implicados. Estas nubes de puntos 3D son creadas de forma automática a partir de un conjunto de imágenes

2D, que pueden ser tomadas por usuarios no expertos de forma rápida, sencilla y no invasiva. Uno de los aspectos más destacables es que estas imágenes 2D pueden ser realizas empleando cámaras digitales de nivel consumidor (no profesionales) como puede ser la de un smartphone actual. Para que los agentes no expertos adquieran las imágenes 2D de la forma adecuada se han elaborado dos protocolos, uno para la reconstrucción de nubes de puntos 3D de 360º y otro para la reconstrucción detallada en áreas específicas del vehículo o accidente.

Una vez adquiridas las imágenes, estas son sometidas a una etapa de preprocesamiento en las que se les aplica un filtro Wallis (Wallis, 1974) para homogeneizar las diferentes imágenes y ajustar el brillo y contraste de los pixeles en ciertas áreas de la imagen, con el fin de evitar problemas con sombras y superficies especulares.

Posteriormente las imágenes son sometidas a una extracción de características empleando el algoritmo ASIFT (Morel & Yu, 2009). A continuación, se las somete a una etapa de orientación de la imagen y autocalibración, utilizando las dos herramientas de código abierto Bundler (Snavely, Seitz, & Szeliski, 2008) y Apero (Pierrot Deseilligny & Clery, 2012). Las estrategias de autocalibración ejecutadas eliminan la dependencia de procesos previos de calibración, lo que le atribuye una gran flexibilidad, acercando la tecnología a personal no cualificado.

Finalmente, se han utilizado dos algoritmos para la reconstrucción 3D de la escena: MicMac (Rosu, Pierrot-Deseilligny, Delorme, Binet, & Klinger, 2015) para las escenas globales del accidente y SURE (Rothermel, Wenzel, Fritsch, & Haala, 2012) para las zonas concretas del vehículo accidentado.

Los métodos de análisis energético basados en la deformación estructural sufrida por los vehículos como el de McHenry (McHenry, 1975) o Prasad (Aloke Kumar Prasad, 1990) (Aloke K. Prasad, 1991), pueden ser aplicados utilizando únicamente los modelos 3D creados. Esto es posible porque los modelos fotogramétricos 3D poseen una resolución y precisión adecuadas y se proporcionan en formatos estandarizados para ser tratados por multitud de herramientas software disponibles, que permiten realizar sobre ellos todas las medidas requeridas por los métodos. Incluso es posible crear mapas de deformación métrica de las zonas afectadas en un vehículo por la colisión que permiten determinar, por ejemplo, el punto de máxima deformación o la deformación media sufrida.

Se ha podido constatar que se obtiene una mayor precisión en ciertas medidas requeridas por los métodos de análisis energético realizándolas sobre los modelos fotogramétricos 3D que sobre el terreno con los métodos tradicionales. Así mismo, los modelos 3D ofrecen la posibilidad incrementar el número de medidas realizadas y, por ende, precisar más ciertos valores como la deformación media. Todo ello supone una mayor precisión en los resultados proporcionados por los métodos de análisis energético aplicados.

La metodología desarrollada ha sido validada en la escena de un accidente real simulado por expertos y miembros de la Policía Local en la Academia de Seguridad Pública de Extremadura, España, obteniéndose resultados muy satisfactorios. Así mismo, está siendo utilizada por la Policía Local de Salamanca.

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Technical Note

Energy Analysis of Road Accidents Based on Close-Range Photogrammetry

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Abstract: This paper presents an efficient and low-cost approach for energy analysis of road accidents using images obtained using consumer-grade digital cameras and smartphones. The developed method could be used by security forces in order to improve the qualitative and quantitative analysis of traffic accidents. This role of the security forces is crucial to settle arguments; consequently, the remote and non-invasive collection of accident related data before the scene is modified proves to be essential. These data, taken *in situ*, are the basis to perform the necessary calculations, basically the energy analysis of the road accident, for the corresponding expert reports and the reconstruction of the accident itself, especially in those accidents with important damages and consequences. Therefore, the method presented in this paper provides the security forces with an accurate, three-dimensional, and scaled reconstruction of a road accident, so that it may be considered as a support tool for the energy analysis. This method has been validated and tested with a real crash scene simulated by the local police in the Academy of Public Safety of Extremadura, Spain.

Keywords: energy analysis; road accident; photogrammetry; computer vision; 3D reconstruction; software development

1. Introduction

Traffic accidents are one of the leading causes of mortality in developed countries, especially in Spain, constituting a concern for the National Department of Traffic, the Road Transport Ministry, and other administrative agencies involved in its management. Road accidents have represented a considerable cost (between 105,000 and 144,000 million euros) to the Spanish society in the last 10 years. In fact, the cost associated with the victims of road accidents account for 2% of GDP (Gross Domestic Product) or, in other words, roughly equivalent to a third of the wealth generated in Spain throughout the automotive industry, one of the most important in our country.

The investigation of road accidents is often a complex task due to the high number of factors involved (such as regulatory, technical, medical-legal, and physiological). These factors hamper the correct evaluation of road accidents [1]. According to this, accurate and reliable strategies to investigate the causes and conditions of the accidents are required, since these properties are important for the different groups involved: (i) persons concerned, who need to know the causes and circumstances of the road accident; (ii) the security forces, who analyze the road accident and control the traffic, (iii) the Justice Department, in order to evaluate responsibilities (civil or penal); and (iv) the administration to improve road and vehicle safety.

In most of the road accidents the main cause was the vehicle's speed, sometimes excessive (considering the type of road), and other times in adequate to the characteristic of the road (e.g. poor state of maintenance, lack of barriers, traffic signs, *etc.*). For this reason, in the reconstruction of road accidents, one of the most critical factors is the speed of the vehicles implied. This variable allows the evaluation of the driver's responsibilities. However, the presence of safety systems such as the ABS (anti-lock braking system), almost prevents the skid marks on the road, thus making the analysis of the impact velocity more difficult. In order to solve this drawback, security forces use an analysis technique based on the deformations and spatial displacements suffered by the different vehicles involved [2]. This analysis requires the acquisition of accurate measurements on both the scene and the vehicles. Additionally, when the gravity of the road accident is important, these measurements are the basis to provide evidence in a subsequent court case.

Nowadays, the acquisition method for these measurements is based on rudimentary procedures using measuring tape [3]; this depends highly on the user's skills resulting in lesser accuracy and reliability. It should be noted that these measurements cannot be double-checked since the geometrical characteristics of the road accident changes when all the required procedures are finished. Deriving from this, it is required to develop procedures which allow an accurate metric reconstruction of the road accident with the aim of its analysis at any moment. Furthermore, this reconstruction has to enable an energy analysis of the accident in order to analyze the dynamics of the collision event.

Regarding the photogrammetric field, Luhmann *et al.* 2006 [4] and González-Aguilera *et al.* 2013 [5] try to estimate the deformation of the vehicles for expert purposes. Nevertheless, its correct application requires the use of sophisticated sensors, which need to be calibrated, cumbersome target systems [6], and photogrammetric knowledge by the agents. Other authors [7,8] deal with robust methods for orientation and camera self-calibration but they required coded targets which support the photogrammetric orientation process. Although some authors have developed new algorithms for coded target detection [9], these targets require optimal exposure to ensure success, so they work properly only in indoor industrial environments. More recently, some authors have tried to determine the collision speed of a vehicle from evaluation of the crush volume using photographs [10].Concerning the field of laser scanners, this sensor provides a real-time 3D point cloud in complete darkness or direct sunlight and without the needed of a photogrammetric knowledge. Some authors [11] have used laser scanner data for a 3D modeling of accident scenes offering new ways to simulate the accident, but lacking a direct computation of the dynamics of the collision event. Other authors [12,13] have dealt with photogrammetry and laser scanning methods for traffic accident analysis and virtual scene reconstruction. The results obtained in terms of 3D models quality are outstanding since external and internal body examinations are possible. Furthermore, one of the main drawbacks is the sensor's cost and availability for all road officers, as well as its slow handling in situations where the time is a priority.

The following table (Table 1) tries to provide a comparative framework about these two main geotechnologies applied to road accidents.

Table 1. Comparison of the main geotechnologies applied to road accidents reconstruction.

	Photogrammetry	**Laser Scanning**
Automation of spatial data retrieval	Semi-automated	Automated
Spatial data accuracy	Accurate	Most accurate
Spatial data resolution	Medium-High	High
Equipment cost	Low (hundreds)	High (thousands)
Equipment portability	Lightweight	Non-portable
Data acquisition time	Low (seconds per image)	High (minutes per scan)
Range distance	Medium	Long range
Operation time	Sensitive to light	Operates day and night but sensitive to rain

All the approaches remarked above exhibit their differences between the extent of their use and measurement accuracy. The pros and cons of these techniques (Table 1) affect the required number of experts, portability, measurement range, applicability depending on the amount of light and weather conditions, time required for data acquisition and processing and the accuracy of the data acquired. Anyway, it seems clear than modern photogrammetry is facing new challenges and changes and the scientific community is replying with new algorithms and methodologies for the automated processing of imagery. However, non-expert users outside the field of photogrammetry have difficulties accessing these solutions and applying them to their specific applications to support their problem solving and decision-making.

To this end, this paper presents a method that tries to connect the photogrammetric workflow, using any image acquired with consumer-grade digital cameras by non-expert users, with the energetic analysis of road accidents, so that the results provided by this approach can respond to the demand required in the expert reports. In particular, this paper proposes a new energy analysis of the road accidents, based on the evaluation of the photogrammetric 3D point clouds which enclose: (i) automatism (in the pass from 2D-images to 3D-point clouds) ; (ii) simplicity, operating with non-metric standard cameras such as smartphones or amateur digital cameras; (iii) quality, providing metric 3D point clouds with an acceptable resolution and accuracy; and (iv) efficiency, allowing for a quick data acquisition in comparison to traditional procedures.

The research presented in this article, is intended to complement those accident reconstruction tools (e.g. VCrash, ARAS360, *etc.*) with dense and accurate 3D point clouds of the scenes, obtained by the photogrammetric procedure shown, which allows the extraction of features needed by this software for the reconstruction and simulation of road accidents.

Taking all of this into account, this article attempts to demonstrate the viability of the 3D point clouds and their derived products, such as deformation maps, in the energy evaluation of road accidents that are analyzed by the computation of impact speeds.

The paper is organized as follows: after this introduction Section 2 describes the different sensors and the proposed methodology for the energy analysis of road accidents; Section 3 shows the numerical results obtained in the simulated accident; and, finally, in Section 4, the conclusions and further investigations are drawn.

2. Materials and Methods

2.1. Photographic Sensors

Two sensors were used for the image acquisition process: (i) a high-resolution Olympus EMP-2 consumer-grade digital camera, equipped with a 14 mm lens; and (ii) a Nokia-Lumia 1020 smartphone. The technical specifications are described in the following table (Table 2).

Table2. Technical specifications of the sensors used.

Camera	Sensor Type	Sensor Size	Effective Pixels	Image Size	Shutter Speed	Weight
OLYMPUS EPM-2	4/3 CMOS	17.3 × 13 mm	17.2 Mp	4608 × 3456	2–1/4000 s	269 gr
NOKIA LUMIA 1020	BSI CMOS	8.8 × 6.6 mm	40.1 Mp	7136 × 5360		158 gr
EPM-2 Lens	Focal length	Crop factor	Field of view	Maximum opening	Minimum opening	Weight
M.ZUIKO DIGITAL 14–42 mm f3.5-5.6 II R	14–42 mm	X2	75°–29°	F3.5 : f5.6	F22	113 gr

2.2. Additional Equipment

In order to evaluate the accuracy of the proposed methodology, the photogrammetric 3D point clouds were compared with those obtained by a terrestrial laser scanner (Faro Focus 3D). The scanner Faro Focus 3D measures distances using the principle of phase shift at a wavelength of 905 nm. Complementary to this, a metallic scale bar and magnetized targets (with known dimensions) (Figure 1) were used with the purpose of providing scale for two different types of 3D point clouds: (i) general point cloud of the accident scene; and (ii) detailed deformation point cloud.

2.3. Methodology

Next to the description of the used materials, the workflow designed for the energy analysis of the accident is described (Figure 2).

Figure 1. (**Left**) Metallic scale bar used in the general point cloud. (**Right**) Magnetized targets used for obtaining the deformation map (detailed point cloud). The metallic scale bar features four branches, each 1 m long from the center point. The magnetized target is 20 cm long.

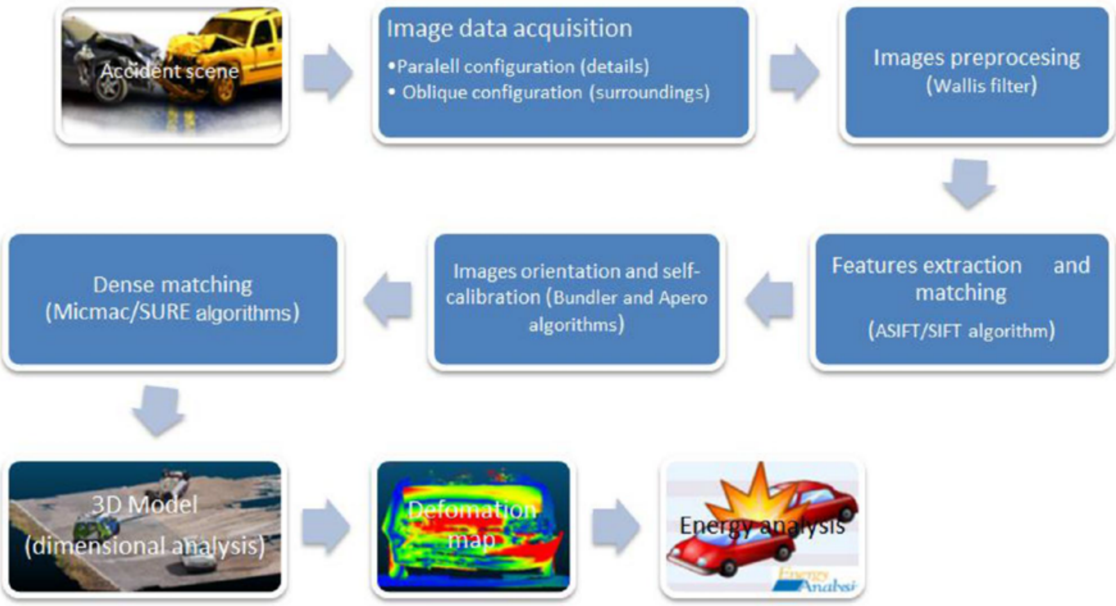

Figure 2. Workflow carried out for the 3D reconstruction and energy analysis of the road accident.

2.3.1. Image Data Protocol Acquisition.

Concerning the photogrammetric procedure, one of the greatest barriers for the non-expert agent is the data acquisition. However, whilst it may be technically simple, the protocol shows several simple rules (e.g. geometrical and radiometric restrictions or camera calibration) which make difficult the data acquisition and, thus, determine the quality of the final result. In this sense, a video-tutorial [14] has been created to help non-expert agents who want to capture a 3D scene with the acquisition of images (through conventional cameras and smartphones).

Regarding the acquisition rules of the images, there are two protocols which can be used by the agent:

- **Parallel protocol.** Ideal for detailed reconstructions in specific areas of the vehicle or accident scene (e.g. skid marks, remains from the crash, *etc.*). In this case, the agent needs to capture five images following a cross shape as shown (Figure 3, left).The overlap between images needs to be at least 80%. The master image or central image (shown in red) will capture the area of interest. The remaining photos (four) have a complementary nature, and should be taken to the left, right (shown in purple), top, and bottom (indicated in green) of the central image. These photos should adopt a certain degree of perspective, turning the camera towards the middle of the interest area. It should be noted that, with the purpose of a complete reconstruction, each photo needs to capture the whole area of interest.
- **Convergent protocol.** Presents an ideal behavior in the reconstruction of a 360º 3D point clouds (accident scene and the whole vehicles). In this case, the agent should capture the images following a ring path (keeping a constant distance to the object). It is necessary to ensure a good overlapping between images (> 80%) (Figure 3 Right). In the situations where the object cannot be captured with a unique ring it is possible to adopt a similar procedure based on the capture of images following a half ring.

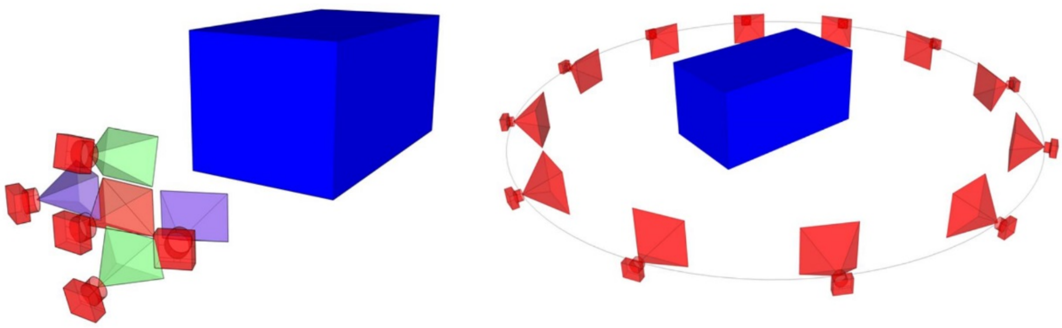

Figure 3. Different adopted acquisition protocols. **(Left)** Parallel protocol. **(Right)** Convergent protocol.

It should be highlighted that the previously-shown protocols do not require an auxiliary camera calibration procedure, since they incorporate self-calibration algorithms as shown (Section 2.3.4).

