IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 26 August 2023, accepted 25 September 2023, date of publication 2 October 2023, date of current version 10 October 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3321142

SURVEY

Drones for Road Accident Management: A Systematic Review

ADEL GOHARI[1], ANUAR BIN AHMAD[1], RUZAIRI BIN ABDUL RAHIM[2,3], NASSRIN IBRAHIM MOHAMED ELAMIN[4], (Member, IEEE), MOHAMMED SALIH MOHAMMED GISMALLA[5], (Senior Member, IEEE), OLORUNTOBI OLAKUNLE OLUWATOSIN[6], RAZI HASAN[7], AMIR SHARIFUDDIN AB LATIP[8], AND ABDULMAJID LAWAL[5]

[1]Department of Geoinformation, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[2]School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[3]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Malaysia
[4]Faculty of Electronics and Electrical Engineering, International University of Africa, Khartoum 12223, Sudan
[5]Center for Communication Systems and Sensing, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran 31261, Saudi Arabia
[6]Faculty of Maritime Studies, Universiti Malaysia Terengganu, Kuala Terengganu, Terengganu 21300, Malaysia
[7]Centre for Accident Research and Road Safety–Queensland (CARRS-Q), Queensland University of Technology (QUT), Kelvin Grove, QLD 4059, Australia
[8]School of Geomatics Science and Natural Resources, College of Built Environment, Universiti Teknologi MARA, Shah Alam, Selangor 40450, Malaysia

Corresponding authors: Nassrin Ibrahim Mohamed Elamin (nisreenalameen@gmail.com) and Mohammed Salih Mohammed Gismalla (mohammed.gismalla@kfupm.edu.sa)

This work was supported in part by the Universiti Teknologi Malaysia (UTM) Research Alliance (RA) ICONIC Grant; in part by the Research Management Centre (RMC) through the Professional Development Research University, UTM, Malaysia, under Cost Center No. Q. J130000.21A2.07E03; and in part by IRC for Communication Systems and Sensing, King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia.

ABSTRACT The aim of this study is to conduct a systematic review of the academic literature regarding applications of drones in road accident management. It is an attempt to address key research questions regarding its status, applications, solutions, challenges, and opportunities. It is the first scholarly study specifically devoted to this topic that we are aware of. A systematic search of the Web of Science and Scopus databases yielded 26 relevant articles out of 147 initially identified records. The findings indicate that the emphasis in earlier studies has predominantly been on accident investigation and analysis, with a specific focus on 3D accident scene reconstruction. This review also shows a growing trend towards adopting emerging technologies like drones and integrating them with Industry 4.0 technologies for efficient road accident management. The advantages of drones for each component of road accident management were explored, and their primary challenges were identified, which are linked to flight (permission or operation) and data (collection or processing). Despite the existence of different solution methodologies and frameworks, there remains a dearth of studies examining their suitability for complex accident cases, real-life scenarios, and large-scale accidents.

INDEX TERMS Drone, road accident management, component, systematic literature review.

I. INTRODUCTION

Road Accident Management (RAM) is the process of responding to and managing road accidents from the time they happen until they are resolved. The objectives of various actions and activities in this process are not only to minimize the impact of accidents on the people involved and on traffic flow but also to prevent further accidents. RAM includes four main components:

The associate editor coordinating the review of this manuscript and approving it for publication was Cong Pu.

1. Detection and reporting [1], which involves identifying accidents as soon as they occur, assessing the severity of the situation, and notifying the necessary emergency services.

2. Response and scene management [2], which includes providing immediate medical attention to injured persons, protecting the accident area to avert more collisions, and managing traffic flow to minimize disruption.

3. Investigation and analysis [3], which involves determining the accident's cause, collecting evidence, and analysing the data to identify patterns and trends that can inform future accident prevention measures.

4. Recovery and clean-up [4], which involves removing damaged vehicles and debris from the accident scene and restoring normal traffic flow as quickly and safely as possible.

Effective RAM necessitates the cooperation and coordination of multiple agencies, such as emergency services, law enforcement, transportation authorities, and healthcare providers. RAM can assist in lessening the frequency and severity of accidents and improving safety for all road users by quickly responding to road accidents, which can be very costly [5], and by applying appropriate preventive measures. However, the reliance on manual data collection, visual examination, and subjective assessment in current RAM systems leads to drawbacks such as high costs, time-intensive processes, and limited effectiveness due to under-reporting and poor data quality [6].

The Fourth Industrial Revolution (Industry 4.0) is the sustainability of innovation, automation, and sophisticated processes [7], and it is characterized by the integration of advanced technologies. Several Industry 4.0 technologies (e.g., Intelligent Transportation Systems (ITS) technology, Geographic Information Systems (GIS), remote sensing, mobile technologies, Artificial Intelligence (AI), wearable technologies, autonomous vehicles, etc.) are used for RAM activities to improve the speed and effectiveness of accident response efforts, reduce the risk of secondary accidents, and enhance the safety of road users and emergency responders. ITS technology, which uses smart technologies to improve transportation efficiency and safety, can be used to monitor traffic flow, detect accidents, and alert emergency responders. GIS technology, which is a system designed to capture, store, manage, analyze, and present spatial or geographical data [8], can be used to map accident locations, identify high-risk areas, analyze accident data, and identify patterns and trends [9], [10], [11]. Remote sensing technologies, such as satellite imagery and aerial drones, can gather real-time data about accidents, traffic patterns, and road conditions. Mobile technologies can be used by emergency responders to access critical accident information quickly. AI technologies, such as machine learning and computer vision, can analyse accident data to identify patterns and trends. Wearable technologies, such as smart helmets and vests, can monitor vital signs of emergency responders in real-time [12]. Autonomous vehicles can transport injured persons quickly and safely to medical facilities [13].

Drones, or Unmanned Aerial vehicles (UAV), are remote sensing technologies equipped with cameras, sensors, and other technologies that gather and transmit data from the air. They are used by a variety of organizations, public agencies, and private companies across industries such as agriculture, transportation and logistics, construction, film and media, energy, insurance, mining, oil and gas, search and rescue, etc. UAVs can be beneficial to RAM in different ways. For instance, they can provide real-time images and data about the accident scene [14], enabling emergency responders to assess the situation quickly. Drones can inspect damaged infrastructure, helping transportation authorities to identify and repair damage [15]. Drones can monitor traffic flow around accident scenes, directing traffic away from the site to reduce the risk of secondary accidents [16]. Drones with thermal imaging can aid in search and rescue operations [17]. Other benefits include improved situational awareness, enhanced safety, cost-effectiveness, increased accuracy, and improved data sharing.

