Evaluation of sinkholes in a civil work by capturing digital images using an unmanned aerial vehicle

Evaluación de socavones en una obra civil mediante la captura de imágenes digitales utilizando un vehículo aéreo no tripulado

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Key Handbooks

The main contribution of this research lies in the implementation of a drone for the acquisition of high-resolution aerial images and their subsequent processing to identify, quantify and characterise damage to the surface of a civil work with great precision. Particularly, in this study it was used for the study of sinkholes in the perimeter surface of a dock manoeuvring area, however, the method is applicable to the assessment of the state of any infrastructure and the early detection of possible damage, which allows intervention and maintenance plans to be made, reducing costs and study times. Among the key aspects of this study is the definition of the acquisition parameters that control the resolution of the images and their relationship with the size of the objects to be studied. By analysing high-resolution aerial images obtained with an unmanned aerial vehicle, 99 sinkholes in the civil works were identified and quantified, with an acceptable margin of error. The results suggest that the formation of these sinkholes is directly related to inadequate structural design, aggravated by natural factors and human activities.

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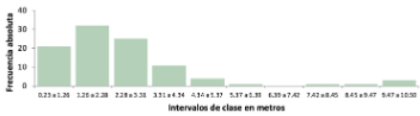
Abstract

This paper presents the results of a study carried out in a civil work located in a port of Ciudad del Carmen, Campeche, to detect the formation of sinkholes and quantify their dimensions using high-resolution aerial digital images acquired with an unmanned aerial vehicle at 60 m elevation and using 20 control points on site. Digital images were analyzed with ImageJ software to quantify and characterize the shape of the sinkholes in the civil work. Descriptive statistics were performed on the dimensions of the sinkhole structures identified, both in the field and in the digital images, to later compare the results obtained and evaluate the validity of the dimensions obtained from them. Likewise, a calculation of the percentage of damage in the perimeter was performed. The mean square and percentage errors were 0.03 m2 and 13%, respectively, which can be attributed to climatic factors during the acquisition of the images and the inherent limitations of the technique. 99 sinkholes were detected in the perimeter of the civil works, whose morphology and distribution suggest an origin related to an inadequate structural design of the retaining wall, aggravated by natural factors such as erosion and marine currents, as well as by anthropogenic activities such as heavy vehicle traffic. This research highlights the importance of implementing long-term monitoring programs based on remote sensing techniques.

- Quantify and characterize sinkholes in a civil work.
- Structure damage analysis.

- Acquisition of aerial photographs and control points.
- Descriptive statistics and damage analysis.



- Identification of damage in a civil work with digital images.

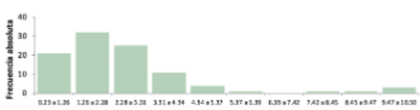
Structure, Anthropogenic, Morphology

Resumen

En este trabajo se presentan los resultados de un estudio realizado en una obra civil ubicada en el Puerto Pesquero de Ciudad del Carmen, Campeche, con la finalidad de detectar la formación de socavones y cuantificar sus dimensiones utilizando imágenes digitales aéreas de alta resolución adquiridas con un vehículo aéreo no tripulado a 60 m de elevación y utilizando 20 puntos de control en el sitio. Las imágenes digitales fueron analizadas con el software ImageJ para cuantificar y caracterizar la forma de los socavones en la obra civil. Se realizó la estadística descriptiva de las dimensiones de las estructuras de daño identificadas, tanto en campo como en las imágenes digitales, para posteriormente realizar la comparación entre los resultados obtenidos y evaluar la validez de las dimensiones obtenidas a partir de estas. De igual forma, se realizó el cálculo de porcentaje de daño en el perímetro. Los errores cuadrático medio y porcentual fueron de 0.03 m^2 y 13%, respectivamente, que pueden atribuirse a factores climáticos durante la adquisición de las imágenes y las limitaciones inherentes de la técnica. Se detectaron 99 socavones en el perímetro de la obra civil, cuya morfología y distribución sugieren un origen relacionado con un diseño estructural inadecuado del muro de contención, agravado por factores naturales como la erosión y las corrientes marinas, así como por actividades antrópicas como el tránsito de vehículos pesados. Esta investigación destaca la importancia de implementar programas de monitoreo a largo plazo basados en técnicas de teledetección.