2.3.2. Image Pre-Processing

Due to the light conditions at the time of the accident, the presence of shadows, textureless, and high specular surfaces (common in vehicles) along the scene, a pre-processing stage is required. This step aims to homogenize the different images captured for the 3D reconstruction improving the keypoint extraction and matching. For this purpose a Wallis filter was applied [15]. Wallis filter is an useful solution when there is lack of texture on the ground or the cars contains an uniform color. In particular, this filter adjusts brightness and contrast of the pixels that lie in certain areas where it is necessary, according to a weighted average. As a result, the Wallis filter provides a weighted combination of the average and the standard deviation of the original image. Although default parameters are defined for

Wallis filter, the average contrast, brightness, standard deviation, and kernel size can be introduced by the user as advanced parameters, which will return a more suitable image for feature extraction and matching.

2.3.3. Feature Extraction and Matching

The feature extraction has been carried out by the ASIFT (Affine Scale-Invariant Feature Transform) algorithm [16]. As its most remarkable improvement, ASIFT includes the consideration of two additional parameters that control the presence of images with different scales and rotations. In this manner, the ASIFT algorithm can cope with images displaying a high scale and rotation difference, common in road accident scenes. The result is an invariant algorithm that considers the scale, rotation, and movement between images. The main contribution in the adaptation of the ASIFT algorithm is its integration with robust strategies that allow us to avoid erroneous correspondences. These strategies are the Euclidean distance [17] and the Moisan-Stival ORSA (Optimized Random Sampling Algorithm) [18]. This algorithm is a variant of Random Sample Consensus (RANSAC) [19] with an adaptive criterion to filter erroneous correspondences by the employment of the epipolar geometry constraints. Once the feature points have been extracted and described, the final matching points are assessed based on their spatial distribution on the CCD. An asymmetric distribution (radial and angular) of matching points regarding the principal point, will affect the correct determination of internal camera parameters and also the image orientation. Therefore, if the matching points do not cover an area more than the 2/3 of the CCD format, the user will be alerted in order to modify the detector (ASIFT) and descriptor (SIFT) parameters. Through this quality control we try to minimize those problems associated with the weakness and common deficiencies in the photogrammetric network geometry of road accidents.

2.3.4. Image Orientation and Self-calibration

The data protocol acquisition, which is far from a normal stereoscopic case of classic photogrammetry, will require robust orientation procedures. For this purpose, a combination between computer vision and photogrammetric strategies is used. This combination is fed by the resulting keypoint extracted in the Section 2.3.3. In a first step, an approximation of the external orientation of the cameras was calculated following a fundamental matrix approach [20]. Later, these spatial (X,Y,Z) and angular (ϖ-omega, φ-phi, andχ-kappa) positions are refined by a bundle adjustment complemented with the collinearity condition [21]. In this field, several open source tools have been developed such as Bundler [22] and Apero [23]. For the present case study, both were combined and integrated. In particular, a specific converter has been developed for reading Bundler orientation files (*.out) and computing the three rotation angles and three translation coordinates of the camera in Apero. In addition, a coordinate system transformation has been implemented for passing from the Bundler to the Apero coordinate system.

It is remarkable that at the same time, thanks to the reliability of the photogrammetric procedures used, it is possible to integrate as unknowns several internal camera parameters (focal length, principal point, and radial distortions). This possibility allows the use of non-calibrated cameras and guarantees acceptable results. Nevertheless, for an accurate camera self-calibration the following requirements should be accomplished: a multi-image convergent camera station geometry, a well distributed array of object points throughout the format of the images and the incorporation of orthogonal camera roll angles, and depth changes. Trying to find a balance between an easy-to-use protocol and some approximations to internal camera parameters, a self-calibration strategy supported by a basic calibration model which encloses five internal parameters (focal length, principal point, and two radial distortion parameters) was used [24,25].

2.3.5. Dense Matching

One of the greatest breakthroughs in recent photogrammetry has been exploiting, from a geometric point of view, the image spatial resolution (size in pixels). This has made it possible to obtain a 3D object point of each of the image pixels. Different strategies have emerged in the recent years, such as the Semi-Global Matching (SGM) approach [26] that allows the 3D reconstruction of the scene, in which an object point corresponds with a pixel in the image. These strategies, fed by the external and internal orientations and complemented by the epipolar geometry, are focused on the minimization of an energy function [26]. However, besides the classical SGM algorithm based on a stereo-matching strategy, multi-view approaches are incorporated in order to increase the reliability of the 3D results and to better cope with the case of road accidents (where the images are captured with considerable baselines and perspective). Considering the two types of protocols needed in road accidents (parallel and convergent protocols), two different multi-view algorithms were used. For the parallel protocol, the multi-view MicMac algorithm [27] was used. Meanwhile, for the convergent protocol, the multi-view SURE algorithm [28] was used, which allows a complete reconstruction of the scene.

Finally, a manual stage is required in order to scale the previously-obtained model (making it metric). For this purpose it is necessary to identify one distance, at least in three images, between targets or using specific objects such as the metallic scale bar or the magnetized targets (Figure 1). It could be remarked that performing scaling after dense matching could transmit possible deformations in object space, especially in those linear configurations of cameras (e.g. recording a corridor or the classical single strip in photogrammetry). In our case, the images acquired following both protocols enclosed: (i) redundancy, since at least one object point appears in five or more images; and (ii) robustness, since the geometry provided by the convergent case following a "ring" is less critical. For the parallel case, the reduced area of interest combined with the convergence provided by images at edges could minimize this problem.

The scaled models generated are grouped as follow:

- Detailed 3D point cloud: the point cloud with high resolution of the damaged areas of the vehicle. This model, which represents the deformation suffered during the crash, is the result of the comparison between the theoretical model (initial model) and the deformed one. The former may be supplied by the vehicle manufacturer or obtained through data collection by measuring undamaged vehicles of the same model (as in this case-study) with the laser scanner.
- General 3D point cloud: the point cloud which represents the whole accident scenario. This point cloud allows the dimensional analysis of the road accident and the final position of the involved vehicles.

2.3.6. Energy Analysis of the Road Accident

Considering the previously-obtained 3D point clouds (general and detailed point clouds), an energy analysis of the road accident is carried out with the aim to evaluate the impact speeds. For this purpose an analysis of the kinetic energy is performed. This analysis implies the evaluation of different types of energies (e.g. deformation energy absorbed by the vehicle's bodywork, friction energy, rotational energy, *etc.*).

The evaluation of the different energies acting on a road accident requires the use of metric information. This metric information can be extracted and evaluated in a simple way thanks to the previously obtained 3D photogrammetric point clouds. The density and photorealistic texture of the point cloud allows the extraction of structural deformations, distances between vehicles, and specific objects or skid marks.

The classical approach for estimating the structural deformation of the vehicle requires the use of several manual measurements with a constant height and equidistance between them using a measuring tape. For the present study case, these measurements were extracted from the detailed 3D point cloud computed (deformation map).

Later, the deformation energy was evaluated through the Prasad's method [29,30]. This method, considered as a reformulation of the McHenry method [31], relates the power developed during the impact with the structural deformation of the vehicle (Equation (1)).

$$E_d = L_i\left[\sum_{i=1}^{n}\left(\frac{d_0^2}{2}\right)+\sum_{i=0}^{n}\left[\left(d_0 d_1\left[\frac{c_i-c_{i-1}}{2}+c_{i-1}\right]\right)+\sum_{i=1}^{n}\frac{d_1^2}{2}\left(\frac{(c_i-c_{i-1})^2}{3}+c_{i-1}^2+(c_{i+1}-c_{i-1})c_{i-1}\right)\right]\right] \quad (1)$$

where L is the length of the affected area during the impact, C_i the resulting deformation values, measured in perpendicular directions to the impact and at constant distances. The rigidity coefficients, d_0 and d_1, are extracted from the tables defined by the NHTSA (National Highway Traffic Safety Administration), according to the vehicle data sheet and the impact.

Complementary to this energy analysis, a force and directional analysis was carried out. As a result, a complete spatial definition (with spatial and angular position) of the different vehicles involved in the accident can be generated. In this sense, the general 3D reconstruction, obtained by the proposed methodology, allows the extraction of essential and basic measurements for accident evaluation.

3. Experimental Results

With the aim to validate the presented methodology, a study case was evaluated in the facilities of the Public Security Academy of Extremadura (APEX), Badajoz (Spain) in March 2014. This road accident was materialized by expert agents and confiscated vehicles (property of the local police of Extremadura). Complementary to the image acquisition, a video was recorded during the accident [32].

3.1. Data Acquisition Protocol

During the simulated accident, two vehicles were used: a Nissan Serena 1.6 SLX and a Fiat Scudo Combi, whose technical specifications are shown in Table 3. The accident was a frontal crash of the Nissan Serena against the side of the Fiat Scudo, which was placed motionless in a fixed position. After the collision between the vehicles, they both moved to their final positions, shown in Figure 4. The direction of the main impact force was straight without angular components, as shows the video [32].

Table3. Properties and category of the used vehicles in the simulated accident.

Vehicle	Wheelbase	Length	Width	Track	Weight	NHTSA Category
Nissan Serena SLX	2.735 m	4.320 m	1.695 m	1.463 m	1480 kg	3
Fiat Scudo Combi	3.000 m	4.800 m	1.900 m	1.574 m	1722 kg	4

The data acquisition, following the protocol detailed in Section 2.3.1, was divided in two groups (Figure 5): (i) a general model, with a total of 65 images captured by the Olympus EPM-2 camera, which represents the complete accident scenario, considering the convergent protocol; and (ii) detailed models of the vehicles (in the impact area), acquired through the Smartphone Nokia Lumia 1020; following a parallel protocol. There was no special reason for using these sensors, just the interest of the local police to use consumer-grade digital cameras. Regarding data acquisition time, approximately 10 min were required to acquire the whole dataset of images.

Figure 4. Final position of the crashed vehicles involved in the simulated accident. It can be appreciated (between both cars) the metallic scale bar used for providing metric capabilities to the photogrammetric reconstruction.

3.2. Photogrammetric Processing

The originality of the method lies in the energy analysis of road accidents using dense point clouds generated from photogrammetry 3D modeling. Considering this, only the most significant photogrammetric steps will be described.

Firstly, the captured images were pre-processed through the Wallis filter using as input parameters: (i) 0.5 for the contrast; (ii) 1 for the brightness; (iii) a standard deviation of 50; and (iv) a kernel size of 2%, which depends on the image radius. As a result a new image set was obtained (Figure 6).

Figure 5. **(Left)** Images captured with the consumer-grade digital camera Olympus EPM-2 following a convergent protocol. **(Right)** Images obtained through a Nokia Lumia 1020 smartphone with a parallel protocol.

Figure 6. Results obtained for the Wallis filter.

Later, during the keypoint extraction and matching, a total of 500 points were matched with a 35% of outliers for the convergent protocol (general model). Meanwhile, for the parallel protocol (detailed models), 1700 keypoints were matched with a 17% of outliers for the Nissan Serena and 2900 keypoints were matched with a 10% of outliers for the Fiat Scudo. Some keypoints and matching results are outlined in Figure 7.

There are a notably higher number of outliers (35%) for the general point clouds in comparison to the detailed ones (17% and 10%). This higher number of outliers for the general point cloud is due to the complexity of the scene, which involves the background as well as several objects and people in movement (e.g. police officers). It is also remarkable that the reconstruction of the Nissan Serena 3D point cloud displayed a higher number of outliers (17%) with a lower number of extracted keypoints (1700) in comparison to the Fiat Scudo 3D point cloud (with a 10% and a 2900 respectively). This phenomenon is related with the surface captured, being more homogenous and adverse in the first case.

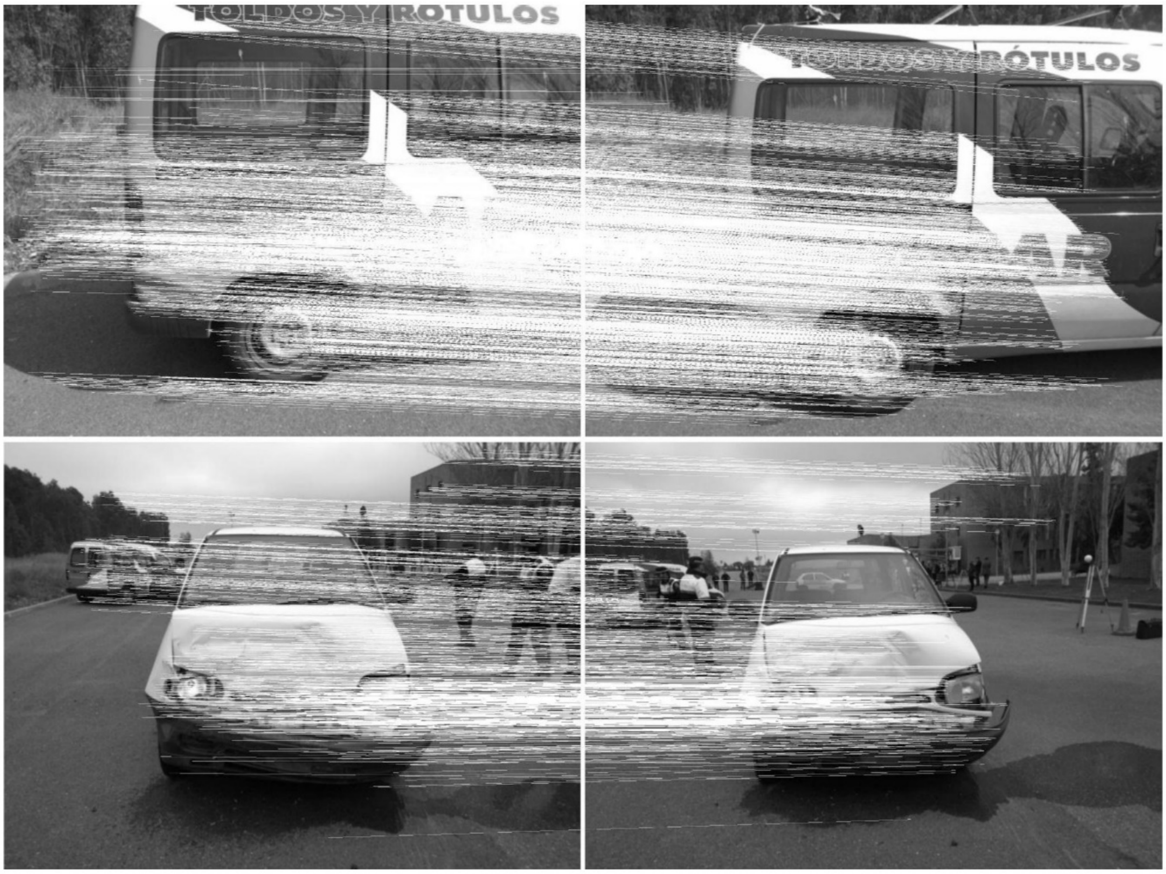

Figure 7. Keypoint extraction and matching through the ASIFT detector and the SIFT descriptor.

Concerning the external orientation, a standard deviation of 0.64 pixels was obtained for the convergent protocol, whereas 1.09 pixels and 0.80 pixels were obtained using the parallel protocol for the Nissan Serena and for the Fiat Scudo, respectively. It is worth noting that a worse adjustment was obtained for the Nissan Serena due to its previously-described unfavorable radiometric properties together with its weak geometry (five images with less convergence than those acquired for the Fiat Scudo). Additionally, the adjustment of the general model (with more complexity) has obtained remarkably better results than those obtained for the detailed models due, in part, to the quality of the camera (Olympus EMP-2 *versus* Nokia Lumia 1020) and the better geometry of the convergent network. Both sensors were self-calibrated following a basic calibration model where internal parameters such as focal length, principal point and radial (K_1 and K_2) distortion were introduced in the adjustment. In order to check the validity of the calibration model, we have performed several self-calibration tests comparing also different calibration models using rotated and non-rotated images, obtaining non-significant differences in terms of accuracy of the final photogrammetric model.

Once the external orientation of the cameras (bundle adjustment) was obtained, it is possible to reconstruct the scene of the accident through the dense matching strategy defined in Section 2.3.5. As a result, a dense 3D point cloud was obtained for the scene (general point cloud) and for the damage areas (detailed point clouds) (Figure 8). Regarding the spatial resolution, the general point cloud shows a density of approximately twice the Ground Sample Distance (GSD) of the Olympus camera (10mm), with a total number of 3,815,302 points. Furthermore, the detailed point clouds show a similar density (two times the GSD of the smartphone camera) with a value of 1.4 mm and a total of 531,700 points for Nissan Serena and 800,006 points in the case of Fiat Scudo. Both GSD were always referred to the cars. In the convergent case car positions represent more or less the centroid of the ring, whereas in the parallel case they represent the interest part for the deformation maps estimation.

Regarding the scaling, two different objects were used for providing metric results: (i) a magnetized target (20 cm) used for scaling the detailed point clouds of the damages; (ii) a metallic scale bar (1 × 1 × 1 m) used for scaling the general scene of the accident. Figure 4 shows the location of the metallic scale bar. Just, one scale bar was used for the scaling although several artificial targets (yellow targets in Figure 4) were put around the scene in order to check the scaling accuracy.