Despite the significant potential of UAV technology to enhance RAM activities, the literature on its applications in this field is currently inadequate. A review of existing literature reveals that Bisio et al. [18] systematically reviewed drone-aided traffic monitoring systems from the standpoint of deep learning. Torbaghan et al. [6] have reviewed the literature to investigate the impact of the adoption of different emerging technologies on the data acquisition of different road safety factors. In another study, Outay et al. [15] has discussed the developments and trends in road safety, traffic and highway infrastructure management. These recent studies have not reviewed the literature with a particular focus on the UAV-assisted RAM. Given the growing interest in this emerging technology for RAM, it is essential to conduct more comprehensive and up-to-date research that can provide a summary of the current state of knowledge as well as identify potential benefits, limitations, and challenges associated with its adoption. Without a proper understanding of these factors, decision-makers, including researchers, policymakers, and practitioners, may struggle to make informed decisions about the implementation of UAVs for RAM. This unawareness could lead to inefficient use of resources and could also negatively impact the safety and privacy of individuals involved in road accidents. So, this work is dedicated to addressing this gap in the literature by conducting a systematic review of existing studies and answering the following research questions:

RQ1. What is the status of UAV applications in RAM?

RQ2. What are the main current UAV applications in RAM?

RQ3. What are the main advantages and challenges of UAV adoption in RAM?

RQ4. What UAV-based solutions are proposed in RAM?

The subsequent sections of this paper are structured as follows: Section II presents a comprehensive explanation of the systematic review methodology, highlighting its key aspects and justifications. Section III, which comprises four subsections, presents the corresponding answers to each of the four research questions individually. Finally, the conclusion is provided in the last section.

II. METHODOLOGY

In this study, a systematic literature review was conducted to achieve its aim. The report of this systematic review was according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement (www.prisma-statement.org), which includes a three-stage flow diagram consisting of identification, screening, and inclusion. The PRISMA-based flow diagram of the review is depicted in Figure 1, created using the PRISMA Flow Diagram tool (https://estech.shinyapps.io/prisma_flowdiagram/) provided by Haddaway et al. [19]. In the identification stage, the Scopus and Web of Science (WoS)-Clarivate Analytics databases were searched on March 14, 2023, using an advanced search tool and the search string in the title, abstract, and keywords. The complete search string was (''drone'' OR ''unmanned aerial vehicle'' OR ''uav'') AND (''traffic accident'' OR ''road accident'' OR ''vehicle accident''). Initially, the search of the Scopus and Web of Science (WoS) databases yielded a total of 147 records. WoS yielded 22 records, while Scopus yielded 125 records. After limiting the WoS search results to only include articles and proceeding papers, 21 records in English remained. The Scopus search results were limited to articles and conference papers, journal and conference proceeding sources, and English language, resulting in 107, 105, and 101 records, respectively. Thus, a total of 122 records (21 from WoS and 101 from Scopus) were deemed relevant for further processing. It should be noted that our search in both databases did not impose any restriction or constraint on the earliest possible publication year. Upon checking the 122 records, it was found that 16 of them were duplicates and were consequently eliminated. This resulted in a total of 106 records that were identified during the identification stage and were subjected to further processing.

In the screening stage, the authors checked the titles and abstracts of the 106 records and excluded 39 records (2 records were survey/review articles and 37 records addressed irrelevant topics to this study). Three articles were excluded as the full text was unavailable. The remaining 64 records were screened in full text to identify articles meeting the inclusion criteria, which focused on UAV applications in RAM activities such as accident detection, analysis, emergency response, traffic monitoring around the accident scene, and accident scene recovery. Six articles were not actual UAV application and 32 articles addressed road traffic monitoring for the accident prevention and reduction purposes, which were out of the scope of this review. Consequently, a total of 26 articles met the inclusion criteria of this review.

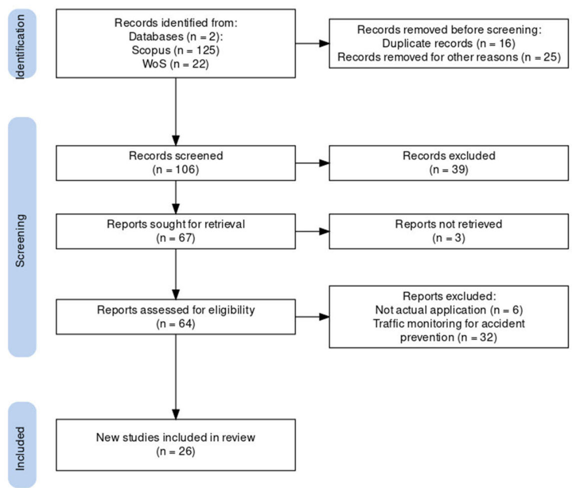

FIGURE 1. **The PRISMA-based process for selecting pertinent literature.**

III. RESULTS

A. STATUS OF UAV APPLICATIONS IN RAM (RQ1)

Despite the significant contribution of innovative UAV technologies to Industry 4.0, the first article that addressed UAV-RAM integration was not published until 2015. The results of the annual number of published articles indicated that the highest number of articles was published in 2021 (7 articles or 26.92%), followed by 2020 (5 articles or 19.23%), 2019 and 2017 (4 articles or 15.38% each), 2022 (3 articles or 11.53%), 2016 (2 articles or7.69%). The lowest publication appeared in 2015 (1 article or 3.84%) while no publication found in 2018. The trend of the data first shows the growth in the number of annual publications from 2015 to 2017. Secondly, there was a significant decrease in 2018, when no publications were recorded. Finally, the number of annual publications has gradually increased from 2019 to 2021. However, the number of publications declined in 2022 compared to the previous year. The trend generally indicates some fluctuations with periods of growth and decline; however, the cumulative number of publications has been growing in recent years.

Table 1 presents the distribution of articles on UAVs in the RAM context by country and year. The results reveal that China and the USA, which are considered leaders in Industry 4.0 investments, accounted for more than 38% of the total number of articles published. Following them, four countries, including Portugal, Russia, Malaysia, and Saudi Arabia, were ranked third. From the continental point of view, the highest contribution was assigned to Asian researchers (51.61%), followed by European authors (32.25%), North American authors (12.9%), and one article from African authors (3.22%). Unfortunately, no articles were found from Latin American or Oceanian institutions. It is worth noting that all countries were included based on the affiliation of authors, even in cases where authors are from different countries. For instance, if an article had authors from two distinct countries, it was counted twice.

B. CURRENT UAV APPLICATIONS IN RAM (RQ2)

Table 2 presents a comprehensive categorization of the application of drones to different RAM components, as outlined in the Introduction Section. The table provides detailed information on the classification of drones' applications by component, context, involved technologies, and theoretical approach, which helps to develop a profound understanding of their practical implementation. 76.92% of the publications concentrated on investigating and analysing accidents (component 3) while the other components have received relatively little attention from researchers. In this regard, 11.53% dealt with detecting and reporting accidents (component 1), response and scene management (component 2) assigned 7.69%, and only 3.84% devoted to recovery and clean-up (component 4).