- Cuantificar y caracterizar socavones en una obra civil.
- Análisis de daño de la estructura.

- Adquisición de fotografias aéreas y puntos de control.
- Estadística descriptiva y análisis de daño.



- Identificación de daño en una obra civil con imágenes digitales.

Estructura, Antropogénica, Morfología

Introduction

Sinkholes are geological depressions that occur when cavities in the subsoil collapse and can range in size from small cracks to large craters, and usually occur suddenly. They can arise from both natural processes and anthropogenic activities, including pipeline leaks, urban development, mining, among others.

The formation of sinkholes in karst environments is common and their origin is due to the dissolution of limestone rocks by seepage of fresh water or sewage (. Other natural causes of sinkhole formation are related to tectonic factors, such as fault displacements, fractures and vibrations produced by earthquakes.

The formation of sinkholes in urban areas and the involvement of civil works will depend on the natural and anthropogenic factors that are present, as well as the particular characteristics of the physical infrastructure affected. Sinkholes have been found to be closely related to groundwater overexploitation because the lowering of the water table creates a cone of depression that causes changes in the fluid pressure in the subsoil, leading to elastic and inelastic compaction, the latter causing the formation of voids.

In coastal areas, sinkholes can additionally be formed by the dynamics of sea currents and groundwater, as well as by extreme events such as storm surges, among others, causing damage to civil structures. However, the causes of damage to coastal civil works can also be associated with inadequate design. describes the occurrence of a sinkhole in a harbour due to poor design of the perimeter walls, where a section was shortened to relocate electricity supply cables.

The study of the physical integrity of civil works can be carried out using different techniques. They can be invasive (boreholes, borings, drilling, pitting, trenching, sampling and testing) and non-invasive (geophysical, aerial or satellite remote sensing), the latter being very useful in complex and difficult to access environments. In the context of sinkhole formation, the use of remotely sensed imagery and digital aerial imagery is restricted by its dimensions, making scale a critical factor; the resolution required for the detection of relatively small subsidence features (1.5 ± 3.0 m wide) comes from aerial imagery with scales between 1: 25,000 and 1: 10,000, although digital imagery from unmanned aerial vehicles now achieves high resolutions, making it possible to identify centimetre-sized objects.

In addition, recent studies are using interferometric synthetic aperture radar (InSAR) and photogrammetry for more precise measurements of sinkholes. To study these images, it is possible to use complex algorithms such as convolutional neural networks, including U-net , or more affordable techniques such as image analysis with ImageJ.

This paper analyses the formation of sinkholes in a civil engineering site in the port area of Ciudad del Carmen, Campeche (Figure 1), which represents a particular risk to infrastructure and economic activities in the region. Understanding the formation of sinkholes and their risks is crucial for urban planning and infrastructure safety.

Box 1

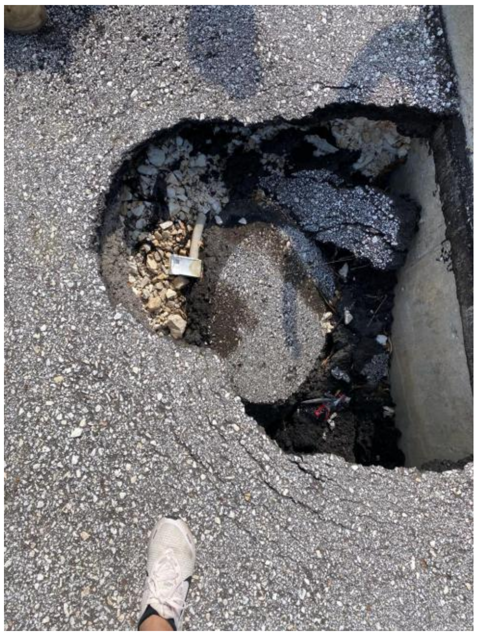


Figure 1

Formation of a sinkhole with collapsed asphalt layer in a port civil works, Ciudad del Carmen, Campeche

Source [O*wn elaboration*]

Furthermore, the study of sinkholes in urban contexts is fundamental in the identification of vulnerable areas and the implementation of preventive measures to protect not only infrastructure but also human lives, contributing to urban planning, land management and avoiding urban development in risk areas. Furthermore, sinkhole research is crucial to understand the natural and anthropogenic processes that trigger their formation and to develop accurate models for the prediction of their occurrence.