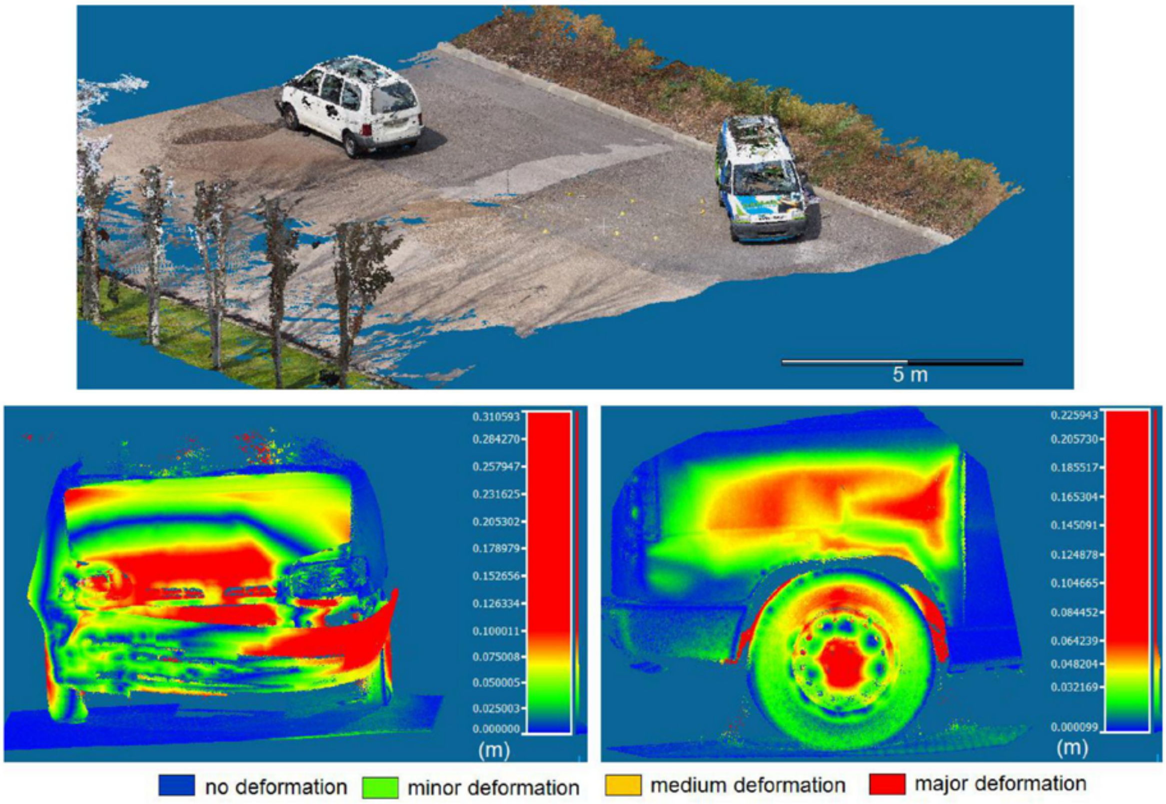

Figure 8. 3D point clouds obtained by the proposed methodology. (**Top**) General point cloud performed with a convergent protocol. (**Bottom**) Detailed deformation point cloud reconstructed with a parallel protocol.

The accuracy of the proposed methodology was contrasted with the data provided by a terrestrial laser scanner (Faro Focus 3D). The scans were acquired with a resolution of 3 mm for an average distance of 10 m seven scans were required to cover the whole road accident (including detailed damages). Each scan was setup with RGB color requiring five minutes per scan, so more than 45 min were required to complete the scene. This evaluation was carried out through a comparison of different measurements around the general point cloud (using previously placed yellows targets) and an analysis of the vehicles deformations. As a result, average discrepancies around 2 cm were obtained for the general point cloud, whereas average discrepancies of 5 mm were obtained for the vehicles deformations.

It is remarkable that the scaling procedure (required for the photogrammetric point cloud) depends on the user's skill, yielding greater errors than the GSD. Nevertheless, the discrepancy values obtained in both analyses (general point cloud and deformation maps) could be considered valid for the energy analysis of road accidents.

Validated the results, the previously obtained point clouds and their deformations maps were used for the energy analysis of the road accident. This analysis allows the evaluation of the different energies involved in the study (i.e. deformation, rolling resistance, and rotational energies).

3.3. Energy Analysis of the Accident

It is observed that the evaluation of the impact speed (Nissan Serena vehicle), based on the skid marks approach, was not possible since there are not evidences of them on the scenario. According to this, a complementary procedure was used, based on the kinematic energy during the accident. This approach evaluates three types of energy, namely: (i) deformation energy, E_d, absorbed by the vehicles involved in the accident; (ii) rolling resistance energy, E_{rr}, needed to stop the Nissan Serena; and (iii) rotational energy, E_r, needed to move the Fiat Scudo until its final position.

For the evaluation of the absorbed energy through the structural deformation suffered by the involved vehicles, the Prasad method described in Section 2.3.6 was used. The values of the unknowns L and C_i (Equation (1)) have been obtained from the 3D deformation point clouds. Thanks to the accuracy of the deformation point clouds, it was not necessary to establish a reference line with complementary measurements (which is a common step in the classical Prasad's approach). The results are shown in the following Table 4.

Table4. Energy deformation results.

Vehicle	L	C_1	C_2	C_3	C_4	C_5	C_6	d_0	d_1	E_d
Nissan Serena SLX	1.62 m	0.05 m	0.1 m	0.12 m	0.11 m	0.05 m	0.03 m	89.31	621.16	14011.56 J
Fiat Scudo Combi	1.05 m	0.02 m	0.04 m	0.06 m	0.05 m	0.06 m	0.03 m	42.64	586.94	3787.23 J

For the analysis of the Nissan Serena rolling resistance energy (E_{rr}), the following Equation (2) was applied.

$$E_{rr} = m \cdot g \cdot d \cdot c_{rr} \quad (2)$$

where m is the vehicle mass, g the gravity, d the distance covered by the vehicle after the impact and c_{rr} the rolling resistance coefficient.

It is remarkable that, in cases where the skid marks do not exist, the application of the rolling resistance coefficient replaces the friction coefficient, since friction coefficient refers to two surfaces which slide between them (as occurs in cases where the wheel is blocked).

For the present case study and, thanks to the density and accuracy of the obtained 3D point cloud (Figure 8 top), it is possible to evaluate the distance covered by the vehicle (Nissan Serena) after the impact, obtaining a value of 16 m.

Considering the obtained results and the technical data of the vehicle (Nissan Serena) (Table 3), it is possible to determine the rolling resistance energy, E_{rr}, with a value of 6969.02 J.

In order to evaluate the rotational energy, E_r, of the Fiat Scudo the Equation (3) was applied, which considers the eccentric forces acting on the vehicle:

$$E_r = m \cdot g \cdot (\mu \pm p) \cdot \alpha \cdot \frac{1}{2} b \tag{3}$$

where m is the vehicle mass, g the gravity, μ the coefficient of adhesion, p the road slope expressed in parts per unit, α the rotational angle of the vehicle (in radians), and b the vehicle wheelbase.

In this case, a vehicle turning angle of 121° has been determined using the general 3D point cloud. The road slope is 0%. The coefficient of adhesion between tires and asphalt (in normal circumstances) is 0.6. Based on these values and considering the technical data of the Fiat Scudo, shown in Table 3, the rotational energy, E_r, determined was 32107.50J.

Through the previously evaluated energies, it is possible to obtain the impact speed, V_i, of the Nissan Serena, as the sum of the calculated energies (Equation (4)).

$$V_i = \sqrt{\frac{2 \cdot (E_d + E_r + E_g)}{m}} \tag{4}$$

where the impact speed, V_i, is a result of the correlation between deformation, rolling resistance and rotational energies (previously obtained) and the vehicle mass.

According to the previously obtained values, the vehicle had an impact speed of 31.55 km/h. This computed speed was compared with the actual impact speed recorded and reported by the Local Police in the expert report being of 32 km/h.

4. Conclusions

This article shows the potential offered by the combination of photogrammetric procedures and energy analysis in the evaluation of road accidents, which usually exhibit geometric and radiometric complexity from a photogrammetric point of view. In relation to the former the network configuration of the cameras together with the object points used to provide weakness for cameras orientation. In relation to the latter, the different illumination conditions and the car texture could weaken the matching results. The proposed methodology guarantees automatism (in the 3D point cloud reconstruction), flexibility (feasible with conventional non-calibrated cameras and smartphone sensors), accuracy (with more precise results that those obtained by classical procedures). In order to validate the methodology, it was applied in a simulated case study. It is worth mentioning that the presented strategy is being used by the local police of Salamanca through a research agreement. One of the most representative contributions of this paper is the integration of photogrammetric results (by means of distances, angles and deformations) with dynamic analysis of road accident parameters (especially speed impact). To this end, metric deformation maps have been generated based on photogrammetric point clouds which exhibit the degree of deformation, very useful for consideration in the Prasad method described in Section 2.3.6.

Further investigations regarding experimental tests will be focused on including a low-cost device that monitors the acceleration and speed of the vehicle, as well as to test the approach proposed at night time using artificial light. Regarding the photogrammetric method a clear future milestone will be the improvement of the scaling procedure (which is strongly influenced by the user's skill) through the use of recognition algorithms for the identification of artificial targets and the metallic scale bar. This should help to develop an automatic procedure able to obtain 3D point clouds with metric properties. Furthermore, the future use of point cloud filters will be considered with the aim of reducing the noise of the obtained 3D point cloud in cases where the vehicles exhibit highly specular surfaces or variable reflections.

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Author Contributions

All of the authors conceived of and designed the study. Diego Gonzalez-Aguilera setup the case of study and proposes the photogrammetric methodology. Alejandro Morales performs the energetic analysis of the road accident defined in the article. Miguel A. Gutiérrez and Alfonso I. López study the road accident numerically and also contributes in the experimental campaign. Diego Gonzalez-Aguilera, Alejandro Morales, Miguel A. Gutiérrez and Alfonso I. López write the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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3.3. Un nuevo enfoque para el cálculo energético en accidentes de tráfico contra elementos fijos de pequeña sección basado en fotogrametría de corto alcance

La publicación científica recogida en este apartado es una continuación de la línea de investigación iniciada en la publicación anterior. En ella se presenta una versión mejorada del enfoque fotogramétrico propuesto anteriormente. Así mismo, se plantea una mejora en la aplicación de los métodos de análisis energético en los accidentes contra elementos fijos de pequeña sección, basada en el uso de una herramienta software desarrollada (CRASHMAP) que permite una mayor precisión geométrica en las medidas necesarias para aplicar el método.

Los accidentes de tráfico contra elementos fijos de pequeña sección son uno de los más comunes según el EuroRAP (Programa Europeo de Evaluación de Carreteras). Los métodos de análisis energético que se emplean en este tipo de accidentes dependen en gran medida de las deformaciones sufridas por los vehículos, por lo que resulta determinante la precisión métrica de las deformaciones.

Ante la aparición de ciertos problemas en la metodología presentada en el artículo anterior en lo relativo a la reconstrucción fotogramétrica de escenas con reflejos o zonas de colores uniformes, esta se ha mejorado gracias a la utilización de la herramienta software de código abierto GRAPHOS (inteGRAted PHOtogrammetric Suite) (Gonzalez-Aguilera et al., 2016) que aporta novedades tales como: (i) la extracción de puntos clave aplicando el algoritmo AMSD (Affine Maximum Self-Dissimilarity) que detecta puntos clave en escenas desfavorables, (ii) el uso de una versión mejorada de la norma euclídea L2 que permite obtener mejores resultados en la etapa de emparejamiento, y (iii) un filtrado espacial en la etapa de orientación y autocalibración de la red fotogramétrica que garantiza una distribución homogénea de los puntos clave a lo largo del sensor de la cámara. Todo ello hace posible la reconstrucción de escenas desfavorables e introduce importantes cambios radiométricos y geométricos sin necesidad de usar etapas de pre-procesamiento.

Del mismo modo, y con el fin de ofrecer una herramienta de asistencia a las Fuerzas de Seguridad para la creación de nubes de puntos 3D y la aplicación de diferentes métodos de análisis energético a partir de estos modelos, se ha desarrollado CRASHMAP, una herramienta software compuesta de:

- Una aplicación en la nube (CRASHMAP_cloud) que realiza la reconstrucción fotogramétrica de los vehículos accidentados a partir de las imágenes tomadas por los agentes y algunos parámetros básicos sobre la cámara y las medidas tomadas (para escalar el modelo), dando como resultado un modelo 3D robusto y preciso.
- Una aplicación de escritorio (CRASHMAP_desktop) que permite al usuario evaluar las deformaciones sufridas por los vehículos a través del análisis de los modelos fotogramétricos en 3D generados por CRASHMAP_cloud y aplicar diferentes métodos de análisis energético a partir de dichas deformaciones.

Como ya se indicó en el artículo anteior, uno de los principales inconvenientes que presentan los métodos tradicionales de análisis energético es que emplean protocolos expeditos basados en mediciones manuales realizadas en el lugar del accidente. Del mismo modo, no tienen en consideración la geometría real del vehículo a la hora de tomar las medidas. Estos aspectos pueden dar lugar a medidas erróneas o poco precisas. CRASHMAP_desktop tiene en consideración la geometría original del vehículo gracias a la posibilidad de comparar el modelo original del vehículo sin accidentar con el del vehículo accidentado, lo que permite generar un histograma de deformaciones.

De los numerosos métodos de análisis energéticos existentes, el de Wood (Wood, Doody, & Mooney, 1993) es considerado uno de los más sofisticados y robustos para la tipología de accidentes contra elementos fijos de pequeña sección. Hemos utilizado este método para realizar un estudio comparativo, en un accidente real, de un vehículo contra el pilar de acero de una marquesina publicitaria. La aplicación de este método requiere medir la deformación máxima sufrida por el vehículo, algo que mediante técnicas de medición manual no siempre resulta sencillo ni preciso. Del mismo modo, requiere determinar la deformación media sufrida en la zona deformada a partir de un mínimo de 2 medidas equidistantes y un máximo de 6. En ambas mediciones existe una simplificación de la geometría deformada ya que las medidas se toman desde una línea imaginaria de referencia.

Este estudio ha servido para determinar la diferencia existente entre aplicar el método de Wood siguiendo el protocolo de medición manual y sin considerar la geometría real del vehículo, y la aplicación del mismo teniendo en consideración esta, mediante la obtención de las medidas por la comparación de los modelos 3D del vehículo accidentado y sin accidentar (utilizando CRASHMAP). Los resultados obtenidos han permitido poner de manifiesto cómo la falta de precisión en la toma de medidas y de consideración de la geometría del vehículo afectan a los resultados de estimación de la velocidad de impacto.

remote sensing

MDPI

Technical Note

A New Approach to Energy Calculation of Road Accidents against Fixed Small Section Elements Based on Close-Range Photogrammetry

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Abstract: This paper presents a new approach for energetic analyses of traffic accidents against fixed road elements using close-range photogrammetry. The main contributions of the developed approach are related to the quality of the 3D photogrammetric models, which enable objective and accurate energetic analyses through the in-house tool CRASHMAP. As a result, security forces can reconstruct the accident in a simple and comprehensive way without requiring spreadsheets or external tools, and thus avoid the subjectivity and imprecisions of the traditional protocol. The tool has already been validated, and is being used by the Local Police of Salamanca (Salamanca, Spain) for the resolution of numerous accidents. In this paper, a real accident of a car against a fixed metallic pole is analysed, and significant discrepancies are obtained between the new approach and the traditional protocol of data acquisition regarding collision speed and absorbed energy.

Keywords: road accidents; impacts with fixed objects; pole impact; computer vision; photogrammetry; software development

1. Introduction

Traffic accidents are one of the most common causes of mortality in the world. More than 1.2 million lives are lost each year, which costs affected countries around 3% of their gross domestic product (GDP) [1]. Commonly, the evaluation of these accidents is carried out through methods of energetic analyses [2–4] that have significant sources of error, which include: (i) geometrical errors derived from the data acquisition protocol; (ii) mathematical errors derived from the linear relation between force and deformation; and (iii) road–car interactions, such as the presence of frictional forces.

These geometrical errors are the result of traditional methods of data collection such as Campbell's [2], McHenry's [3] and Prasad's [4], which rely on expedited measurements taken manually in the field. These measurements are then inserted into mathematical equations to measure the collision speed and energy transformed during accidents. These measurements are obtained through a discrete manual strategy that uses measuring tapes and plummets, as well as an idealization of the reference geometry (an undamaged vehicle). As a result, errors are introduced that worsen the accuracy of the obtained results, which is a critical problem for the court and judicial cases that assign responsibilities for speeding on urban roads.

According to the European Road Assessment Program (EuroRAP), the three most common types of traffic accidents are: (i) run-off road collisions; (ii) front–rear impacts; and (iii) side impact accidents at intersections. Currently, local and national authorities pay particular attention to road accidents against fixed and rigid elements (e.g., natural trees or artificial steel poles). The complex deformation suffered by the car along the contact area can induce errors of up to 30% in the linear mathematical models [5]. It should be noted that errors in measurements taken in the field can increase this deviation. A lack of consideration of the frictional forces involved also introduces great discrepancies between the computed collision speed and its real value.

From a mathematical point of view, several authors have investigated traffic accidents against rigid elements through the use of the equivalent barrier speed (*EBS*) [6,7]. This index was initially proposed by the National Transportation Safety Board (NTSB) in 1981 [8] for the evaluation of traffic accidents against trees, using the following three factors: (i) the maximum deformation on the impact area; (ii) the collision speed at which the rigid element does not suffer any deformation; and (iii) the linear relation between the collision speed and the deformation suffered by the vehicle. This equation was later extended to poles made with wood, including the dimensions of the pole, the vehicle's mass, the maximum deformation suffered by the vehicle, and the absorbed energy as variables [9]. Since this equation did not take into account the energy absorbed by the pole, Nystron and Kost [10] proposed a new formula for the energetic analysis of traffic accidents against rigid elements based on the relation between the mass of the vehicle, the maximum deformation suffered by the car, and two empirical constants derived from a total of 19 tests carried out with rigid steel poles [10]. Parallel to this, Vomhof [11] proposed a new approach for the evaluation of the *EBS* based on a minimum speed equation. This equation related the deformation suffered by the vehicle to a drag factor (derived from the crush of the vehicle in the impact), and also included a correction factor that depended on the properties of the pole (rigid or not) [11]. This drag factor was obtained from an experimental campaign that involved a total of 1000 study cases. In 1993, Craig [12] developed a new equation for the analysis of this type of accident. This formula related the maximum deformation suffered by the vehicle to its size through using results provided by 49 frontal accidents against poles. However, if the accident implied an eccentric collision due to the rotation of the car, this equation's results could underestimate the real effects [12]. Parallel to Craig, Wood et al. (1993) [5] developed a more realistic model for traffic accidents against rigid elements based on a total of 202 tests that involved the impact of a vehicle against a rigid element. Wood et al. concluded that the energy absorbed during the traffic accident was proportional to the mass of the vehicle and the normalised crushing distance through using measurements taken in the field, as well as two experimental coefficients that depend on the deformation and length of the vehicle [5].