TABLE 1. Involvement of countries in the publications related to UAV-RAM until march 2023.

Country	Year								Percentage %
	2015	2016	2017	2018	2019	2020	2021	2022	
China	-	1	1	-	2	-	3	1	25.8
USA	1	-	2	-	-	-	1	-	12.9
Portugal	-	-	-	-	1	1	-	-	6.45
Russia	-	1	-	-	-	-	-	1	6.45
Malaysia	-	-	-	-	-	1	1	-	6.45
Saudi Arabia	-	-	-	-	-	-	2	-	6.45
Italy	-	-	-	-	1	-	-	-	3.22
India	-	-	-	-	-	-	-	1	3.22
UAE	-	-	-	-	-	-	1	-	3.22
Spain	-	-	-	-	1	-	-	-	3.22
Croatia	-	-	-	-	-	1	-	-	3.22
UK	-	-	-	-	-	1	-	-	3.22
Kuwait	-	-	-	-	-	1	-	-	3.22
Morocco	-	-	1	-	-	-	-	-	3.22
Singapore	-	-	-	-	-	-	1	-	3.22
Czech	-	-	1	-	-	-	-	-	3.22
Bulgaria	-	-	-	-	-	1	-	-	3.22

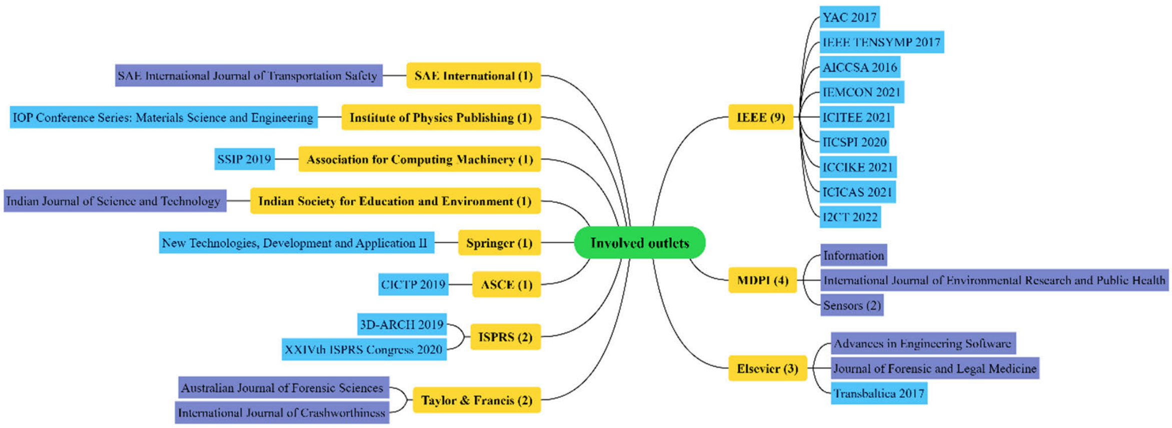

FIGURE 2. involved publishers (yellow), journals (purple), and conferences (blue).

When it comes to the application context of drones in RAM components, the most popular contexts were reconstructing the 3D accident scene in component 3 and accident detection in component 1. According to Table 2, twenty-four articles addressed topics related to vehicle-to-vehicle accidents. In addition, twenty articles addressed the reconstruction of 3D accident scenes. Eighteen out of these twenty articles specifically focused on car-to-car accidents, while car-to-bicycle and car-to-pedestrian accidents were only discussed in one article each. Within the car-to-car accident category, twelve articles focused on reconstructing 3D accident scenes in normal environmental conditions. Additionally, one article investigated accidents in extreme environments. Three articles conducted comparative studies, with one assessing accidents under different environmental and light conditions and in the presence of obstacles, another presenting a comparison between two vehicle detection algorithms. One article specifically classified road accidents. Finally, one article aimed to address both accident vehicle identification and 3D accident scene reconstruction, encompassing two components of RAM. The application context of the remaining six out of twenty-six articles was about accidents and their location detection (3), first aid delivery (2), and debris object detection (1). The classification of articles is illustrated in Figure 3.

The integration of UAVs with important technologies in Industry 4.0 was also noted as a common trend in this field. As for theoretical approaches, most articles proposed various algorithms, frameworks, systems, and methodologies. However, it is important to note that the efficiency and performance of these proposed solutions were mainly verified in a simulation environment, and only a few articles presented real-world case studies.

C. ADVANTAGES AND CHALLENGES OF UAV ADOPTION IN RAM (RQ3)

1) ADVANTAGES

There are several advantages of using UAVs for each component of RAM. For accident detection and reporting, UAVs are capable of flying over accident-prone areas and collecting real-time information, which can then be relayed back to a

TABLE 2. Categorization of the drones' applications according to RAM components.

Database	Reference	Component	UAV application context	Involved technologies	Theoretical approach
WoS	Almeshal et al. [20]	3	Reconstruct the 3D accident scene under extreme environments	UAV, SFM	Framework, real accidents
	Cappelletti et al. [21]	3	Reconstruction of the accident site	UAV, laser scanning	Experimental test
	Liu et al. [22]	3	Reconstruct the 3D accident scene (Intelligent distance measurement)	UAV	Algorithm
	Liu et al. [23]	3	Reconstruct the 3D accident scene	UAV, SFM	Framework, case study
	Nejjari et al. [24]	1	Real-time accident detection in highways	UAV, vehicular sensors, Smartphone, ground WSN	System
	Pérez et al. [25]	3	Reconstruct the 3D accident scene	UAV, SFM, and MVS	Methodology, case study
	Raj et al. [26]	3	Accident vehicle identification and reconstruct the 3D accident scene	UAV, graphical programming software	Comparative study, algorithm, case study
	Saveliev et al. [27]	3	Reconstruct the 3D accident scene	UAV, deep learning model	Framework, simulation, case study
	Škorput et al. [28]	3	Reconstruct the 3D accident scene	UAV	Simulation
	Su et al. [29]	3	Reconstruct the 3D accident scene	UAV	Real-world case study
	Wang et al. [30]	3	Reconstruct the 3D accident scene (car-to-pedestrian)	UAV, laser and structured-light scanners, numerical simulations	Simulation, case study
Scopus	Alam and Valles [4]	4	Debris object detection	UAV, deep learning model	Framework
	Alkinani et al. [31]	2	First aid delivery	UAV, 5G, IoT, edge computing	System
	Chen et al. [32]	3	Accident scene diagramming	UAV, feature point algorithms, image fusion algorithm	System
	Damyanov [33]	3	Reconstruct the 3D accident scene	UAV, image processing software	Experimental study
	Feng-Hui et al. [34]	1	Accident detection	UAV, Resnet–Single-Shot Multibox Detector (R-SSD) algorithm	Algorithm
	Hng et al. [35]	1	Locate traffic accident	UAV, computer vision (object detection convolutional neural network)	Algorithm
	Jurkofsky [36]	3	Accident scene diagramming	UAV, image processing software	Methodology
	Khan et al. [2]	2	First aid delivery	UAV, mobile applications	System, use case diagram
	Kim [37]	3	Classifying traffic accidents	UAV	Conceptual
	Koshe et al. [38]	3	Road accident analysis	UAV, SFM, machine learning	System
	Liu et al. [39]	3	Reconstruct the 3D accident scene (car-to-bicycle)	UAV, Multi-view stereo	Framework, case study
	Amin et al. [40]	3	Reconstruct the 3D accident scene	UAV, image processing software	Methodology, case study
	Pádua et al. [41]	3	Reconstruct the 3D accident scene under normal condition, adverse light condition, and presence of obstacles	UAV, image processing software	Comparative study, methodology, experimental tests: simulated and real scenarios
	Stáňa et al. [41]	3	Traffic accidents scene documentation	UAV	Comparative study
	Wang et al. [3]	3	Reconstruct the 3D accident scene	UAV, 3D laser scanner	Methodology, simulation