The added value of the present research lies in the combination of innovative, easily accessible and lower cost techniques (drones and specialised software) compared to traditional methods, to obtain a detailed characterisation of sinkholes and identify areas of higher risk. This information is essential for informed decision making in terms of management and mitigation of the problem.

Specifically, the study carried out in a dock of the fishing port of Ciudad del Carmen, Campeche, has employed a methodology that combines remote sensing techniques with an unmanned aerial vehicle for the capture of high-resolution digital images and statistical analysis, with the aim of characterising and quantifying the sinkholes present in the area. The results obtained have made it possible to identify critical areas with a higher frequency of sinkhole formation, and although further research is required to establish causality with greater certainty, it is possible to suggest some relevant factors in their formation, both natural and anthropogenic, which have been added to the high traffic and manoeuvres within the civil works. The study also lays the groundwork for more detailed future research, which should include geophysical analysis, numerical modelling and long-term monitoring, with the aim of understanding the mechanisms of sinkhole formation and developing effective mitigation strategies.

Methodology

During May and June 2023, two visits were made to the civil works under study. During the first visit, an inspection of the civil works site was carried out to identify the areas with the greatest presence of sinkholes, as well as to collect information on the dimensions of 20 randomly distributed sinkholes around the perimeter. The first visit mentioned that the shape of the sinkholes is usually conical, where the wide end opens at the surface, and is of variable shape, while the narrow end is located at the bottom (Figure 2). The depth of sinkholes can range from a few centimetres to more than several metres deep, and this parameter is measured from the ground surface, regardless of whether the cover is natural or artificial. In the present study, the dimensions of the selected control points were quantified by approximating an ellipse on the surface, with a major axis (parallel to the perimeter of the civil structure) and a minor axis (perpendicular to the major axis).

Although some voids were similar in shape to those described by the author, for practical purposes, the depth was not estimated in this study due to the variability of this parameter in the same void.

Box 2

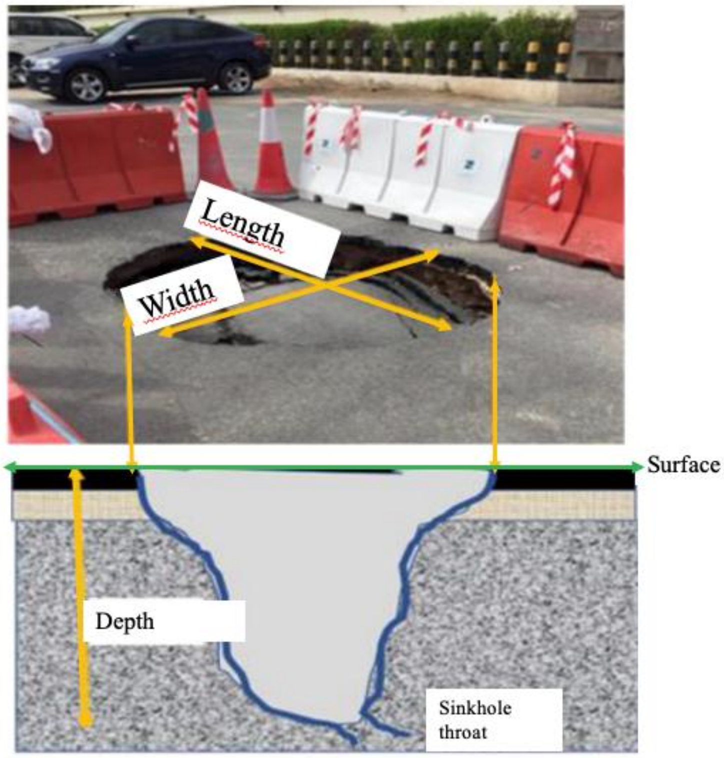


Figure 2

Measurement of the dimensions of an undercut

Source: [Modified from *Essa Al-Ansari et al. (2023*)

In the second visit to the study site, the acquisition of digital aerial images was carried out, focusing the investigation on the perimeter of the dock due to the initial identification of a greater presence of sinkholes in this area compared to the central area. The acquisition of the digital images was carried out with a DJI Mini 2 commercial drone, without vehicle movement in each shot and at a height of 60 m, taking into consideration that the sinkholes could be identified in at least two different images. The drone's camera has a resolution of 12 megapixels, focal length of 4.49 mm, sensor size 1/2.3 inches and in all shots it was positioned vertically. In addition, the acquisition of the digital images was performed around noon, with moderate cloud conditions and winds reported for the locality between 5.6 and 13 km/h.