Wood's method has been considered the most sophisticated and robust model for the study of traffic accidents against fixed elements. As a result, data acquisition protocol is manual and expedited, which can entail the presence of large deviations and thus large discrepancies between the computed collision speed and its real value. Authors such as Luhmman et al. (2006) [13] and González-Aguilera et al. (2013) [14] among others, have proposed the use of photogrammetric approaches in order to estimate the deformation suffered by the vehicle after the traffic accident. This type of approach requires the use of metric cameras and/or coded targets for the external orientation of the photogrammetric network [13–15]. Recently, Morales et al. (2015) [16] have proposed the use of a motion approach for the energetic analysis of traffic accidents that combines the advantages offered by computer vision (automation and flexibility) and photogrammetry (accuracy and reliability). This combination obtains accurate 3D digitalisations of both damaged cars and their deformations, which enables accurate estimations of collision speed [16].

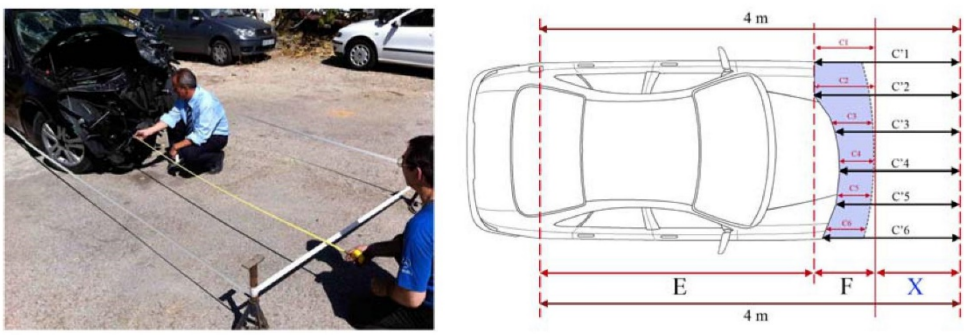
This paper extends this research [16] through focussing on accidents against small rigid elements, with special emphasis on the geometrical errors that arise from the traditional protocols. Additionally, this paper introduces an enhanced version of the photogrammetric approach proposed previously by Morales et al. (2015) [16]. Enhancements relate to the extraction of key points and the orientation and self-calibration of the photogrammetric network. For the former, the affine maximum self-dissimilarity (AMSD) algorithm is introduced. The aim of the AMSD algorithm, a novel detector, is to detect key points in unfavourable scenes characterised by important geometric and radiometric changes. An enhanced and robust version of the traditional L2-Norm (Euclidean Norm) is used as a complement to obtain better results in the matching stage. As for orientation and self-calibration, the proposed methodology includes a spatial filtering that ensures a homogeneous distribution of the key points along the camera's sensor. This will guarantee more reliable results during the resolution of the bundle adjustment of the photogrammetric network.

Within this context, the paper has been organised as follows: Section 2 describes in detail the method proposed for the evaluation of traffic accidents against rigid poles; Section 3 defines CRASHMAP, the in-house tool developed; Section 4 shows the experimental results after applying the proposed method, and compares them with those obtained by the traditional approach; and finally, Section 5 summarises the conclusions arising from the use of the proposed method, as well as suggestions for future research.

2. Energy Analysis of the Accident in Impacts against Fixed Elements

2.1. Data Acquisition

Traditional methods such as those developed by McHenry et al. [3] and Wood et al. [5] have proposed the use of expeditious protocols based on manual measurements taken in the field. These procedures are highly dependent on the operator's skills [15], as they require the use of complex tools for data acquisition (Figure 1a) and a high user intervention. These methods also depend on an idealisation of the vehicle's geometry in order to obtain referenced measurements (Figure 1b). In the case of frontal accidents against rigid elements, this idealisation includes marking a line on the asphalt parallel to the rear axle of the car, at a distance from the deformed shape of the vehicle, for which all of the measurements are positive (Figure 1b). Once the reference line is placed, the user needs to take a total of two, four, or six measurements, in which the first and the last measurement should be in line with the lateral limits of the vehicle (Figure 1b). The number of measurements considered for the energetic analysis are dependent on the width of the vehicle, using a minimum of six measurements for widths over 60 cm [5].



(a) (b)

Figure 1. Classical protocol: (**a**) procedure used to take the measurements, and (**b**) graphical representation of the measurements considered during the energetic analysis.

From the measurements taken, C_n, it is necessary to deduce the distance between the reference line considered and the hypothetical position of the car's front without deformation (X). This value can be obtained from Equation (1):

$$X = D - [E + F] \tag{1}$$

where X is the distance between the reference line and the front of the vehicle without any deformation, D is the distance between the reference line and the rear axle of the vehicle, E is the vehicle's wheelbase, and F is the distance between the front axle and the front of the vehicle. The last two variables, E and F, can be obtained from the technical specifications of the vehicle.

As can be observed, the method does not consider the real geometry of the car. The measurements reference a horizontal line parallel to the rear axle of the vehicle, which is an element that can be damaged as a result of the impact. These measurements are taken at the height of the car bumper, which requires the use of several tools such as a measuring tape, a plummet, or ropes (Figure 1a).

The limitations of this method relate to the introduction of geometrical errors from the idealisation of car's geometry, the limited number of measurements used to define the deformation, and human errors during the data acquisition. A simple photogrammetric protocol can address these limitations. This protocol has been designed to assist non-expert users in this type of data acquisition through using conventional cameras or even smartphones. In particular, the user only needs to focus on the part of the vehicle that has suffered the impact with the fixed object, and capture between five and nine images following a cross shape, as shown (Figure 2). The overlap between adjacent images needs to be at least 80%. The master image or central image will capture the area of interest. The remaining photos (between two and four images) are complementary, and should be taken above, below, and to the left and right of the central image. These photos should adopt a certain degree of perspective, turning the camera towards the middle of the interest area. This perspective enables the reconstruction of the surroundings parts of the vehicle without deformation.

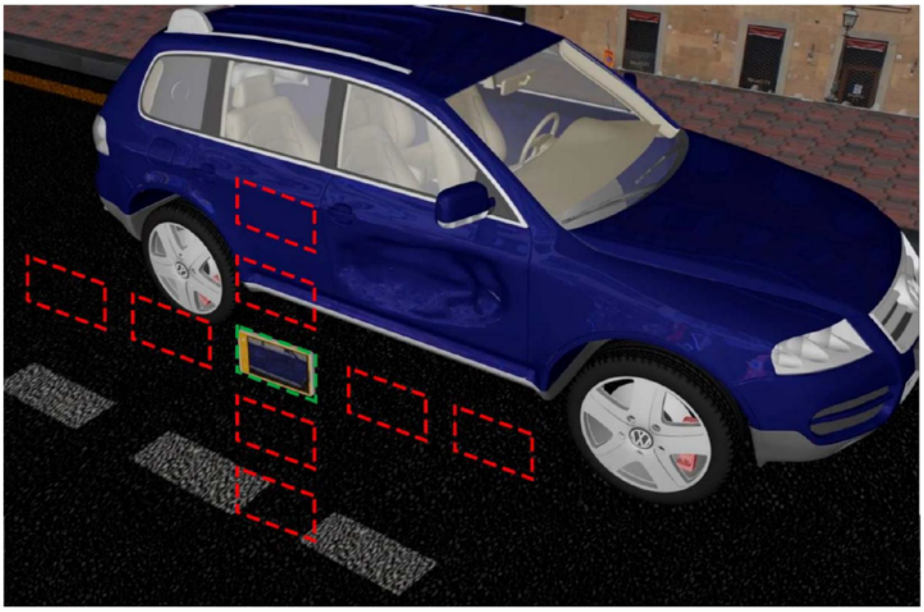


Figure 2. Photogrammetric data acquisition protocol based upon capturing between five and nine images of the part of the vehicle that has suffered an impact. The master image is in green, and the complementary photos are in red.

2.2. Photogrammetric Processing

The photogrammetric processing was performed using the GRAPHOS open source tool (inteGRAted PHOtogrammetric Suite) developed by Gonzalez-Aguilera et al. (2016) [17] (available at https://github.com/itos3d/GRAPHOS). More details about the tool and the implemented photogrammetric workflow can be found in González-Aguilera et al., (2016) [17].

Next, the most representative novelties of the photogrammetric workflow are compared with those previously developed for the analysis of accidents [16], and improvements in feature extraction, matching, and orientation steps are highlighted.

2.2.1. Feature Extraction

A new detector, the affine maximal self-dissimilarity (AMSD) algorithm, was used to extract key points on the different images acquired. This algorithm can be considered a variant of the maximal self-dissimilarity (MSD) detector developed by Tombari and Di Stefano (2014) [18], as it includes the same main perspective and geometric parameters.

The MSD detector relies on a saliency operator, $\mu^{(k)}$ (Equation (2)), which measures the contextual self-dissimilarity of a point, p, i.e., how much the patch around p is dissimilar from the most similar one in its surroundings, which in this case is the patch around a point, q. The terms p and q denote the pixel centre belonging to the patches under comparison:

$$\mu^{(k)}(p, p_\omega, p_a) = \frac{1}{{p_\omega}^2 \cdot k} \sum_{i=1}^{k} \delta^i(\omega(p, p_\omega), \omega(q, p_\omega)) \quad (2)$$

where p_ω and p_a define the size of the patches under comparison, and the size of the area from which the patches are drawn, respectively. $\omega(p, p_\omega)$ denotes the operator defining a square image region centred at pixel p with a size equal to p_ω pixels, while k is the number of neighbours considered during the computation of $\mu^{(k)}$, and δ^i denotes the distances between the vectors collecting the intensities of two equally-sized image patches, similar to the squared $L2$ distance.

It should be noted that p_a defines the spatial support (local or global) of the saliency criterion. In our case, we replace the local self-dissimilarity that is usual in the most popular interest point detectors in photogrammetry (e.g., Förstner operator based on a 1-nearest neighbour (1-NN) search problem) with a contextual self-dissimilarity notion. As a result, the most similar patch among a set of candidates can be interpreted as a search of k-NN nearest neighbours, through estimating the minimum as the average across the k most similar patches. The parameter k provides distinctiveness and computational efficiency for repeatability and accurate localisation in noisy conditions, since the classical 1-NN search is potentially prone to noise, which could induce considerable variations in saliency scores, and thus hinder an accurate detection of salient points.

Through Equation (2), we determine a saliency map that encloses the dissimilarity of the patch centred at each pixel with respect to the surrounding area. In order to provide a more independent score of the patch size, p_ω, about the saliency, a normalisation by means of the number of pixels involved in the computation of the self-dissimilarity is considered.

However, while MSD performs well with radiometric changes (multimodal matching), the new AMSD algorithm also includes the main perspective geometric parameters, i.e., the angles defining the camera axis orientation (ϕ, θ). In this manner, the AMSD algorithm can find maximal self-dissimilarities in images that have a high scale and rotation difference, which is common in close-range scenes of road accidents. The result is an invariant detector that supports the hypothesis that image patches that are highly dissimilar over a relatively large extent of their surroundings hold the property of being repeatable and distinctive.

This result provides the next expression:

$$A_F = \begin{bmatrix} a & b \\ c & d \end{bmatrix} = H_\lambda R_1(\psi) T_t R_2(\phi) = \lambda \begin{bmatrix} cos\psi & -sin\psi \\ sin\psi & cos\psi \end{bmatrix} \cdot \begin{bmatrix} t & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} cos\phi & -sin\phi \\ sin\phi & cos\phi \end{bmatrix} \quad (3)$$

where $\mathbf{A_F}$ is the affinity transformation that contains scale, λ, which is related to the zoom parameter; and ψ controls the camera rotation angle around the optical axis. This angle does not generate perspective; ϕ controls the longitude angle between the optical axis and a fixed vertical plane; θ = arccos $(1/t)$ controls the latitude angle between the optical axis and the normal to the image plane. Tilt: $t > 1$; $\theta \in [0°, 90°]$. (ϕ, θ) control the perspective geometric parameters that correspond to the inclination of the camera optical axis.

Equation (3) comes from the singular value decomposition (SVD) of an affine map, and is based on the work of Morel and Yu [19], in which the second eigenvalue is set equal to one, and the first (variable t) has to be higher than one. The translations are dismissed by assuming (without loss of generality) that the camera axis meets the image plane at a fixed point [19].

Equation (3) is combined with Equation (2) following the same strategy established by Morel and Yu, (2009) [19]; that is, Equation (3) allows us to generate different viewpoints (transition tilts), which are employed to feed the MSD detector (Equation (2)). In particular, different transition tilts are generated to support the affine transformations. The images are transformed to simulate changes in the camera optical axis. These simulations are carried out by latitude (θ) and longitude (ϕ) rotations. The t (tilt) variable controlled by the user is employed to set, firstly, the longitude (ϕ) rotations defined as 72°/t, and secondly, the latitude rotation as $t = 1/\cos(\text{latitude}(\theta))$.

2.2.2. Robust Matching

Once the key points are extracted, a matching strategy should be applied to identify identical points between images. To this end, a robust matching approach was incorporated that provides considerable improvements in comparison with the classical L2-norm (Euclidean norm) matching strategy [20], or even the efficient FLANN (fast library for approximate nearest neighbours) strategy [21], independently from the protocol followed in data acquisition.

The robust matching approach applies a brute force matching strategy based on L2-norm distance but adding a twofold filtering process. The idea for implementing the sequential twofold process is to get the best matches, and avoid those that provide worse quality and possible outliers.

- First, for each extracted point, the *distance ratio* between the two best candidates in the other image is compared with a threshold. If a high distance ratio is obtained, the match could be ambiguous or incorrect. According to the probability distribution function defined by Lowe (2004) [22], a threshold >0.8 provides a good separation among correct and incorrect matches. The greater the ratio value, the greater the amount of matched points, and thus the presence of outliers.
- Second, those matches that overcome the ratio test are filtered by a threshold K, accepting only the matches for which the difference in descriptors is below K. To this end, the descriptors distances are normalised in the range [0,1], and the computation of the threshold K is established by multiplying the maximum descriptor distance for a factor between 0 and 1. The matches' pairs whose distance is greater than the threshold K are rejected. A $K = 1$ factor implies that no refinement is done (all matches are kept).

2.2.3. Images Orientation and Self-Calibration

As result, the final set of valid correspondences is used to compute the relative orientation (fundamental matrix) between image pairs. Previously, the final image correspondences are filtered and assessed by a camera´s sensor assistant, which graphically checks the spatial distribution of interest points along the camera sensor. An asymmetric distribution of the key points will negatively affect the correct determination of image orientation and the camera's self-calibration parameters, as well as increase the computation time. Therefore, if the matching points do not cover an area of more than two-thirds of the camera sensor format, the user will be alerted in order to modify the detector and matching parameters. Once the camera´s sensor spatial filtering has been applied, the images are oriented and self-calibrated through a bundle adjustment based on collinearity conditions [23]. This iterative adjustment can be performed with internal constraints (i.e., free network), or with external constraints (e.g., known distances or ground control points).

2.3. Energetic Analysis of Pole Impacts

As for energetic analysis, Wood's method [5] was used to evaluate the energy absorbed by the car during the pole impact. This model relates the energy absorbed with the normalised deformation experienced by the vehicle. This is calculated using the following expression:

$$\frac{E_a}{m_T} = A\left(\left(\frac{D_{med}}{D_{max}}\right)Ln\left(\frac{1}{\left(1-\frac{D_{max}}{L}\right)}\right)+B\right) \tag{4}$$

where E_a is the energy absorbed by the car, m_T is the total weight of the car (including passengers), and A and B are empirical coefficients obtained by Wood [5] (Equations (5) and (6)), while D_{med} is the average deformation, obtained from two, four or six measurements, and D_{max} is the maximum deformation suffered by the vehicle.

$$\text{If } \frac{D_{med}}{D_{max}}\text{Ln}\left(1-\frac{D_{max}}{L}\right)^{-1} < 0.05 \qquad A = 537 \text{ and } B = 0.00072 \tag{5}$$

$$\text{If } \frac{D_{med}}{D_{max}}\text{Ln}\left(1-\frac{D_{max}}{L}\right)^{-1} > 0.05 \qquad A = 1191 \text{ and } B = 0.0235 \tag{6}$$

where L is the length of the car.

Once the energy of deformation has been obtained in Equation (4), it is possible to calculate the *EBS* through the application of the following expression, Equation (7):

$$EBS = \sqrt{\frac{2E_a}{m_T}} \tag{7}$$

Finally, the collision speed, V_{col}, is obtained through Equation (8). During this analysis, it is necessary to consider the presence of eccentricity (collision for which the longitudinal axis is not aligned with the contact surface generated between the car and the rigid element). In this case, the presence of eccentricity is corrected through the vehicle's mass, according to the expression proposed by Wood et al. [5], which is shown in Equation (8):

$$V_{col} = \left(\frac{m_T}{m_S}\right)EBS \tag{8}$$

where m_s is the weight of the car, and m_T is the total weight (considering the weight of the car and its occupants):

$$m_{se} = m_s\left(\frac{k_r^2}{k_r^2 + D^2{}_{cent}}\right) \tag{9}$$

where m_{se} is the corrected mass of the vehicle, k_r is the horizontal pivot radius, and D_{cent} is the orthogonal distance between the action line of the principal impact force and the gravitational center of the vehicle.