base station or other relevant entities. The use of UAVs also enables a rapid evaluation of the extent of the damage [24]. By streaming live footage of the accident, UAVs can help to reduce the amount of time paramedics spend assessing the situation [35]. This can ultimately lead to faster response times and more efficient accident management.

UAVs in response and scene management possess the advantage of unhindered navigation to specific GPS positions, bypassing traffic and facilitating the collection of additional information, ultimately enhancing the potential for saving human lives [2].

In regard to accident investigation and analysis, by using UAV photogrammetry, accident scenes can be reconstructed in 3D models, which can replace the current classical accident measurement approach and enhance accident investigation procedures [20], [22], [29], [33], [39], [40].

Application of UAVs for 3D reconstruction of accident scenes with other conventional methods are compared and presented by Stáňa et al. [42] and Pádua et al. [41]. Using UAVs can assist in short-time documenting of the whole accident location area, which significantly reduces the time needed for reopening the road, gathering detailed information, and documenting accident parameters [28], [29], [33]. UAV-based approach allows for collecting more data with higher precision compared to current methods and offers a reliable and accurate alternative to reconstructing the accident scene [28], [40], especially for road traffic accidents in extreme environment [20]. Additionally, the use of UAVs in

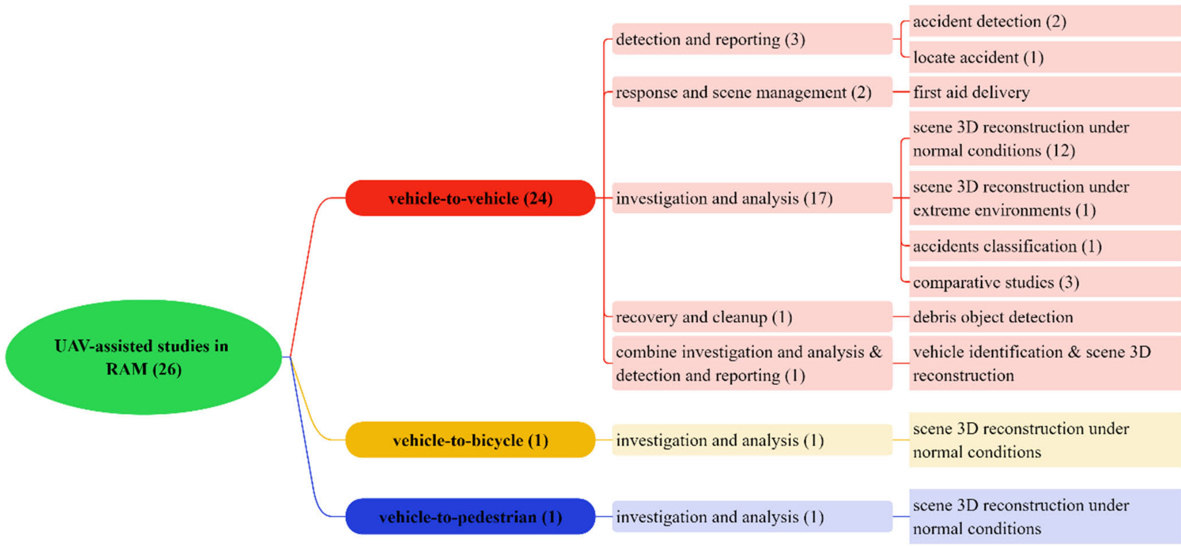

FIGURE 3. Classification of articles according to accident type and RAM components.

accident investigation reduces the need for physical attention of the person in charge [40] and reduces injury risks for employees of police, court, and other services during the investigation process [22], [28], [40].

UAVs in recovery and clean-up offer the advantage of efficiently locating debris and ensuring the safety of individuals involved in road accidents, enabling the prompt removal of hazardous materials from roads and highways [4]. This dual benefit enhances human safety while expediting the overall cleaning process following a vehicle accident.

2) CHALLENGES

Despite of the benefits of the use of UAVs in each of the RAM components, but there are some limitations and challenges that can be categorised into flight permission/operation and data collection/processing.

a: FLIGHT PERMISSION/OPERATION CHALLENGES

Implementing UAV flights encounters restrictions in certain areas [23] and faces legal complexities [25], necessitating official permissions and clearances. Additionally, adverse weather conditions such as wind, rain, and fog, as well as complicated flight circumstances, such as trees, bridges, and road-side electronic facilities, can pose safety threats to UAV operations. This can lead to incomplete or inaccurate data collection, which can hinder the accuracy of the results of data analysis or produced models. Moreover, there may be situations where the use of UAVs may not be applicable, such as in fly-restricted zones and hard-to-access areas like tunnels and areas with severe obstructions [20], [23]. This can limit the ability to obtain accurate data of the accident scene.

b: DATA COLLECTION/PROCESSING CHALLENGES

In the context of 3D reconstruction accident modelling, one of the main issues is the security of data privacy since these models may contain sensitive information useful for further investigation and insurance claims [23]. Hence, measures must be taken to ensure that the data is well protected and available only to authorized personnel. Another important concern is related to the modelling process which can be inconvenient due to the large amount of data that needs to be processed. This can lead to longer analysis times and the use of multiple software programs, which can increase the complexity of the analysis process [3]. This challenge can be addressed by simplifying the analysis process using more efficient software tools or reducing the amount of data collected during the UAV flight. Accident detection also faces its own set of challenges. UAV ground target detection technology encounters issues such as inadequate target resolution, scale variations, environmental influences, interference from multiple targets, complex background surroundings, and repeated target detection [34]. To address these challenges, potential solutions include improving sensor resolution, developing sophisticated algorithms, using advanced image processing techniques, and investigating advanced tracking and recognition algorithms to enhance UAV ground target detection capabilities and improve accuracy.