The analysis of the undercuts was developed by processing the aerial digital images in ImageJ software (Schneider et al., 2012), with the aim of 1) mapping the totality of the surface exposed structures, 2) identifying the areas with the highest number of undercuts and 3) digitally quantifying the surface dimensions of the undercuts and their dimensions were estimated through the approximation of a surface ellipse, extracting the lengths of the major and minor axes of the same structure in two different shots and calculating their average.

In order to carry out a quality control of the measurements obtained in the images, the mean square error and the percentage error were estimated, taking as a reference the measurements obtained from the 20 undercuts of the reconnaissance visit to the site.

On the other hand, the calculation of the eccentricity of the cross-sectional areas of the undercuts and the percentage of structures with eccentricities above different thresholds was carried out.

Subsequently, descriptive statistics of the dimensions of the undercuts were developed and frequency histograms were elaborated. Similarly, the percentage of damage to the perimeter of the study site was estimated, considering the length of the major axis of the structures as the damaged perimeter, given that most of the undercuts are oriented with this axis parallel to the perimeter. In addition, the count of sinkholes per perimeter line (Figure 3) and the assignment of the orientation of the axis that is parallel to the perimeter was carried out, to finally determine the percentage of damage in each line of the perimeter in order to detect areas with greater damage.

Box 3

Figure 3
Location of the perimeter lines of the civil works.

Source [*own elaboration*]

Results

The results of the comparison between the dimensions of the undercuts obtained in situ and in the aerial images indicate a mean square error of 0.03^{m2} and a percentage error of 12.67%, both errors are considered low given the average size of the major axis of the characterised structures. The errors can be associated to different causes, mainly to the resolution of the acquired aerial images, which is related to the flight altitude and weather conditions during the acquisition, which makes it difficult to achieve a correct stability and positioning of the camera, resulting in complications when identifying the edges of the structures to be characterised in some images.

Box 4

Figure 4
Location of the sinkholes on the perimeter of the dock under study

Source [O*wn elaboration*]

The analysis of the digital images identified 99 shallowly exposed sinkholes (Figure 4), whose dimensions for the major axis range from 0.23 to 10.50 m, with an average of 2.56 m and a standard deviation of 1.97 m, while the minor axis measurements show an average of 1.31 m and a standard deviation of 0.70 m (Table 1).

Box 5

Table 1

Descriptive statistics on the dimensions of undercuts

	Minimum	Maximum	Medium	Average	Standard deviation
Major axis (m)	0.23	10.50	2.10	2.56	1.97
Minor axis (m)	0.23	3.68	1.18	1.31	0.70
Surface area (m^2)	0.04	20.62	2.11	3.11	3.42
Eccentricity (A)	0	0.99	0.82	0.75	0.24

Source [O*wn elaboration*]

Likewise, it is identified that the highest frequency of occurrence for the length of the major axis is found in the interval from 1.26 to 3.31 m, with 53% of the total number of sinkholes within this size (Figure 5), and for the length of the minor axis, the most frequent classes are found in the intervals between 0.23 and 1.96 m, grouping 83% of the total number of sinkholes in this range (Figure 6). The areas of the undercuts are in the range of 0.04 and 20.62 m2, with an average of 3.11 m2 and with a higher occurrence of those with areas smaller than 4.16 m2 (79%, Figure 7).