For the pivot radius, the following expression can be used:

$$k_r^2 = 0.931 \frac{\left(L_f{}^2 + L^2\right)}{12} \quad (10)$$

where L_f represents the width of the car, and L is the total length of the vehicle.

As can be observed, the mathematical model proposed by Wood depends on the values of the measurements taken in the field: the average deformation (D_{med}), the maximum deformation (D_{max}), and the horizontal pivot radius (k_r). Usually, these measurements are taken in the field through the use of expedited techniques (e.g., the use of rods to mark the reference line, or the use of measuring tapes). This requires, in most of the cases, the visual interpretation of several factors, such as the point of maximum deformation or the estimation of the non-deformed front of the car. The geometrical errors introduced by using this method will affect the accuracy of the results provided by the subsequent energetic analysis.

3. CRASHMAP: A Software for the Energetic Analysis of Road Accidents

Currently available commercial products devoted to the reconstruction and energetic analysis of traffic accidents bypass the use of robust and accurate 3D models. In light of this limitation, in-house software named CRASHMAP has been developed in order to provide a robust tool for security forces. Based on the advantages offered by the structure from motion approach (low-cost and flexibility) and photogrammetry (accuracy and reliability), the different measurements defined before and the corresponding energetic analysis of traffic accidents can be computed and analysed. As a result, objective and accurate expert reports can be generated by the security forces.

Inside this software, two plugins can be highlighted (both programmed in C++/QT):

- A desktop application, **CRASHMAP_desktop** (Figure 3), whose main goal is to assist the user during the energetic analysis of traffic accidents that involve one or several vehicles. This tool allows, among other things, the evaluation of the deformations suffered by the vehicle/s through the analysis of the 3D photogrammetric models. For these deformations, CRASHMAP_desktop can carry out energetic analysis. In its current version, CRASHMAP_desktop allows the evaluation of the following:
  - The analysis of the deformation energy and the equivalent barrier speed in different types of traffic accidents (including impacts against small-section elements) through the use of Prasad's [24] and Wood's [5] methods.
  - The energy dissipated during the traffic accident due to the friction and the deformation experience, by means of the analysis of the braking time, braking distance, and the evaluation of the skid marks on the road.
  - The calculation of the speed of the vehicle through the analysis of the skid marks.
  - The evaluation of the braking distance by means of the speed of the vehicle.
  - Analysis of pedestrian accidents using Searle's method [25].
- A cloud application, **CRASHMAP_cloud** (Figure 4), allows the photogrammetric reconstruction of crashed vehicles in a semi-automatic way (see Section 2.2) through using proprietary architecture built on the cloud, and avoiding the use of high-end computers by the user. This requires only the uploading of the images acquired, as well as basic information about the camera and the measurements taken in the field (in order to scale the model). Once CRASHMAP_cloud ends the reconstruction of the damaged vehicle, the user receives an alert to download the generated 3D model.

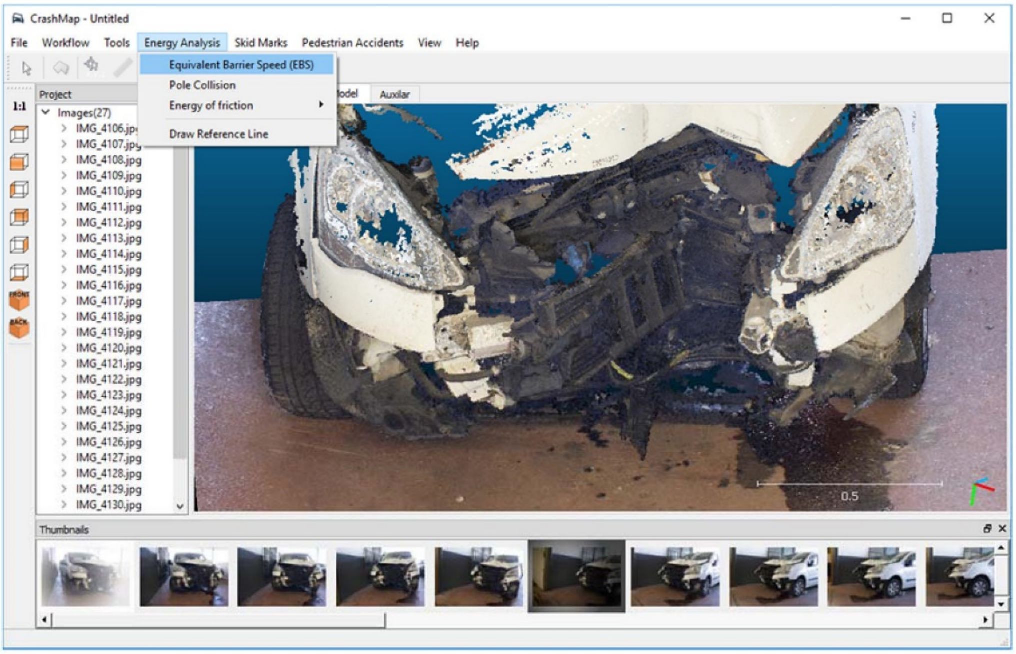


Figure 3. CRASHMAP_desktop interface: tool for the visualisation of photogrammetric 3D models, which can create deformation maps for comparison, dimensional analysis, and energetic analysis.

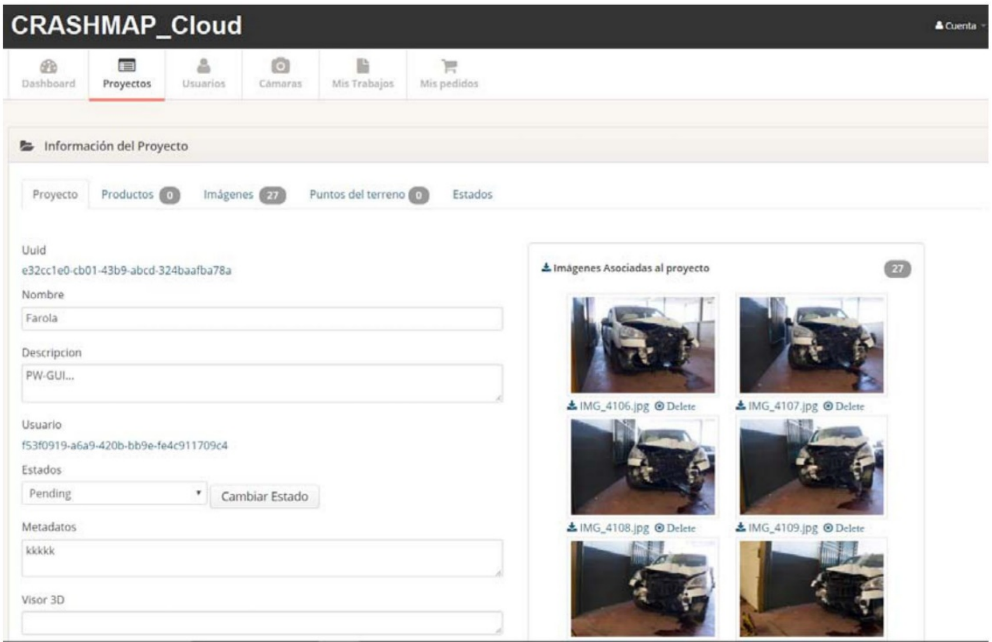


Figure 4. CRASHMAP_Cloud interface: tool for photogrammetric cloud computing. In addition, an external database is created for each accident, as well as a 3D database of original vehicles, which is useful for automatically computing deformations.

The CRAHSMAP_desktop offers two possibilities for obtaining the measurements required for energetic analysis:

- *Manual approach:* This option is a reproduction of the traditional method. In this case, the user selects a point on the damaged model, and the software computes the orthogonal distance between this point and the undamaged model. This approach offers a more robust and reliable alternative to measurements taken in the field. Complementary to this, the software provides additional tools to create lines and rotate the model or the measurement of angles, among other options.
- *Automatic approach:* If the user selects this option, the software loads a 3D model (without deformation) of the car. Then, the software carries out an automatic registration of both models by means of the approach proposed by Makadia et al. [26], considering the undamaged model as reference. Once the model is properly registered, the CRASHMAP_desktop applies the symmetrical Hausdorff metric [27] with the aim of obtaining the discrepancies (deformations) presented between the damaged and the undamaged models. Thanks to this, it is possible to get the required values, D_{max}, D_{med}, and D_{cent} (in the case of eccentric accidents), in order to evaluate the speed of the vehicle at the moment of the impact, as well as the *EBS*.

4. Experimental Results

In order to validate the proposed methodology, a frontal collision between a Citroën Berlingo Combi and an advertising marquee (rigid steel pole) was evaluated (Figure 5a). The technical specifications of the van are shown in Table 1. Based on the visual inspection of the van, the presence of an asymmetric deformation pattern is observed (Figure 5b), suggesting the occurrence of an eccentric frontal accident against a fixed element.

(**a**) (**b**)

Figure 5. Traffic accident evaluated: (**a**) results after the impact of the van against the fixed element, and (**b**) detailed view of the car's frontal after the accident.

Table 1. Technical characteristics of the vehicle involved in the traffic accident.

Vehicle	Wheelbase	Length	Width	Track	Weight
Citroen Berlingo Combi	2.728 m	4.380 m	1.810 m	1.505 m	1482 kg

4.1. Data Acquisition Protocol

With the aim of analysing the energy involved in the traffic accident, two reconstructions were carried out: (i) the reconstruction of the car after the crash (damaged model), and (ii) the reconstruction of the car without any damage (undamaged model). For the reconstruction of the undamaged model, a similar vehicle (same model and year) was used (Figure 6).

Concerning the photogrammetric protocol, both models (damaged and undamaged) were reconstructed following the guidelines defined in Section 2.1. Seven images were captured: five following a cross shape in the center of the interest area, and two complementary images to capture the non-deformed shape (Figure 6). A consumer reflex camera Canon 700D equipped with a zoom lens 18–70 mm was used to capture the images (Table 2). During the image acquisition, a constant focal length of 18 mm was maintained. In order to scale the photogrammetric model, several magnetic scaled stickers were placed along the interest area (Figure 6).

Figure 6. Data acquisition protocol used to digitalise the car's frontal: (**a**) deformed model; and (**b**) non-deformed model.

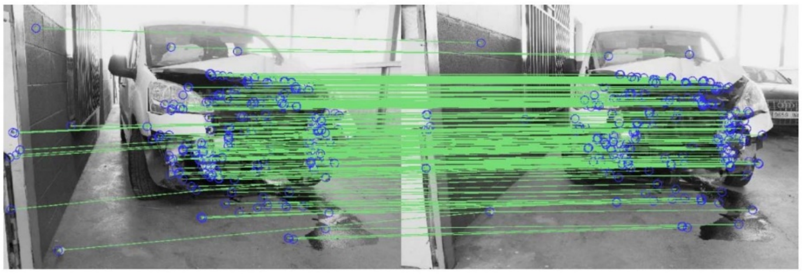
Table 2. Technical specifications of the photographic sensor and lens system used for the photogrammetric reconstruction.

Canon EOS 700D	
Sensor type	CMOS (Complementary Metal-Oxide-Semiconductor)
Sensor size	22.3 × 14.9 mm
Pixel size	4.29 µm
Image size	5184 × 3456 pixels
Resolution	18 Mp
Focal length	18 mm

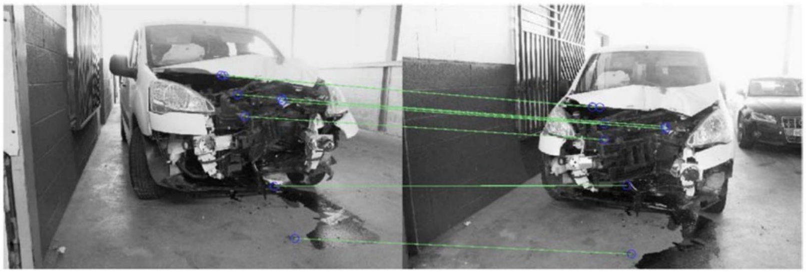
4.2. Photogrammetric Processing

With regard to the photogrammetric processing, the proposed method (AMSD and robust matching) showed better results during the stages of detection and the matching of key points in comparison with its predecessor (MSD + L2-Norm) [18]. The proposed method allowed the extraction of 1500 key points (738 key points were extracted through the use of the MSD detector) and the matching of 246 points (only eight points were matched by means of the MSD + L2-norm)

(Figure 7). Both cases were carried out in similar conditions of repeatability (e.g., similar thresholds and illumination conditions).



(a)



(b)

Figure 7. Results obtained during the key point extraction and matching stage: (**a**) affine maximum self-dissimilarity (AMSD) with robust matching; and (**b**) maximal self-dissimilarity (MSD) and L2-norm matching approach.

Previous to the orientation and self-calibration of the photogrammetric network (Table 3), an analysis of the distribution of the matching points along the camera's sensor was performed (Figure 8). This analysis allowed the evaluation of their spatial distribution, forcing a better distribution of the points considered during the orientation and self-calibration phases.

Concerning the final accuracy of the photogrammetric network, the proposed approach (AMSD + robust matching + camera´s sensor spatial filtering) obtained a root mean square error (RMSE) of 1.2 pixels (Figure 8a). This approach showed better accuracy than the results obtained by the application of the AMSD algorithm + robust matching without applying the camera´s sensor spatial filtering, with a RMSE of 2.8 pixels (Figure 8b).

Table 3. Internal parameters obtained during the photogrammetric reconstruction of the damaged and undamaged model.

Parameter		Values (Damaged Model)	Values (Undamaged Model)
Focal length (mm)		18.57	18.45
Format size (mm)	Height (mm)	22.30	22.30
	Width (mm)	14.90	14.90
Principal point (mm)	X value	10.90	11.24
	Y value	7.37	7.53
Radial lens distortion	K_1 value (mm^{-2})	0.05	0.05
	K_2 value (mm^{-4})	-1.01×10^{-2}	-0.91×10^{-2}
Decentring lens distortion	P_1 value (mm^{-1})	-1.40×10^{-4}	-2.25×10^{-4}
	P_2 value (mm^{-1})	-2.06×10^{-4}	-9.78×10^{-4}

Based on the robust orientation obtained from applying the AMSD algorithm, the robust matching, and camera´s sensor spatial filtering, a dense reconstruction process was carried out through applying the MicMac algorithm [28]. As a result, two point clouds were obtained: (i) the damaged point cloud composed by 1,922,543 points, and (ii) the undamaged point cloud composed by 1,721,951 points. Both models were placed in different coordinates systems and registered following the approach defined in Section 2.1, which allowed the evaluation of the deformation suffered by the car during the traffic accident. This analysis was carried out using the symmetrical Hausdorff distance as a metric of comparison [27].

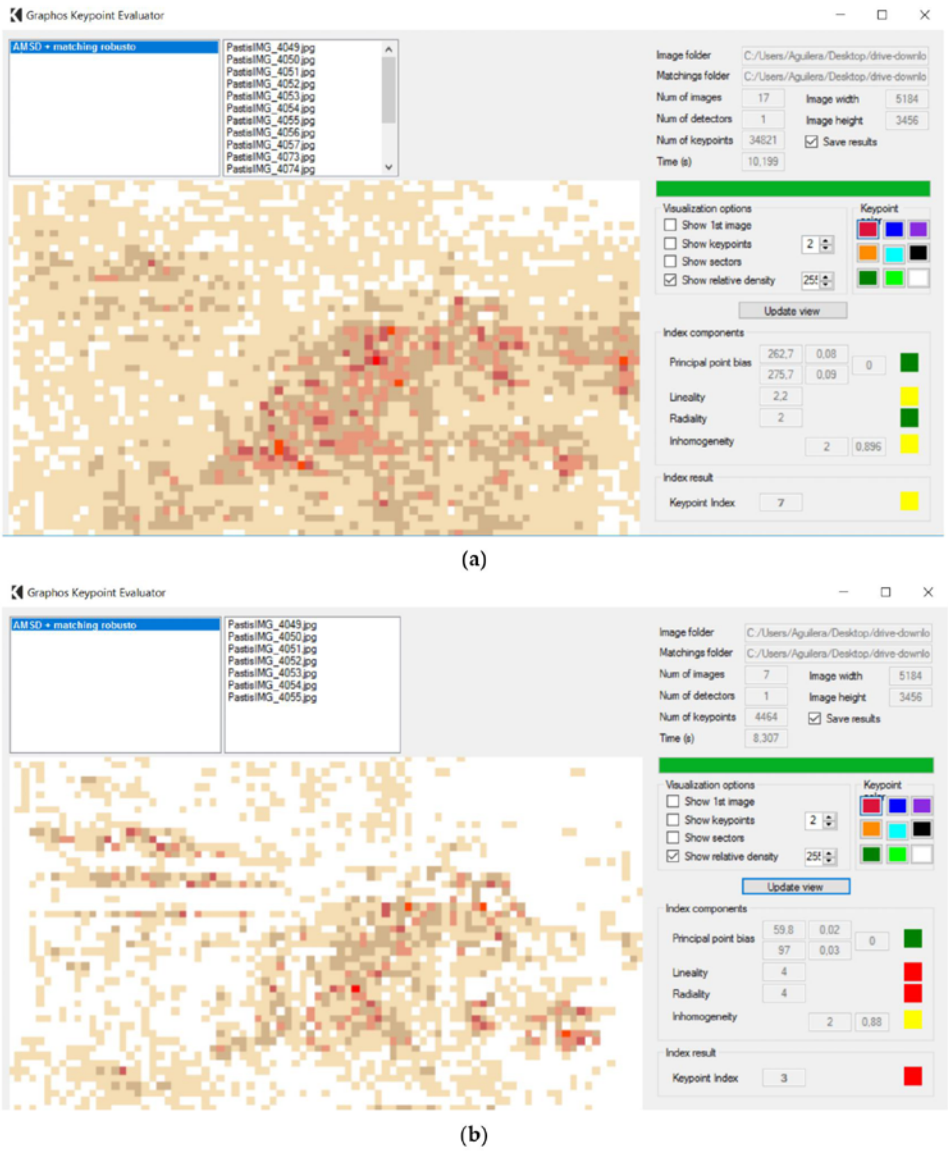


Figure 8. Results obtained during the analysis of the distribution of the key points extracted along the camera's sensor: (**a**) AMSD, robust matching, and camera´s sensor spatial filtering; and (**b**) AMSD and robust matching without camera sensor´s spatial filtering.