D. PROPOSED SOLUTIONS (RQ4)

Regarding reconstruction of the 3D car-to-car accident scene in a normal situation, Jurkofsky [36] utilized Unmanned Aerial System (UAS), which is a system that includes the airplane attached with all its necessary equipment without human pilot, and image processing software to collect aerial images and analyse them. The study concluded that the photogrammetric method provides accurate measurements that fall within acceptable limits for reconstructing the accident. Su et al. [29] developed a system that uses UAV/camera hardware and image processing software for easy and rapid accident scene mapping from rectified images. Liu et al. [22] suggested an algorithm that utilizes UAV image mosaic technology to enable intelligent distance measurement in road traffic accident scenes. The system enables lens distortion and perspective distortion elimination. Liu et al. [23] presented a framework to obtain both the Digital Surface Model (DSM) and the Digital Elevation Model (DEM) of the accident scene. A DSM represents the Earth's surface, encompassing both natural and man-made features, while a DEM provides digital terrain and elevation data. Pérez et al. [25] introduced a method to create orthophotos that effectively document scenes of traffic accidents. The methodology captures high-resolution video and selects images that meet overlapping criteria, rejecting those with noise or a lack of sharpness, allowing for flexibility in choosing alternative images that meet the criteria. Additionally, the methodology includes adjusting the photogrammetric block using measured distances between control points obtained through Global Navigation Satellite System (GNSS) techniques, eliminating the need for expensive equipment and simplifying the reconstruction process for road accidents. GNSS is a network of satellites providing worldwide location and navigation information. Damyanov [33] conducted an experimental study using UAVs and 3D image processing software to demonstrate the potential of photogrammetric methods in accident investigation and reconstruction. Škorput et al. [28] presented a methodology that combines UAV-based aerial photography with computer 3D tools to generate 3D point cloud models and orthophotos that can be used for accident scene reconstruction. Amin et al. [40] proposed a four-step methodology that includes preliminary work, data acquisition involving two different flight plans (Point of Interest (POI) and Waypoint (Aerial Nadir)) and camera calibration, data processing encompassing image processing, dense cloud generation, meshing, texturing, and 3D model processing, and finally, data analysis involving accuracy assessment and frequency table analysis. Pádua et al. [41] proposed a four-step methodology for digitally documenting road traffic accidents, involving acquisition planning (including evaluation of the crash scenario and selecting an appropriate process), data acquisition (including scene imagery and measurements), and data processing and analysis using photogrammetric software. Chen et al. [32] adopted a methodology that involves preprocessing and rectifying UAV images using plane homography. This was followed by stitching two images together through feature point matching and image fusion to create a comprehensive view image. Finally, the accident mosaic image was utilized as a background to draw the accident scene map. Wang et al. [3] proposed a methodology that utilizes fused scene data from a UAV and a 3D laser scanner to digitize the accident scene, enabling accident reconstruction and generating accident process data along with a 3D model. Furthermore, the recreated accident scene and process are analysed to identify the underlying accident causes. Koshe et al. [38] presented the integration of machine learning and videogrammetry techniques to analyse road accidents using videos and images from UAVs, where the machine learning model classifies accident site images based on accident causes and videogrammetry employs Structure from Motion (SFM) techniques to generate a point cloud mesh from the captured video. SFM is a photogrammetric technique that reconstructs 3D structures from 2D images. Saveliev et al. [27] created a system that leverages UAV technology and deep learning methods to achieve precise measurements and automate the reconstruction process of road accidents with high accuracy.

Stáňa et al. [42] presented a comparative analysis of accident scene documentation, evaluating the results obtained from advanced methods involving GNSS and UAV as well as conventional methods. Cappelletti et al. [21] evaluated the effectiveness of employing UAV photogrammetry and laser scanning in contrast to conventional surveying techniques for capturing detailed data from accident scenes.

Almeshal et al. [20] examined the precision of UAV photogrammetry in road accident scenarios under both typical and challenging operating conditions, including extreme temperatures, light intensities, and environmental factors, with the experiments demonstrating favourable and acceptable measurement accuracy in normal and extreme operating conditions, respectively.

Kim [37] developed a methodology to classify traffic situations by analysing the captured scene from UAVs after the event. The methodology consists of four components: receiving video information, formulating descriptions of the observed scenes, identifying the traffic class through situation analysis, and describing the situations, including the objects of interest, their attributes, and the interrelationships between them.

Raj et al. [26] proposed an algorithm for car detection in accident scenes and compared the resulting 3D model of the accident scene, utilizing both the point cloud and image stitching techniques, with a focus on preserving the accuracy of accident data.

Car-to-pedestrian and car-to-bicycle accidents are addressed in two articles. In this regard, Wang et al. [30] used multiple geomatics techniques, including a UAV, laser scanner, and structured-light scanner, for data collection, while different numerical simulations, including Multi-Body System (MBS) and Finite Element (FE) simulations, were conducted to reconstruct the kinematics of the collision between the car and pedestrian and to forecast potential injuries. Liu et al. [39] proposed a method for car-to-bicycle accident scene reconstruction that involves the use of a UAV to capture images, an imaging system to reconstruct 2D and 3D scenes, and subsequent 3D reconstruction, point cloud generation, and model optimization.

Regarding the use of UAVs in road accident detection, Nejjari et al. [24] presented a system that enables real-time accident detection by integrating UAVs, ground Wireless Sensors Networks (WSNs), vehicular sensors, and smartphones. Feng-Hui et al. [34] proposed an algorithm that utilizes feature information fusion to enhance the accuracy of accident detection, minimize feature redundancy, and meet real-time requirements. In another study, Hng et al. [35]

presented the use of a UAV integrated with computer vision algorithms (for object detection and tracking) and a proprietary MATLAB algorithm (for data reading) to identify the accident location.

UAV-assisted systems for improving first-aid delivery in RAM were also introduced. Khan et al. [2] developed a user-friendly system utilizing a UAV and a mobile app to provide emergency health services in hard-to-reach areas, addressing time constraints faced by ambulances. On the other hand, Alkinani et al. [31] presented a reporting and detection system that integrates the Internet of Things (IoT), 5G, and UAVs to enhance accident detection accuracy and reduce response time.

Lastly, Alam and Valles [4] attempted to develop an optimized two-step framework utilizing UAVs and deep learning techniques to enhance the efficiency of road accident debris cleaning. The framework involves UAV operations for photography and videography purposes and the application of machine learning algorithms to detect objects.