Box 6

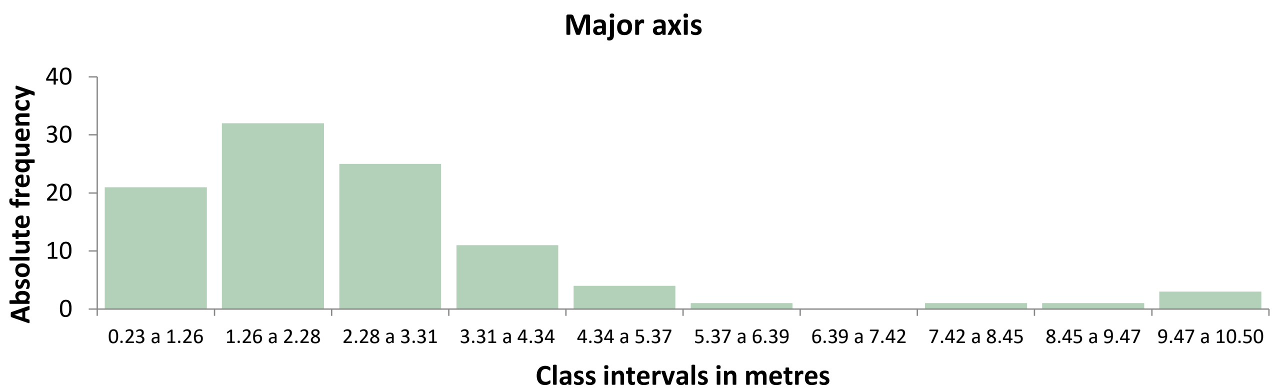


Figure 5

Histogram of absolute frequency of major axis of sinkholes identified in the basin under study

Source [*own elaboration*]

Box 7

Figure 6

Histogram of absolute frequency of minor axis of sinkholes identified in the basin under study

Source [*own elaboration*]

Box 8

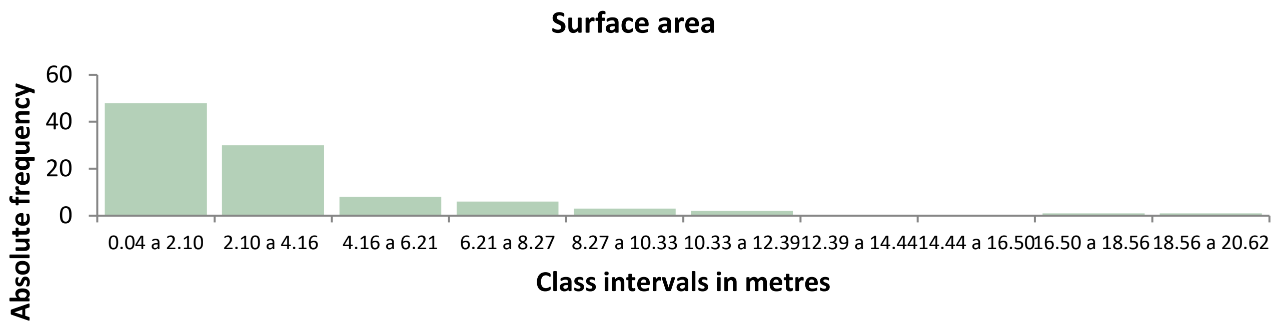


Figure 7

Absolute frequency histogram of the surface area of sinkholes identified in the basin under study

Source [*own elaboration*]

On the other hand, the analysis of the eccentricities of the surface areas of the undercuts indicates that most of them have highly eccentric shapes. The average for this parameter is 0.75 with a standard deviation of 0.24. In addition, 87% of them were identified as having values equal to or greater than 0.5 and 58% with values greater than 0.7 (Table 2). Similarly, of all the undercuts, 80% are found with the major axis oriented parallel to the perimeter, 9% with the minor axis parallel to the perimeter and 11% have similar lengths between the major and minor axes.

Box 9

Table 2

Percentage of undercuts with eccentricities greater than one value

	Minimum	Maximum	Medium	Average	Standard deviation
Major axis (m)	0.23	10.50	2.10	2.56	1.97
Minor axis (m)	0.23	3.68	1.18	1.31	0.70
Surface area (m^2)	0.04	20.62	2.11	3.11	3.42
Eccentricity (A)	0	0.99	0.82	0.75	0.24

Source [*own elaboration*]

The analysis of perimeter damage due to the formation of sinkholes indicates that 27.72% of the perimeter was affected. In addition, the analysis of the percentage of damage in each line of the perimeter shows that this is greater in line 1 and 2, with 48.87% and 37.62%, respectively, and with a greater average shaft size than the global average (Table 3).