4.3. Energetic Analysis of the Pole Impact

As outlined in Section 2.3, Wood's method was used to analyse the energy involved in the traffic accident [4]. During this evaluation, the following considerations were taken into account: (i) the energy absorbed by the car through the deformation of its non-structural components, and (ii) the rotation energy generated due to the eccentricity of the impact. The frictional energy due to the lack of skid marks on the road, and the energy absorbed by the structural components due to their rigidity and resistance were both dismissed.

It should be noted that the accuracy of this method depends on the accuracy of the following values: D_{max}, D_{med}, and $D_{cent,}$ in the case of eccentric accidents against fixed elements. With the aim of evaluating this dependency, two tests were carried out: (i) **test A** was based on the traditional protocol; and (ii) **test B** was carried out following the proposed method. The results provided by these two approaches were compared as follows:

- Evaluation of the discrepancies between the traditional methods and the proposed method.
- Analysis of the average deformation (D_{med}) through the traditional protocol (with a total of six measurements manually taken in the field), and through the proposed method (with 30 automatic measurements equally spaced along the width of the car).
- Comparison of the results obtained by both methods (*EBS* and the collision speed of the vehicle).

For the first test, **test A**, the traditional protocol was applied. In this case, the first step was the creation of an approximate reference line at the height of the vehicle's bumper, and parallel to the rear axle of the car. Once the reference line was created, a total of six equally-spaced measurements were taken between the limits of the reference line in order to calculate the average deformation (D_{med}). An additional measurement was taken for the maximum deformation (D_{max}). Since the accident presented an eccentricity, the evaluation of the variable D_{cent} was required. This variable was calculated through measuring the orthogonal distance between the point of maximum deformation and the longitudinal axis of the vehicle (placed in the middle of the car), obtaining the results shown in Table 4. The difficulty of guaranteeing that both profiles (in tests A and B) were taken at the same height should be noted. This reflects some of the main limitations of the traditional protocol, which is based on expeditious methods using an approximate reference line and collecting data under unfavourable conditions.

Table 4. Results derived from the six measurements taken with a measuring tape following the traditional protocol.

D_1	D_2	D_3	D_4	D_5	D_6	D_{med}	D_{max}	D_{cent}
0.250 m	0.207 m	0.217 m	0.305 m	0.552 m	0.193 m	0.287 m	0.625 m	0.231 m

According to Wood's method, six equidistant measurements were taken following a specific protocol (Section 2.1). In addition, the officer should appreciate the area with the highest deformation and take an additional measurement, D_{max}.

With respect to the second test, **test B**, the photogrammetric models obtained in Section 4.2 were used to evaluate the deformations suffered by the vehicle after the traffic accident. The software CRASHMAP, through the use of the plugin CASHMAP_desktop, was used to evaluate the discrepancies between the damaged and the undamaged models, allowing the analysis of the energy absorbed (*EBS*) and the collision speed (V_{col}). In the first stage, the automatic registration method proposed by Makadia et al. [26] was used to place both models in the same coordinate system, considering the undamaged model as reference. During this stage, different 3D detectors (e.g., VoxelGrid, Harris3D) and descriptors (e.g., SHOT, PFH) were used in order to find the best registration solution. It should be noted that these detectors/descriptors are only applied to the common parts of the vehicle without deformation; otherwise, the automatic alignment would be impossible. Following the proper registration of the damaged model, the software applied the symmetrical Hausdorff metric [27] with the aim of evaluating the discrepancies (deformations) between the original car's shape (undamaged model) and the shape of the car after the traffic accident (damaged model). During this evaluation, the CRASHMAP_desktop creates a pseudo-colour map, assigning a pseudo-colour to each deformation value. This pseudo-colour map allows the full-field evaluation of the deformations suffered by the vehicle (Figure 9).

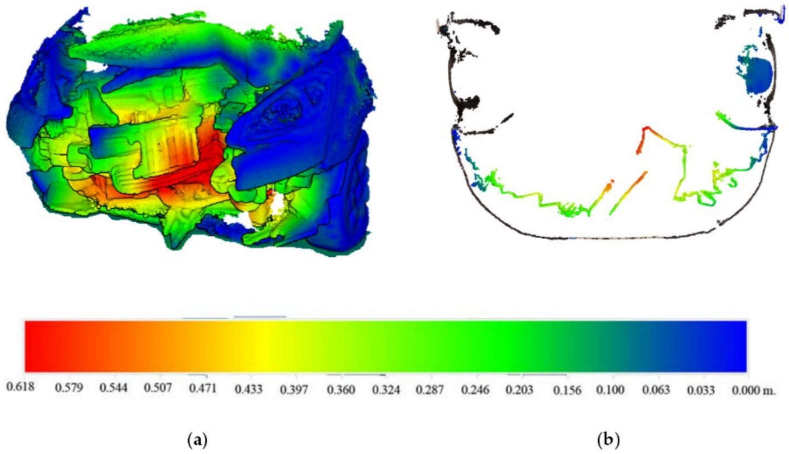


Figure 9. Comparison between 3D photogrammetric models: (**a**) isometric view of the damaged model, and (**b**) plan view of the section considered for the energetic analysis. The points belonging to the undamaged model are in black.

In order to obtain the values of the deformations experienced by the vehicle (D_{max} and D_{med}), the CRASHMAP_desktop applies the following workflow (Figure 10): (i) analysis of the histogram of discrepancies; (ii) extraction of the maximum value (D_{max}); (iii) creation of the comparison section at the height of the point with maximum deformation; (iv) extraction of the deformations based on a user-input threshold (spacing between measurements); and (v) evaluation of the average deformation (D_{med}). Through the histogram of discrepancies generated from our method, we can know the whole deformation geometry of the vehicle and also estimate D_{max} and D_{med} with more accuracy. The results obtained are shown in Table 5.

Table 5. Values of deformation obtained from the comparison between photogrammetric point clouds. An interval of 5 cm between measurements was used.

Measurement	Value (m)	Measurement	Value (m)
D_1	0	D_{16}	0.226
D_2	0.052	D_{17}	0.291
D_3	0.092	D_{18}	0.352
D_4	0.182	D_{19}	0.618
D_5	0.179	D_{20}	0.581
D_6	0.193	D_{21}	0.547
D_7	0.224	D_{22}	0.518
D_8	0.247	D_{23}	0.225
D_9	0.188	D_{24}	0.235
D_{10}	0.199	D_{25}	0.159
D_{11}	0.126	D_{26}	0.200
D_{12}	0.141	D_{27}	0.184
D_{13}	0.134	D_{28}	0.227
D_{14}	0.230	D_{29}	0.185
D_{15}	0.150	D_{30}	0.113

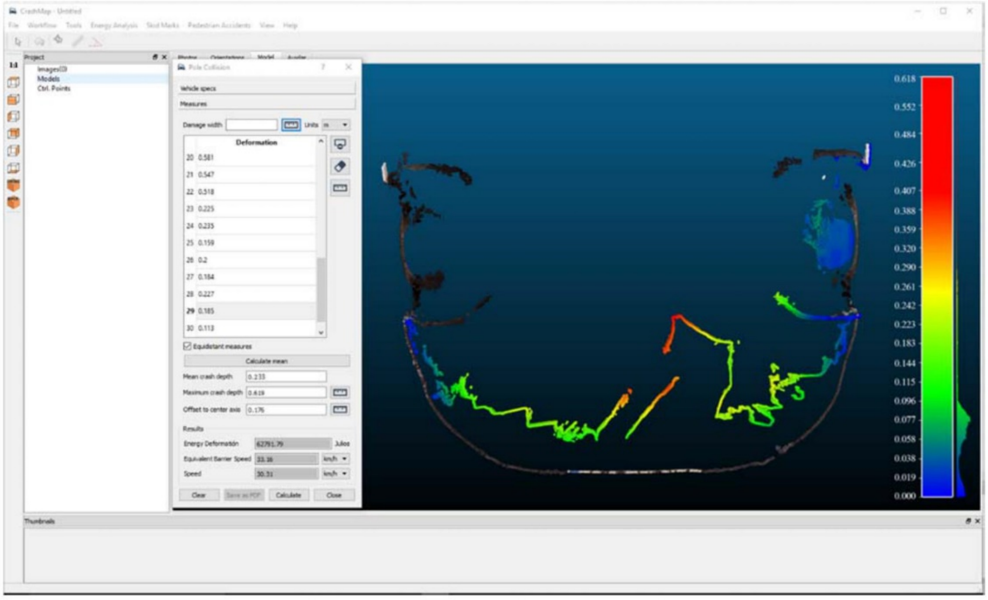


Figure 10. Interface of the CRASHMAP_desktop during the energetic evaluation.

Additionally to this, and due to the presence of eccentricity during the traffic accident, it was necessary to evaluate the orthogonal distance, D_{cent}, between the longitudinal axis of the vehicle and the point with the maximum deformation. The CRASHMAP_desktop evaluates the width of the vehicle (undamaged model), calculates the longitudinal axis of the car, and obtains the value of the variable D_{cent} (Table 6).

Table 6. Results obtained from energetic analysis.

	D_{max}	D_{med}	D_{cent}	Ea	EBS	V_{col}
Traditional method	0.625 m	0.287 m	0.231 m	84,619.46 J	39.45 km/h	36.50 km/h
Proposed method	0.619 m	0.233 m	0.176 m	62,791.79 J	33.16 km/h	30.31 km/h

As expected, the value of the deformations (D_{max} and D_{med}), as well as the value of the distance between the longitudinal axis and the point of maximum deformation (D_{cent}) differ between both methods (Table 6). These discrepancies can be attributed to the introduction of human errors during the data acquisition, which can include the stress of the situation, the expeditious nature of the method, the idealisation of the front of the car, and the use of a low number of measurements to represent the whole deformation of the vehicle. As a result, a discrepancy of 21,827.67 J (17% of variation) in the absorbed energy and a variation of 6.19 km/h in the collision speed, is observed (Table 6). This discrepancy can be considered critical if the speed limit of the road is close to the collision speed of the vehicle (e.g., limitation of 30 km/h for the present study case).

5. Conclusions

This article proposes a new approach for the energetic analysis of traffic accidents against fixed elements. It exploits the geometrical features of photogrammetric point clouds in order to evaluate the energy that is transformed during a traffic accident, and thus, the speed at which the car impacts against a fixed element.

In comparison with the previous work carried out by the authors, several improvements were introduced during the photogrammetric reconstruction, namely: (i) the novel algorithm AMSD (affine maximal self-dissimilarity); (ii) a robust matching of key points; and (iii) an analysis of the spatial distribution of the matching points along the camera´s sensor. This photogrammetric approach has shown a better performance in comparison with its predecessor, which is based on the MSD algorithm and the standard L2-norm. It makes the reconstruction of unfavourable scenes possible, and introduces important radiometric and geometric changes, without requiring the use of pre-processing stages.

Concerning the energetic method used to evaluate the traffic accident, the present approach has enabled the minimisation of the geometrical errors derived from the traditional method, which was based on expeditious protocols and relied on an idealisation of the geometry of the car. It can also use a large number of measurements for the evaluation of the maximum (D_{max}), the average deformations (D_{med}), and the orthogonal distance between the longitudinal axis of the car and the point with maximum deformation (D_{cent}).

With respect to the case study analysed to validate the method, it is possible to observe relevant discrepancies between the results derived from the traditional protocol (with a collision speed of 36.05 km/h and an absorbed energy of 84,619.46 J) and those obtained by the proposed approach (collision speed of 30.31 km/h and an absorbed energy of 62,791.79 J). These discrepancies emphasise the importance of the geometry in the rigorous evaluation of traffic accidents, and thus the use of robust 3D modelling strategies. These energetic analyses were carried out with CRASHMAP, an in-house tool developed for this purpose. CRASHMAP has been built following a client–server architecture composed by a total of two plugins: (i) CRASHMAP_cloud, a plugin that allows the 3D reconstruction of traffic accidents on the cloud, avoiding the use of high-end computers and; (ii) CRASHMAP_desktop, a plugin that enables the evaluation of traffic accidents through the analysis of the deformations suffered by the vehicle. From this analysis, the energy involved during the accident and the collision speed can be obtained. This last parameter is a critical factor for the resolution of court and judicial cases.

Future works will be focussed on carrying out further experimental campaigns that simulate different traffic accidents and conditions in order to improve the empirical coefficients used in the different equations. In particular, a robust comparison of photogrammetric and manual results with controlled experiments that also include a calibration of coefficients will be considered in future study. Last but not least, several approaches will be tested in order to automatically recognise the scale bars used during the data acquisition. This recognition will enable the full automatic reconstruction of traffic accidents.

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Conflicts of Interest: The authors declare no conflict of interest.

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CAPÍTULO IV

CONCLUSIONES Y PERSPECTIVAS FUTURAS

4. CONCLUSIONES Y PERSPECTIVAS FUTURAS

Las investigaciones realizadas durante el desarrollo de esta Tesis Doctoral han permitido cumplir con los objetivos propuestos en la línea de investigación y realizar una aportación al desarrollo de las áreas de conocimiento en que se han apoyado. Esta aportación se ha visto materializada con la publicación en revistas de impacto especializadas de artículos que recogen las metodologías y resultados obtenidos como fruto de estas investigaciones. A continuación, se desarrollan en detalle las conclusiones derivadas de cada una de las publicaciones científicas, así como un desglose de las líneas de trabajo futuras, abiertas durante las investigaciones realizadas, que permitirán continuar avanzado en esta línea de investigación.

4.1. CONCLUSIONES

En relación a la metodología propuesta para la asistencia a los servicios de emergencia en el rescate de víctimas atrapadas tras un accidente de tráfico, conviene destacar:

- Que se ha complementado la información que hasta ahora se proporcionaba por los fabricantes en la RS relativa al vehículo con otra requerida por profesionales del rescate, tanto del vehículo como de sus ocupantes.
- Que se ha desarrollado un sistema que garantiza el acceso a la misma en todo tipo de accidentes, algo que hasta ahora no existía, de forma gráfica e inmediata.
- Que se trata de una solución fácilmente incorporable a los protocolos de actuación de los servicios de emergencia.

Estos tres aspectos permiten, tal y como se ha podido constatar en 4 ensayos de accidentes reales realizados por los Bomberos del Ayuntamiento de Ávila en las instaciones de la empresa CESVIMAP, mejorar aspectos claves del rescate, tales como:

- La seguridad de víctimas y rescatadores, al tener localizados los elementos propios del vehículo constitutivos de riesgo.

- La eficacia en las labores de descarcelación, al planificar las acciones sabiendo de antemano la ubicación de los elementos peligrosos.
- Los tiempos de extracción de las víctimas.
- La atención médica inicial, al disponer de información biosanitaria de las víctimas que puede contribuir en la toma de decisiones.

En los 4 ensayos realizados por los Bomberos del Ayuntamiento de Ávila en diferentes tipos de accidentes, con diferente casuística y número de víctimas, los tiempos de rescate se vieron reducidos un 14% de media, al incorporar a sus protocolos de actuación la metodología propuesta.

En cuanto al uso de fotogrametría terrestre en esta Tesis Doctoral, esta ha demostrado ser una herramienta geomática que, complementada con visión computacional, proporciona una solución de bajo coste, rigurosa y eficaz para la generación de modelos tridimensionales con los que poder documentar y realizar un análisis energético de accidentes de tráfico. Una gran ventaja del uso de estas herramientas es la capacidad de procesar imágenes procedentes de cámaras no profesionales con sensores de baja calidad o estabilidad, como los incluidos en Smartphones, gracias a las estrategias de autocalibración empleadas durante el proceso fotogramétrico. Esto permite que pueda ser utilizado por personal no cualificado y aplicado en cualquier tipo de área de conocimiento.

Conviene destacar la existencia inicial de ciertos problemas en la correspondencia de puntos provocados por las condiciones de iluminación y textura de las superficies de los vehículos, los cuales se han visto solucionados con la utilización de la herramienta software de código abierto GRAPHOS (Gonzalez-Aguilera et al., 2018).