IV. CONCLUSION

This research contributed to existing knowledge by conducting a systematic review of academic literature focused on drone-assisted solutions for road accident management. First, an overview of the status of drone applications from the viewpoint of annual publications, countries involved, and interested publishers is provided. Next, the study classified the included articles based on the types of road accidents and components of road accident management. Next, it identified the benefits and challenges associated with adopting drone technology to address road accident management concerns, drawing insights from the reviewed articles. Lastly, the research delved into the proposed strategies, providing valuable insights that contribute to further advancements in the field.

This review highlights that the research on the utilization of drones for road accident management is still at an early stage, as evidenced by the limited number of relevant articles published thus far, starting from the first publication in 2015 until the present. Most of these publications primarily focus on investigating and analysing accidents, while the other components of road accident management have received comparatively less attention. Among the various applications, reconstructing the 3D accident scene emerges as the most prevalent context, followed by accident detection. The adoption of drones offers significant advantages, including real-time and efficient data collection, seamless navigation to specific GPS positions, enhanced precision, and reduced risks to personnel involved. These advancements have the potential to positively impact traffic flow, expedite response times, and, most importantly, save the lives of injured individuals. However, challenges impede their widespread adoption. Flight permission and operation hurdles include restrictions, legal complexities, adverse weather conditions, and limited access to certain areas. Challenges related to data collection and processing encompass data privacy, handling large volumes of data, complex analysis procedures, and issues with target detection. Overcoming these challenges and leveraging the potential of drones in conjunction with Industry 4.0 technologies can improve situational awareness, decision-making, and resource allocation, resulting in more efficient road accident management.

Note that there were limitations associated with the outcomes of this systematic review. Only relevant publications from the Scopus and Web of Science databases were included, while other scholarly databases were overlooked. Additionally, non-academic resources, such as technical reports, newspapers, blogs, and magazines, were not considered in this review.

REFERENCES

[1] S. Sharma and S. Sebastian, "IoT based car accident detection and notification algorithm for general road accidents," *Int. J. Elect. Comput. Eng.*, vol. 9, no. 5, pp. 4020–4026, Oct. 2019.

[2] N. A. Khan, M. Ahmad, S. Alam, A. M. U. Siddiqi, D. Ahamad, and M. N. Khalid, "Development of medidrone: A drone based emergency service system for Saudi Arabian healthcare," in *Proc. Int. Conf. Comput. Intell. Knowl. Economy (ICCIKE)*, Dubai, United Arab Emirates, Mar. 2021, pp. 407–412.

[3] X. Wang, Y. Fan, B. Gong, and R. Wei, "Research in traffic accident analysis based on multi-source data fusion," in *Proc. Int. Conf. Intell. Comput., Autom. Syst. (ICICAS)*, Chongqing, China, Dec. 2021, pp. 264–270.

[4] H. Alam and D. Valles, "Debris object detection caused by vehicle accidents using UAV and deep learning techniques," in *Proc. IEEE 12th Annu. Inf. Technol., Electron. Mobile Commun. Conf. (IEMCON)*, Vancouver, BC, Canada, Oct. 2021, pp. 1034–1039.

[5] A. Karimi and E. Kashi, "Investigating the effect of geometric parameters influencing safety promotion and accident reduction (case study: Bojnurd–Golestan national park road)," *Cogent Eng.*, vol. 5, no. 1, Oct. 2018, Art. no. 1525812.

[6] M. E. Torbaghan, M. Sasidharan, L. Reardon, and L. C. W. Muchanga-Hvelplund, "Understanding the potential of emerging digital technologies for improving road safety," *Accident Anal. Prevention*, vol. 166, Mar. 2022, Art. no. 106543.

[7] A. O. Adeniran, "Impacts of the fourth industrial revolution on transportation in the developing nations," *Int. Educ. Sci. Res. J.*, vol. 2, no. 11, pp. 56–60, Nov. 2016.

[8] A. Gohari, "Route planning system based on geographic information system," M.S. thesis, Dept. Geoinf., Univ. Tech. Malaysia, Johor, Malaysia, 2010.

[9] M. Shahzad, "Review of road accident analysis using GIS technique," *Int. J. Injury Control Saf. Promotion*, vol. 27, no. 4, pp. 472–481, Aug. 2020.

[10] K. G. Le, P. Liu, and L.-T. Lin, "Determining the road traffic accident hotspots using GIS-based temporal–spatial statistical analytic techniques in Hanoi, Vietnam," *Geo-Spatial Inf. Sci.*, vol. 23, no. 2, pp. 153–164, Apr. 2020.

[11] A. Al-Omari, N. Shatnawi, T. Khedaywi, and T. Miqdady, "Prediction of traffic accidents hot spots using fuzzy logic and GIS," *Appl. Geomatics*, vol. 12, no. 2, pp. 149–161, Jun. 2020.

[12] S. Rajendran, S. Chaudhari, and S. Giridhar, "Advancements in healthcare using wearable technology," in *Computational Intelligence in Healthcare*. Cham, Switzerland: Springer, 2021, pp. 83–104.

[13] N. Pulsiri, R. Vatananan-Thesenvitz, T. Sirisamutr, and P. Wachiradilok, "Save lives: A review of ambulance technologies in pre-hospital emergency medical services," in *Proc. Portland Int. Conf. Manage. Eng. Technol. (PICMET)*, Portland, OR, USA, Aug. 2019, pp. 1–10.

[14] M. Ayamga, S. Akaba, and A. A. Nyaaba, "Multifaceted applicability of drones: A review," *Technol. Forecasting Social Change*, vol. 167, Jun. 2021, Art. no. 120677.

[15] F. Outay, H. A. Mengash, and M. Adnan, "Applications of unmanned aerial vehicle (UAV) in road safety, traffic and highway infrastructure management: Recent advances and challenges," *Transp. Res. A, Policy Pract.*, vol. 141, pp. 116–129, Nov. 2020.

[16] J. Desai, J. K. Mathew, Y. Zhang, R. Hainje, D. Horton, S. M. Hasheminasab, A. Habib, and D. M. Bullock, "Assessment of Indiana unmanned aerial system crash scene mapping program," *Drones*, vol. 6, no. 9, p. 259, Sep. 2022.

[17] F. A. Almalki and B. O. Soufiene, "Modifying Hata–Davidson propagation model for remote sensing in complex environments using a multifactional drone," *Sensors*, vol. 22, no. 5, p. 1786, Feb. 2022.

[18] I. Bisio, C. Garibotto, H. Haleem, F. Lavagetto, and A. Sciarrone, "A systematic review of drone based road traffic monitoring system," *IEEE Access*, vol. 10, pp. 101537–101555, 2022.