Box 10

Table 3

Analysis of damage caused by sinkholes in the perimeter of the study basin

Perimeter line no.	Longitud (m)	Rumbo	No. of sinkholes	Average length of major axis	Standard deviation	Percentage of perimeter with damage (%)
1	106.32	N68.4ºE	10	5.20	2.82	48.87
2	435.45	N33.6ºW	59	2.78	1.69	37.62
3	198.67	N36.7ºE	23	1.29	0.62	14.94
4	177	N52.4ºW	7	1.10	1.18	4.34

Source [*own elaboration*]

The causes of the formation of the sinkholes and the damage identified at the site can be associated with various natural and anthropic factors, such as coastal erosion, sea currents and vibrations produced by waves, maritime traffic, heavy machinery and other factors inherent to the structures. At the same time, it is important to point out that the damage to the perimeter of the dock may be aggravated by the high traffic of heavy vehicles and machinery that carry out loading and unloading manoeuvres, together with the vehicles that pass through on a daily basis due to the activities inherent to the port.

The results of the characterisation of the sinkholes, i.e. their size, shape, location, orientation and frequency of occurrence, suggest that the main control of their formation is related to the inadequate design of the civil works, particularly the perimeter retaining wall, and the damage is increased by the natural and anthropic factors to which it is exposed. In this regard, a study of sea currents is recommended in the design of this type of civil structures, in order to estimate the maximum stresses to which they will be subjected, as well as to consider future scenarios of rising sea levels and other effects associated with climate change, given that a rising sea level implies an increase in the magnitude of the stresses on the retaining walls. Similarly, a monitoring of environmental vibrations would provide relevant information for the rethinking of port manoeuvres and activities, in order to avoid further damage to the structure, giving a guideline to carry out the necessary actions to solve the problem of damage faced by the perimeter of the dock.

On the other hand, the high eccentricities found in the shape of the sinkholes indicate that immediate attention is required in terms of the operability of the basin, as there are important implications for the stability of the terrain. Sinkholes with cross-sectional areas with low eccentricity values will allow stresses on the surrounding ground to be more evenly distributed around the cavity, which may suggest greater stability, while those with more eccentric shapes will concentrate stresses at the narrower ends, decreasing stability and increasing the risk of collapse.

Complementary studies are necessary for the identification of unexposed voids, particularly with geophysical methods since, during the reconnaissance visit, voids were identified adjacent to the exposed voids on the surface but still covered by the asphalt layer. In addition, geophysical surveys would provide relevant information on the formation process of the sinkholes. Continuous monitoring of the civil structure, particularly the retaining wall, is also recommended in order to detect any signs of deterioration and take corrective measures in time.

Finally, it should be noted that given the dimension of the problem at the site at the time of the study, the sinkholes were constantly filled with granular materials of different sizes and the most affected perimeter has been delimited to avoid overloading the civil structure.

Conclusions

99 sinkholes of varying dimensions were identified with the analysis of digital images obtained with an unmanned aerial vehicle and validated with 20 control points.

A mean square error of 0.03^{m2} and a percentage error of 12.67% were obtained between the control points and the dimensions extracted from the digital images, associated with the non-ideal environmental conditions during the acquisition. This error can be reduced by performing the digital image acquisition under more appropriate environmental conditions, particularly with lower wind speeds.

Statistical analysis of the surface morphology of the sinkholes, as well as their location and frequency of occurrence, suggest that the origin of their formation is related to the inappropriate design of the wall on the perimeter of the dock, the damage being increased by the natural and anthropic factors to which it is exposed, particularly on the perimeter lines that have a greater activity of manoeuvres and traffic of vehicles and heavy machinery.

It is necessary to carry out complementary studies using geophysical methods to identify unexposed sinkholes and the physical characteristics of the subsoil at depth, as well as marine currents and groundwater, in order to provide more information on the causes of their formation.

Regular monitoring of the civil structure with the implementation of automated techniques for damage detection is also recommended.

Declarations

Conflict of interest

The authors declare that they have no conflicts of interest. They have no financial interests or personal relationships that could have influenced this book.

Authors' contributions

Pavón-Moreno, Julio: Original drafting, data acquisition and revision.
Escorza-Reyes, Marisol: Original drafting, statistical analysis and review.
Vergara-Huerta, Filiberto: Data processing and review.
Canto-Pérez, Emily: Data acquisition and review.

Availability of data and materials

The information contained in this paper is available on request from the lead author.

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Abbreviations

DJI Da-Jiang Innovations

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