En cuanto a la aplicación de los métodos de análisis energético para estimar la velocidad de colisión, podemos afirmar que los modelos 3D fotogramétricos constituyen una herramienta adecuada y precisa sobre la que poder realizar las mediciones exigidas por los diferentes métodos, tal y como se ha podido validar en el accidente simulado en las instalaciones de la Academia de Seguridad Pública de Extremadura (APEX), que permitió realizar un análisis energético, a partir de los modelos 3D, para estimar la velocidad de colisión, obteniéndose una velocidad de 31.55 km/h frente a la real de 32 km/h. Y no sólo son una herramienta válida, sino que aporta numerosas ventajas frente a los métodos tradicionales de medición, como son:

- Permite disponer de la escena y detalles necesarios para la aplicación de los métodos de análisis energético en cualquier momento, lo que posibilita la revisión o contraste de las medidas.
- Permite minimizar los errores geométricos derivados de los métodos tradicionales.
- Permite considerar la geometría original del vehículo a la hora de medir las deformaciones y no hacerlo desde una línea imaginaria como los métodos tradicionales.
- Permite crear, a partir de las nubes de puntos 3D, subproductos como los mapas de deformación métrica, que pueden resultar de gran utilidad en algunos de los métodos de análisis energético como el de McHenry, Prasad o el de Wood.
- Permite asistir, e incluso automatizar, procesos de medición para aplicar de forma automática diferentes métodos de análisis energético, tal y como se ha realizado en la herramienta software desarrollada CRASHMAP_desktop. Todo ello se traduce en una mayor precisión en los resultados estimados.

Se ha podido constatar, con la aplicación de la metodología propuesta a un accidente real del tipo de accidente frontal contra elementos rígidos de pequeña sección, que el empleo de modelos 3D fotogramétricos de la zona deformada del vehículo para la toma de medidas requeridas por el método de análisis energético de Wood permite mejorar los resultados en comparación con los métodos tradicionales. Esto es debido a que el método de Wood requiere determinar el punto de máxima deformación sufrida por el vehículo, así como la deformación media producida en la zona afectada. Estas medidas son muy complicadas de realizar con métodos manuales, ya que no siempre es posible determinar visualmente el punto de máxima deformación, y, puesto que la zona afectada por el impacto es muy reducida, tomar las medidas equidistantes necesarias (mínimo 2 y máximo 6) para calcular la deformación media suele ser complicado y poco preciso. Sin embargo, es posible extraerlas con total precisión a partir de los mapas de deformación métrica generados a partir de los modelos fotogramétricos.

Conviene mencionar que la metodología desarrollada esta siendo utilizada por la Policía Local de Salamanca a través de un acuerdo de investigación, y ha sido puesta en práctica en varios accidentes reales.

4.2. PERSPECTIVAS FUTURAS

Las técnicas, herramientas y materiales empleados en esta Tesis Doctoral han permitido llevar a cabo las investigaciones que dan respuesta a las cuestiones que se han planteado antes y durante su realización. No obstante, debido al rápido avance técnico y metodológico, se plantean nuevas cuestiones y posibilidades que quedan abiertas para futuras investigaciones.

En relación a la metodología desarrollada para proporcionar información relativa al vehículo y sus ocupantes que permita a los servicios de emergencia mejorar el rescate de personas atrapadas tras un accidente de tráfico, se plantean como futuros trabajos:

- Estudiar la posibilidad de mejorar el acceso a la información contenida en la ASR utilizando etiquetas NFC (Near Field Communication) en lugar de códigos QR, puesto que las etiquetas NFC podrían situarse en el interior del vehículo, evitando así tener que localizar alguno de los códigos QR para su lectura y eliminando la posibilidad de que los tres códigos colocados en el vehículo pudieran resultar dañados durante el accidente o no ser accesibles tras este.
- Desarrollar un sistema que permita identificar a cada uno de los ocupantes del vehículo cuando acceden a este. Podría estar basado en la lectura de huella dactilar de forma que permita saber con exactitud qué personas viajan en el vehículo.
- Adaptar la metodología desarrollada al transporte de mercancías peligrosas, de forma que, en caso de accidente, los servicios de emergencias puedan acceder a toda la información relativa a la mercancía transportada, número de identificación del peligro, número de identificación de la materia, tratamientos, etc., y actuar de la forma más segura y eficiente posible.

En cuanto a la metodología desarrollada para realizar el análisis energético de los accidentes a partir de modelos fotogramétricos 3D, se plantean como futuros trabajos:

- Validar la aplicación de la metodología desarrollada sobre otra tipología de accidentes (e.g. atropellos) que requieran la aplicación de otros métodos de análisis energético y analizar si esta permite incrementar la precisión del método.

- Automatizar el reconocimiento de las barras de escala que se emplean durante la adquisición de datos con el objetivo de dotar de escala a los modelos fotogramétricos de manera autmática.
- Crear una base de datos de modelos 3D de vehículos que pueda ser utilizada por la herramienta CRASHMAP_desktop para comparar los modelos originales con los accidentados e incrementar la precisión en la obtención de datos métricos.
- Valorar la posibilidad de mejorar ciertos métodos de análisis energético muy empleados en la actualidad, como el de Prasad o el de Wood, mediante el uso de coeficientes de deformación específicos de cada modelo de vehículo. Muchos de los métodos de análisis energético basan su formulación matemática en una serie de coeficientes de deformación estadísticos obtenidos a partir de un conjunto de ensayos, en muchos de los casos sobre vehículos muy antiguos.

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ANEXO I

INDEXACIÓN Y FACTOR DE IMPACTO DE LAS PUBLICACIONES

Publicación I

Morales, A., González-Aguilera, D., López, A.I. & Gutiérrez, M.A. (2016). A new approach to road accident rescue. *Traffic Injury Prevention.* 17 (3), pp. 278-284. *DOI*: 10.1080/15389588.2015.1062885

A. CITAS RECIBIDAS POR EL ARTÍCULO

WOS: 1
SCOPUS: 2
GS: 2

B. REVISTA

Título: Traffic Injury Prevention
Editor: Taylor & Francis
ISSN: 1538-9588

C. INDICADORES DE CALIDAD DE LA REVISTA

WOS
SJR
GSM

<u>WOS. WEB OF SCIENCE (2016)</u>

- FI 1,290
- Rank 125/176
- Q3, Categorie PUBLIC HEALTH, ENVIRONMENTAL AND OCCUPATIONAL HEALTH
- JIF PERCENTILE: 34,588

Traffic Injury Prevention

ISSN: 1538-9588
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Titles
ISO: Traffic Inj. Prev.
JCR Abbrev: TRAFFIC INJ PREV

Categories
PUBLIC, ENVIRONMENTAL & OCCUPATIONAL HEALTH - SCIE

Languages
English

8 Issues/Year;

Key Indicators

Year	Total Cites Graph	Journal Impact Factor Graph	Impact Factor Without Journal Self Cites Graph	5 Year Impact Factor Graph	Immediacy Index Graph	Citable Items Graph	Cited Half-Life Graph	Citing Half-Life Graph	Eigenfacto Score Graph	Article Influence Score Graph	% Articles in Citable Items Graph	Normalized Eigenfacto Graph	Average JIF Percentile Graph
2017	1,904	1.274	1.077	1.407	0.391	156	5.4	8.3	0.00...	0.496	98.08	0.56...	29.062
2016	1,677	1.290	1.073	1.451	0.199	156	5.2	8.3	0.00...	0.524	97.44	0.55...	34.588
2015	1,370	1.148	0.904	1.384	0.267	180	5.3	8.3	0.00...	0.579	99.44	0.54...	33.226
2014	1,232	1.413	1.233	1.465	0.397	116	5.0	8.5	0.00...	0.595	98.28	0.49...	47.927
2013	1,106	1.286	1.045	1.556	0.296	125	5.1	8.2	0.00...	0.559	99.20	0.43...	43.634
2012	829	1.042	0.825	Not ...	0.333	93	4.8	7.6	0.00...	Not ...	96.77	Not ...	33.652
2011	700	1.079	0.781	Not ...	0.122	82	4.3	7.2	0.00...	Not ...	98.78	Not ...	41.127
2010	602	1.401	1.228	Not ...	0.202	84	3.8	7.3	0.00...	Not ...	97.62	Not ...	51.844

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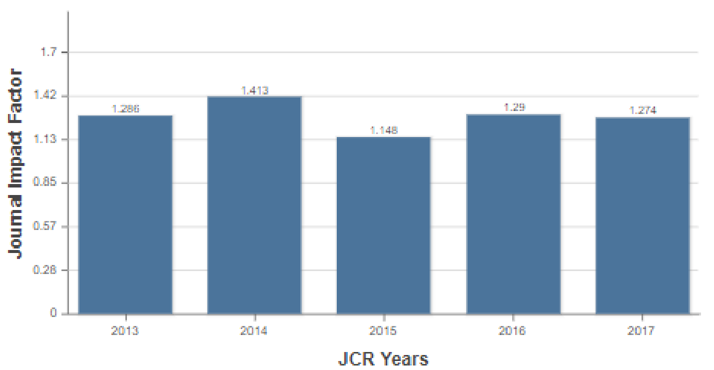
Cited Journal Data
Citing Journal Data
Box Plot
Journal Relationships
Metric Trend

Metric Trend

View All Years



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Journal Relationships

JCR Impact Factor

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2016	125/176	Q3	29.261
2015	128/173	Q3	26.301
2014	95/165	Q3	42.727
2013	99/162	Q3	39.198
2012	119/161	Q3	26.398
2011	105/158	Q3	33.861
2010	79/142	Q3	44.718

<u>SJR. SCIMAGO JOURNAL & CONTRY RANK</u>

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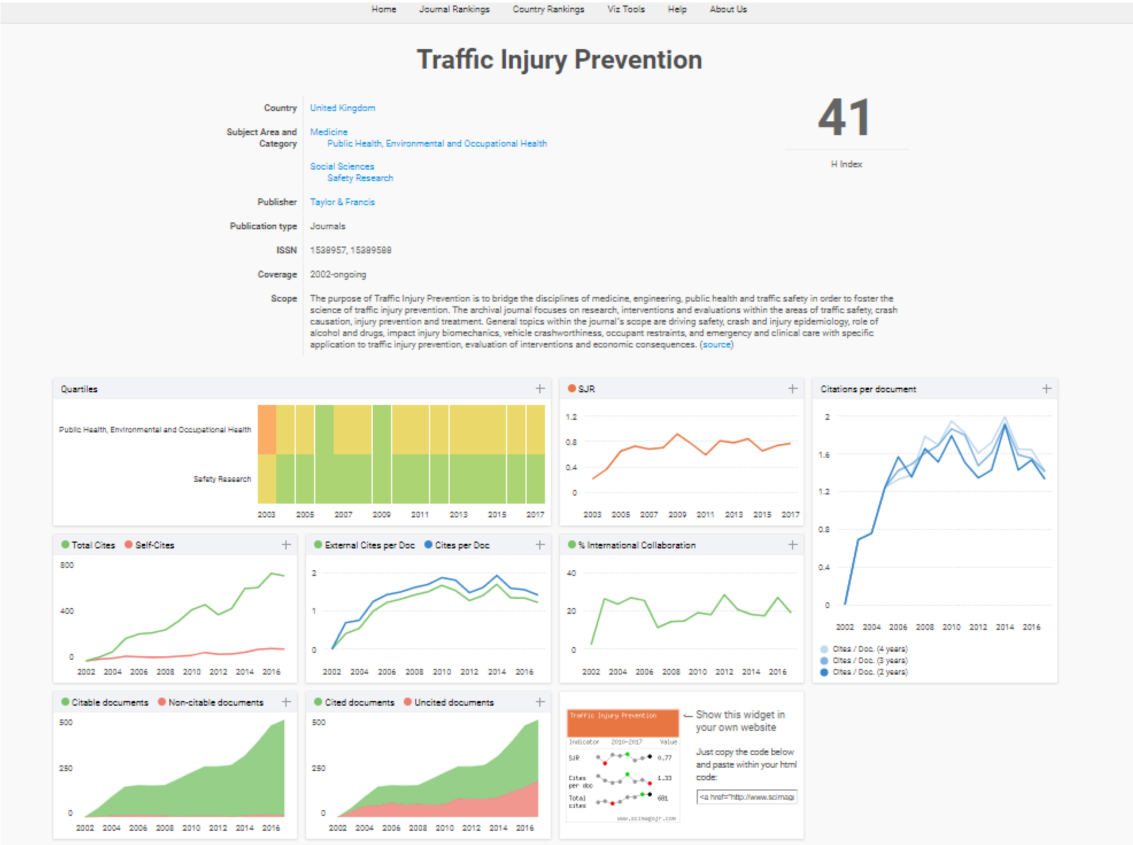

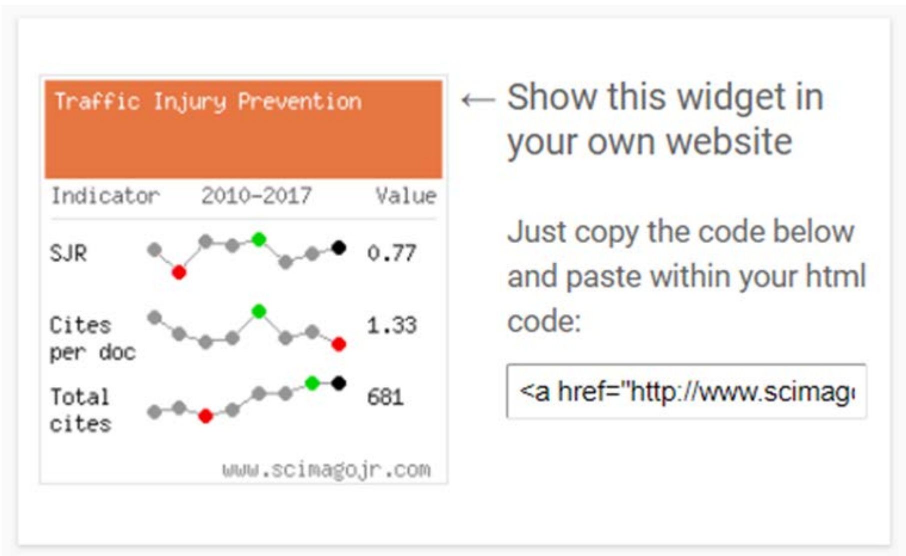

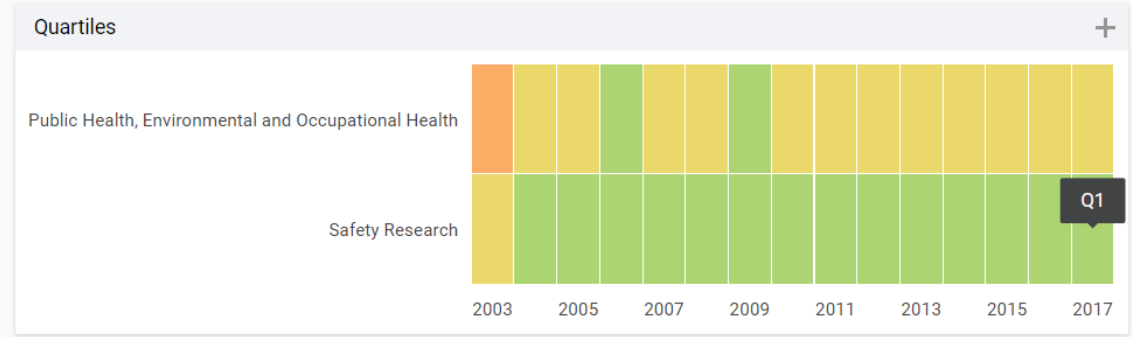

GOOGLE SCHOLAR METRICS

- H5 GSM: 27. Mediana H5: 32

Publicaciones que coinciden con *Traffic Injury Prevention*

	Publicación	Índice h5	Mediana h5
1.	Traffic Injury Prevention	27	32

Las fechas y los recuentos de citas son estimados y se determinan de forma automática mediante un programa informático.