[19] N. R. Haddaway, M. J. Page, C. C. Pritchard, and L. A. McGuinness, "*PRISMA*2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis," *Campbell Systematic Rev.*, vol. 18, no. 2, Jun. 2022, Art. no. e1230.

[20] A. M. Almeshal, M. R. Alenezi, and A. K. Alshatti, "Accuracy assessment of small unmanned aerial vehicle for traffic accident photogrammetry in the extreme operating conditions of Kuwait," *Information*, vol. 11, no. 9, p. 442, Sep. 2020.

[21] C. Cappelletti, M. Boniardi, A. Casaroli, C. I. De Gaetani, D. Passoni, and L. Pinto, "Forensic engineering surveys with UAV photogrammetry and laser scanning techniques," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 42, pp. 227–234, Jan. 2019.

[22] Y. Liu, B. Bai, and C. Zhang, "UAV image mosaic for road traffic accident scene," in *Proc. 32nd Youth Academic Annu. Conf. Chin. Assoc. Autom. (YAC)*, Hefei, China, May 2017, pp. 1048–1052.

[23] X. Liu, Z. Guan, Q. Fan, Q. Chen, and T. Gao, "Remote sensing and scene reconstruction of traffic accident based on unmanned aerial vehicle platform," in *Proc. 19th COTA Int. Conf. Transp. Professionals (CICTP)*, Nanjing, China, Jul. 2019, pp. 3331–3342.

[24] F. Nejjari, L. Benhlima, and S. Bah, "Event traffic detection using heterogeneous wireless sensors network," in *Proc. IEEE/ACS 13th Int. Conf. Comput. Syst. Appl. (AICCSA)*, Agadir, Morocco, Nov. 2016, pp. 1–6.

[25] J. A. Pérez, G. R. Gonçalves, J. M. G. Rangel, and P. F. Ortega, "Accuracy and effectiveness of orthophotos obtained from low cost UASs video imagery for traffic accident scenes documentation," *Adv. Eng. Softw.*, vol. 132, pp. 47–54, Jun. 2019.

[26] C. V. Raj, B. N. Sree, and R. Madhavan, "Vision based accident vehicle identification and scene investigation," in *Proc. IEEE Region 10 Symp. (TENSYMP)*, Cochin, India, Jul. 2017, pp. 1–5.

[27] A. Saveliev, V. Lebedeva, I. Lebedev, and M. Uzdiaev, "An approach to the automatic construction of a road accident scheme using UAV and deep learning methods," *Sensors*, vol. 22, no. 13, p. 4728, Jun. 2022.

[28] P. Škorput, S. Mandžuka, M. Gregurić, and M. T. Vrančić, "Applying unmanned aerial vehicles (UAV) in traffic investigation process," in *New Technologies, Development and Application II*. Sarajevo, Bosnia and Herzegovina: Springer, 2020, pp. 401–405.

[29] S. Su, W. Liu, K. Li, G. Yang, C. Feng, J. Ming, G. Liu, S. Liu, and Z. Yin, "Developing an unmanned aerial vehicle-based rapid mapping system for traffic accident investigation," *Austral. J. Forensic Sci.*, vol. 48, no. 4, pp. 454–468, Jul. 2016.

[30] J. Wang, Z. Li, F. Ying, D. Zou, and Y. Chen, "Reconstruction of a real-world car-to-pedestrian collision using geomatics techniques and numerical simulations," *J. Forensic Legal Med.*, vol. 91, Oct. 2022, Art. no. 102433.

[31] M. H. Alkinani, A. A. Almazroi, N. Jhanjhi, and N. A. Khan, "5G and IoT based reporting and accident detection (RAD) system to deliver first aid box using unmanned aerial vehicle," *Sensors*, vol. 21, no. 20, p. 6905, Oct. 2021.

[32] Q. Chen, D. Li, and B. Huang, "SUAV image mosaic based on rectification for use in traffic accident scene diagramming," in *Proc. IEEE 3rd Int. Conf. Safe Prod. Informatization (IICSPI)*, Chongqing City, China, Nov. 2020, pp. 430–433.

[33] I. S. Damyanov, "Use of modern software solutions and systems for analysis and reconstruction of road accidents," in *Proc. 9th Int. Sci. Conf. TechSys Eng., Technol. Syst.*, Plovdiv, Bulgaria, 2020, Art. no. 012043.

[34] W. Feng-Hui, L. Ling-Yi, L. Yong-Tao, T. Shun, and W. Lang, "Road traffic accident scene detection and mapping system based on aerial photography," *Int. J. Crashworthiness*, vol. 26, no. 5, pp. 537–548, Sep. 2021.

[35] T. J. Hng, E. L. Weilie, C. S. Wei, and S. Srigrarom, "Relative velocity model to locate traffic accident with aerial cameras and YOLOv4," in *Proc. 13th Int. Conf. Inf. Technol. Electr. Eng. (ICITEE)*, Chiang Mai, Thailand, Oct. 2021, pp. 238–243.

[36] D. A. Jurkofsky, "Accuracy of SUAS photogrammetry for use in accident scene diagramming," *SAE Int. J. Transp. Saf.*, vol. 3, no. 2, pp. 136–152, Apr. 2015.

[37] K. N. Vladimirovich, "Classifying traffic accidents with unmanned aerial vehicle," *Indian J. Sci. Technol.*, vol. 9, no. 27, p. 97701, Jul. 2016.

[38] S. Koshe, S. Kumar, D. Shah, and J. Justin, "Road accident analysis using structure from motion and machine learning," in *Proc. IEEE 7th Int. Conf. Converg. Technol. (I2CT)*, Mumbai, India, Apr. 2022, pp. 1–5.

[39] X. Liu, H. Zou, W. Niu, Y. Song, and W. He, "An approach of traffic accident scene reconstruction using unmanned aerial vehicle photogrammetry," in *Proc. 2nd Int. Conf. Sensors, Signal Image Process.*, Prague, Czech Republic, Oct. 2019, pp. 31–34.

[40] M. A. M. Amin, S. Abdullah, S. N. A. Mukti, M. H. A. M. Zaidi, and K. N. Tahar, "Reconstruction of 3D accident scene from multirotor UAV platform," *Int. Arch. Photogramm., Remote Sens. Spatial Inf. Sci.*, vol. 43, pp. 451–458, Aug. 2020.

[41] L. Pádua, J. Sousa, J. Vanko, J. Hruška, T. Adão, E. Peres, A. Sousa, and J. J. Sousa, "Digital reconstitution of road traffic accidents: A flexible methodology relying on UAV surveying and complementary strategies to support multiple scenarios," *Int. J. Environ. Res. Public Health*, vol. 17, no. 6, p. 1868, Mar. 2020.