Publicación II

Morales, A., González-Aguilera, D., Gutiérrez, M.A. & López, A.I. (2015). Energy Analysis of Road Accidents Based on Close-Range Photogrammetry. *Remote Sensing.* 7 (11), pp. 15161-15178. DOI: 10.3390/rs71115161

A. CITAS RECIBIDAS POR EL ARTÍCULO:

WOS: 1
SCOPUS: 1
GS: 2

B. REVISTA. INDICADORES DE CALIDAD

Título: Remote Sensing
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D. INDICADORES DE CALIDAD DE LA REVISTA

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- FI 3,036
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12 Issues/Year;

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Key Indicators

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2017	13,600	3.406	2.440	3.952	0.667	1,314	3.0	7.1	0.03...	0.872	98.86	3.99...	75.000
2016	8,883	3.244	2.374	3.749	0.664	1,016	2.7	7.6	0.02...	0.802	98.52	2.60...	77.586
2015	5,061	3.036	2.033	3.278	0.528	762	2.5	7.7	0.01...	0.759	98.29	1.76...	83.929
2014	3,061	3.180	2.124	3.257	0.505	572	2.5	7.9	0.01...	0.772	97.03	1.16...	83.929
2013	1,739	2.623	1.635	2.729	0.883	316	2.4	7.5	0.00...	0.625	98.42	0.61...	79.630
2012	895	2.101	1.363	2.171	0.723	184	2.2	7.3	0.00...	0.504	98.91	Not ...	75.926

Source Data

Rank

Cited Journal Data

Citing Journal Data

Box Plot

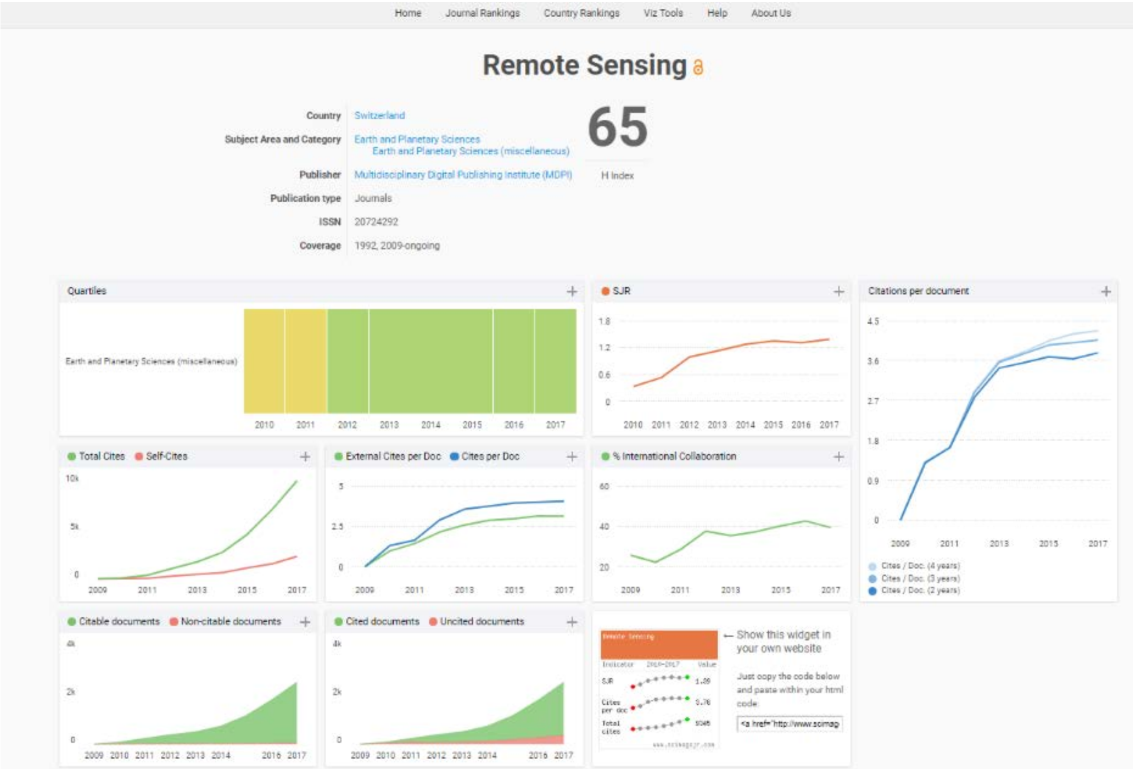
Journal Relationships

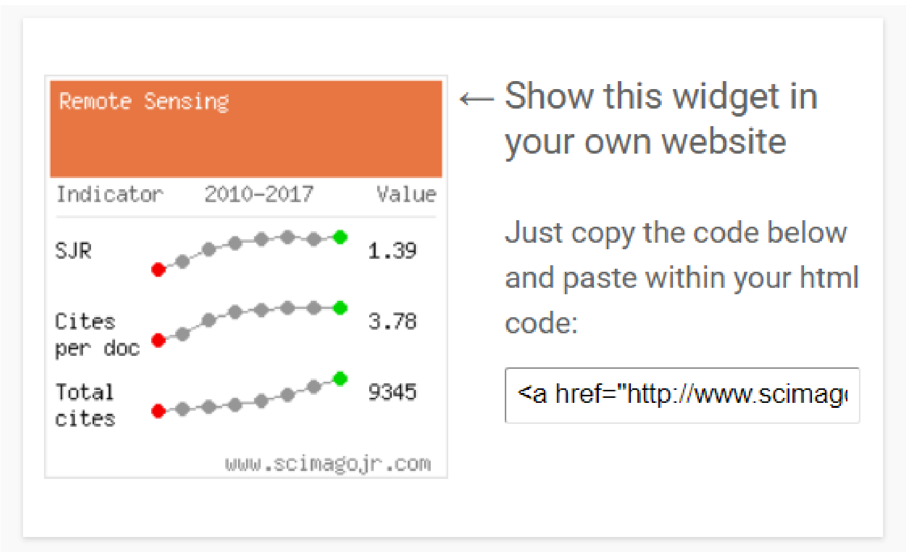
JCR Impact Factor

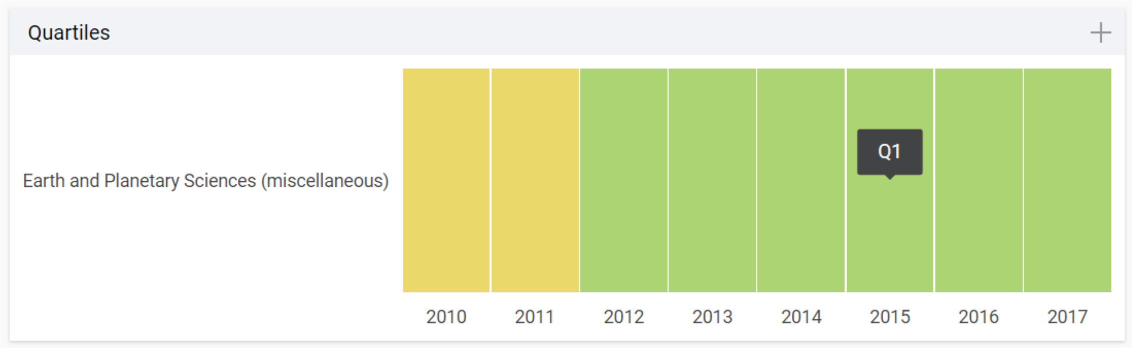
JCR Year	REMOTE SENSING Rank	Quartile	JIF Percentile
2017	8/30	Q2	75.000
2016	7/29	Q1	77.586
2015	5/28	Q1	83.929
2014	5/28	Q1	83.929
2013	6/27	Q1	79.630
2012	7/27	Q2	75.926

SJR. SCIMAGO JOURNAL & CONTRY RANK

- SJR: 1,39
- Q1 Categorie EARTH AND PLANETARY SCIENCES (miscellaneous)







GSM. GOOGLE SCHOOLAR METRICS

- H5 GSM: 57. Mediana H5: 78

Google Académico

Publicaciones principales

Categorías > Engineering & Computer Science > **Remote Sensing**

	Publicación	Índice h5	Mediana h5
1.	Remote Sensing of Environment	89	127
2.	IEEE Transactions on Geoscience and Remote Sensing	77	102
3.	Remote Sensing	57	78
4.	ISPRS Journal of Photogrammetry and Remote Sensing	56	72
5.	International Journal of Applied Earth Observation and Geoinformation	50	67
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14.	Journal of Applied Remote Sensing	23	32
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16.	IEEE Radar Conference	22	28

Publicación III

Morales, A., Sánchez Aparicio, L.J., Gómez-Aguilera, D., Gutiérrez, M.A., López, A.I., Hernández-López, D., Rodríguez-Gonzalvez, P. (2017). A New Approach to Energy Calculation of Road Accidents against Fixed Small Section Elements Based on Close-Range Photogrammetry. *Remote Sensing*. 9 (12), 1219. *DOI*: 10.3390/rs9121219

A. CITAS RECIBIDAS POR EL ARTÍCULO:

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SCOPUS: 1
GS: 0

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Título: Remote Sensing
Editor: MDPI AG
ISSN: 2072-4292

C. INDICADORES DE CALIDAD DE LA REVISTA

WOS
SJR
GSM

WOS. WEB OF SCIENCE (2017)

- FI 3,406
- Rank 8/30
- Q2, Categorie REMOTE SENSING, 2017
- JIF PERCENTILE: 75,000

InCites Journal Citation Reports — Clarivate Analytics

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Remote Sensing

ISSN: 2072-4292

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SWITZERLAND

Go to Journal Table of Contents   Go to Ulrich's

Titles
ISO: Remote Sens.
JCR Abbrev: REMOTE SENS-BASEL

Categories
REMOTE SENSING - SCIE

Languages
English

12 Issues/Year;
Open Access from 2009

Key Indicators

Year	Total Cites Graph	Journal Impact Factor Graph	Impact Factor Without Journal Self Cites Graph	5 Year Impact Factor Graph	Immediacy Index Graph	Citable Items Graph	Cited Half-Life Graph	Citing Half-Life Graph	Eigenfacto Score Graph	Article Influence Score Graph	% Articles in Citable Items Graph	Normalizec Eigenfacto Graph	Average JIF Percentile Graph
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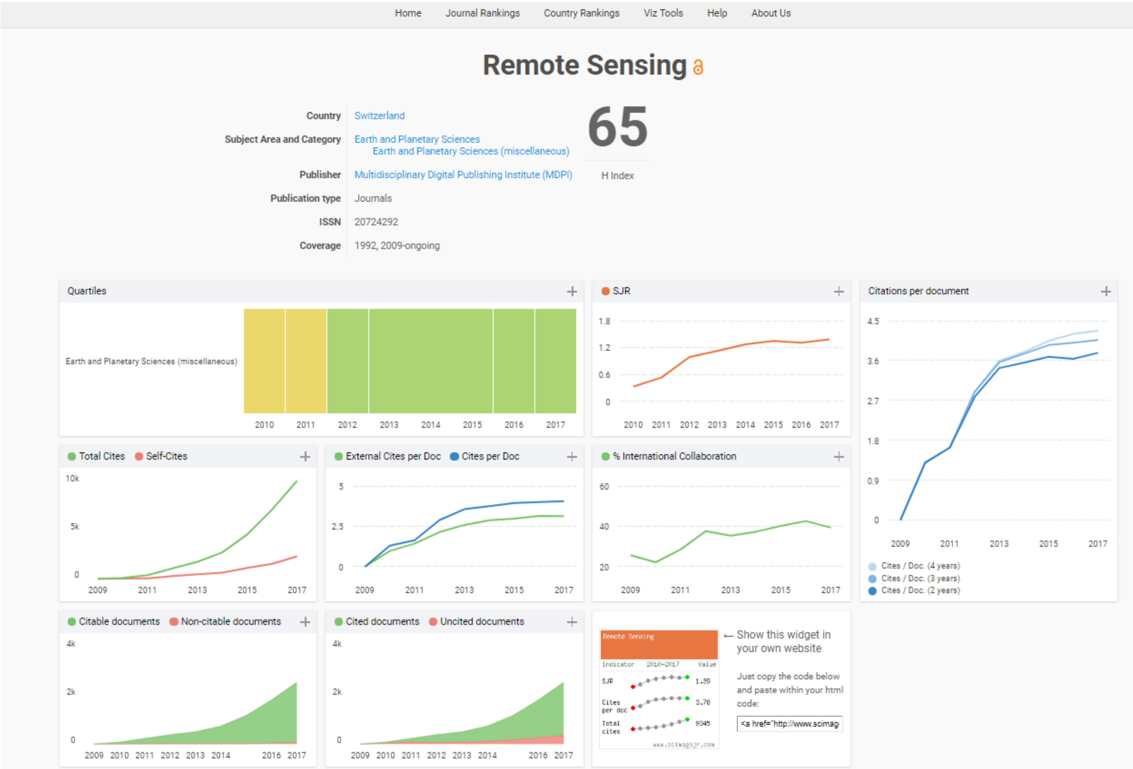

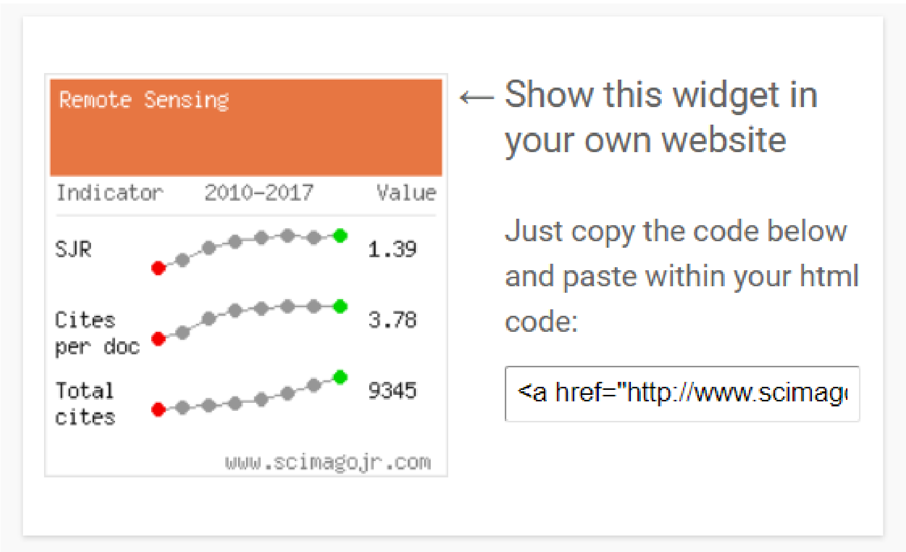

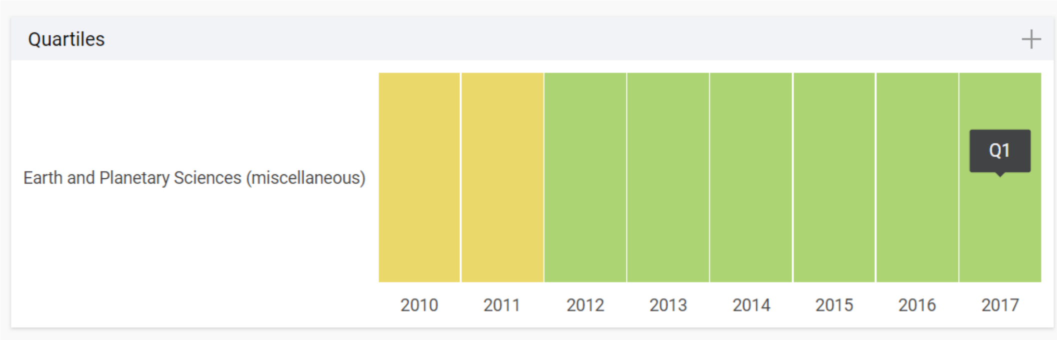

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ANEXO II

SOFTWARE

QRescue ®

QRescue ® - Quick Rescue Response in Road Accidents

Tipo: Registro de propiedad intelectual

Número de Asiento Registral: SA-00/2015/2740

Universidad: Universidad de Salamanca

Autores:

- Alejandro Morales Sánchez
- Diego González Aguilera
- Alfonso Isidro López Díaz
- Miguel Ángel Gutierrez García

Resumen:

QRescue ® es una herramienta que se concreta en el desarrollo de dos aplicaciones:

La primera, denominada *AWebRescue*, es una aplicación Web (Figura A) que permite al usuario generar e imprimir códigos QR (Quick Response) con información relativa a elementos de seguridad de un modelo concreto de vehículo y sanitaria de los ocupantes habituales del mismo. Esta información se almacena codificada mediante un sistema numérico propio que garantiza la confidencialidad de la información que representan. Estos códigos se colocan en posiciones estratégicamente estudiadas del vehículo, para que en caso de accidente puedan ser leídos por los servicios de rescate.

Figura A: Captura de pantalla de la interfaz de la aplicación aWebRescue

La segunda, denominada *tagForRescue*, es una aplicación desarrollada para dispositivos móviles (Smartphones y Tablets) con sistema operativo IOS (Figura B). Se trata de una aplicación robusta, fiable y rápida que es capaz de leer y decodificar los códigos QR generados por la aplicación AWebRescue. A partir de los datos numéricos obtenidos de la lectura del código QR la aplicación extrae de una base de datos local toda la información técnica relativa al vehículo y sanitaria de sus ocupantes, mostrándola por pantalla de forma gráfica.

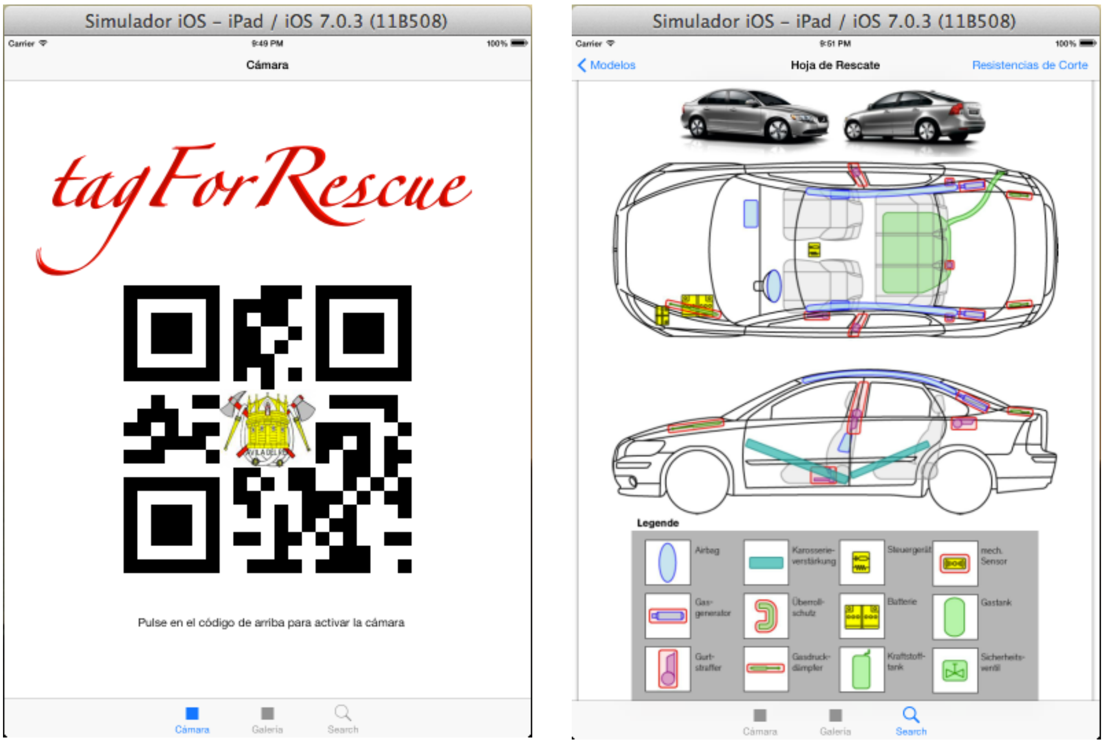

Figura B: Capturas de pantalla de de la aplicación tagForRescue