[42] I. Stáňa, S. Tokař, K. Bucsuházy, and M. Bilík, "Comparison of utilization of conventional and advanced methods for traffic accidents scene documentation in the Czech Republic," *Proc. Eng.*, vol. 187, pp. 471–476, May 2017.

ADEL GOHARI received the M.Sc. degree in geoinformatics from Universiti Teknologi Malaysia (UTM), Skudai, Johor, Malaysia, and the Ph.D. degree in civil engineering from Universiti Teknologi PETRONAS (UTP), Seri Iskandar, Perak, Malaysia, in 2018. He joined the Geoinformation Department, Faculty of Built Environment and Surveying, UTM, as a Postdoctoral Research Fellow, in July 2021. Prior to his current position, he was a Research Officer with UTP. He has been an Associate Professional Member with the Institute of Geospatial and Remote Sensing Malaysia (IGRSM), since June 2020. He has been involved in the publication of more than 20 academic papers in international journal outlets indexed by ISI and Scopus so far. His research interests include transportation science, geographic information system (GIS) and its applications, unmanned aerial vehicle (UAV), and multi-criteria decision making (MCDM) techniques and their applications.

ANUAR BIN AHMAD received the B.Sc. degree (Hons.) in surveying science and the M.Phil. degree in photogrammetry from Newcastle University, Newcastle upon Tyne, U.K., in 1987 and 1992, respectively, and the Ph.D. degree in photogrammetry from Universiti Teknologi Malaysia, Skudai, Johor, Malaysia, in 2005. Since 1983, he has been with Universiti Teknologi Malaysia, where he is currently a Professor with the Faculty of Built Environment and Surveying. His research interests include aerial photogrammetry, close range photogrammetry, geoinformation, and mapping using unmanned aerial vehicle (UAV) or drone. He is actively involved in research and consultation work related to UAV/drone technology especially for mapping applications.

RUZAIRI BIN ABDUL RAHIM received the degree (Hons.) in electronic system and control engineering from Sheffield City Polytechnic, Sheffield, U.K., in 1992, and the Ph.D. degree from Sheffield Hallam University, U.K. His Ph.D. thesis was titled "A Tomographic Imaging System for Pneumatic Conveyor using Optical Fibres." He was a Tutor with the Department of Control and Instrumentation Engineering, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), in 1992. He was an Associate Professor with UTM, in 1999, and a Professor, in 2006, where he is currently the Dean of the Faculty of Engineering. He has published more than 17 original books, more than 284 papers in indexed journals, produced more than 124 conference papers as well as numerous other writings, including chapter in a book, articles in popular publications, manuscripts, and technical reports. His expertise and research interest comprises optical tomography, electrical capacitance tomography, electrical resistance tomography, ultrasonic tomography, and gamma ray tomography for process industries application. His research interests include process tomography and sensor technology. He has received more than 35 academic and research awards, including the Top Researcher Scientist Malaysia 2013 from the Academic Science Malaysia.

NASSRIN IBRAHIM MOHAMED ELAMIN (Member, IEEE) was born in Wad Madani, Sudan, in April 1979. She received the B.Sc. degree in electronics and telecommunication engineering from the University of Gezira, Sudan, in 2004, the M.Sc. degree in telecommunication and information systems from the University of Khartoum, Sudan, in 2009, and the Ph.D. degree in multiple-band antennas for long term evolution applications from the University of Technology Malaysia (UTM). She is currently an Associate Professor with the Faculty of Electronics and Electrical Engineering, International University of Africa (IUA), Sudan. She has published many papers in the reputed journals and conferences, including IEEE Antenna and Wireless Propagation Letters, Antennas and Propagation in Wireless Communications (APWC), *Progress in Electromagnetics Research* (PIER), and *PLOS One*. She has two inventions: a Multiband antenna pattern No: PI 2014700881, and a MULTIPLE-INPUT-MULTIPLE-OUTPUT antenna, patent No: PI 201470080.

MOHAMMED SALIH MOHAMMED GISMALLA (Senior Member, IEEE) received the B.Sc. degree (Hons.) in electronic and electrical engineering (communication) from the International University of Africa (IUA), Sudan, in 2010, the M.Sc. degree in electronic engineering (communication) from the Sudan University of Science and Technology, in 2015, and the Ph.D. degree in electrical engineering (communication) from the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Malaysia, in March 2021. From 2010 to 2017, he was a Teaching Assistant and a Lecturer with the Department of Communication Engineering, Faculty of Electronic and Electrical Engineering, IUA, and the University of Bahri. He was a Postdoctoral Fellow with the Lightwave Communication Research Group, School of Electrical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM). He is currently a Postdoctoral Fellow with the Center of Communication Systems and Sensing, King Fahd University of Petroleum and Minerals (KFUPM). His research interests include the device-to-device communication, visible light communication, optical communication, unmanned aerial vehicle (UAV), and 5G/6G networks.

OLORUNTOBI OLAKUNLE OLUWATOSIN received the M.Sc. and Ph.D. degrees in transport planning from Universiti Teknologi Malaysia, in 2012 and 2021, respectively. He is a dedicated scholar in the field of Transport and Maritime operations. He has notable experiences include working with SMS Marines Pte., Ltd., Singapore; and RedMart, Singapore. He is currently a Lecturer of maritime studies with Universiti Malaysia Terengganu (UMT), where he inspires academic excellence and conducts high-quality research in maritime transport and operations, warehousing, offshore logistics, public transport studies, and accidence investigation analysis.

RAZI HASAN received the master's degree in civil engineering from University Technology PETRONAS. He is currently pursuing the Ph.D. degree with CARRS-Q, Queensland University of Technology. He has published some high-quality research papers in the field of road safety and transport engineering. He is a road safety enthusiast with a solid background in transport and civil engineering, nine years of research and academic experience, with comprehensive writing and statistical analysis skills.

AMIR SHARIFUDDIN AB LATIP received the bachelor's degree (Hons.) in geomatics engineering and the master's degree in GNSS from Universiti Teknologi Malaysia, in 2008 and 2013, respectively, and the Ph.D. degree in InSAR from Universiti Teknologi PETRONAS, in 2019. Since 2020, he has been with the School of Geomatics Science and Natural Resources, Universiti Teknologi MARA, as a Senior Lecturer. His research interests include GNSS and InSAR for deformation monitoring and atmospheric correction.

ABDULMAJID LAWAL received the B.Eng. degree in electrical engineering from Bayero University, Kano, in 2012, and the master's and Ph.D. degrees in electrical engineering from the King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia, in 2016 and 2021, respectively. He is currently a Postdoctoral Fellow with the Center for Communication Systems and Sensing, KFUPM. His research interests include blind source separation, blind and semi-blind signal/channel identification, sparse signal representations, the application of artificial intelligence in wireless communication, signal processing, applied machine learning, multidimensional modeling, and signal classification.