Unmanned aerial vehicles (UAV) for safety in the construction industry: a systematic literature review

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Abstract. The construction industry is one of the most dangerous sectors with poor safety performance. With recent technological developments, Unmanned Aerial Vehicles (UAV) are demonstrating the potential to be a valuable innovation to improve construction safety. To date, several studies have been conducted to evaluate the applications of UAV for safety in the construction industry. In order to systematically assess the research status on UAV to improve construction safety, this research investigated published journal articles (in English) within the Scopus database to determine the current research gaps and future work suggested by the publications. Thirty-three articles and reviews were included in the study. The analysis revealed a positive trend in publications in this area. Publications were also analysed based on the country of origin of the research and the journal. Prototype and experiments were identified as the most frequently used research methods. The majority of the studies, irrespective of the type of construction, focused on the construction stage. Where health and safety aspects were concerned, the use of UAV for visualisation and identification of hazards were found to be the most frequent applications. Some research gaps and recommendations for future research are also discussed in the paper

1. Introduction

The construction industry is on a path of changing its focus to digitalisation and automation for faster task completion time, higher work quality, enhanced safety standards, and cost reduction [1]. With emerging technologies such as building information modelling (BIM), internet of things (IoT), artificial intelligence (AI), unmanned aerial vehicles (UAV), virtual reality (VR), augmented reality (AR), 3D printing, robots, and blockchain, the construction industry is shifting its focus more and more to an information system-based environment.

The construction industry, with poor safety performance, is one of the most dangerous industrial sectors. According to the Bureau of Labour Statistics, Occupational Safety and Health Administration [2] reports approximately 150,000 construction site accident injuries each year in the US, while fall hazards are the leading cause of injury. At the same time, the International Labour Organization (ILO) estimates that at least 60,000 fatal accidents occur each year worldwide [3]. The study by Larsson and Field [4] on occupational injury risk in Victoria, Australia, concluded that the injury severity identified within all the occupational groups' in construction was above average. Martinez, Gheisari and Alarcón [5] revealed that frequently inspecting inaccessible, hard-to-reach or unsafe locations on such high-rise building construction projects leads to dangerous acts and conditions in a construction project. Therefore, methods and solutions that avoid such risk-taking behaviours are expected to improve health and safety in the construction environment.

Among the emerging technologies, UAV, also referred to as unmanned aerial systems (UAS), flying robots or drones, have the potential to play a significant role in safety planning and monitoring. With embedded features such as cameras, motion detectors, heat sensors, infrared, radar, and communication devices, UAV provide safety managers with "another set of eyes" on the construction site at a relatively low cost [6, 7]. Developments in battery life, autonomous navigation features, weight reduction, and flight control have resulted in significant growth in the use of the technology [5]. They have become more affordable, reliable and easier to operate, making them an attractive addition to any construction site [8].

Consequently, numerous studies in different areas of application have been undertaken to evaluate the effectiveness of UAV in the construction industry. Although the findings of these studies act as the foundation to improve construction safety, a systematic analysis of the UAV for the construction safety studies would provide an indispensable resource for current and future trends. In addition, the previous studies have focused on a particular application of UAV for construction safety rather than providing a comprehensive and systematic insight into their use and application. For instance, Umar [9] evaluated the safety-related applications, focusing mainly on the Gulf cooperation council countries. Rey, De Melo and Costa [10] proposed a computerised system to perform safety inspections. Sakib, Chaspari and Behzadan [11] evaluated the effectiveness of UAV training with virtual reality technology for construction safety. To solve the lack of direct visual operation to ensure safety, Yamaguchi et al. (2020) experimented with the use of UAV attached to construction equipment.

In contrast to past research, this study contributes to the body of knowledge by investigating the progress of current research on UAV to improve construction safety and determine the current research gaps, and future work suggested by the publications. The present review supports the new researchers by providing an in-depth enquiry to bridge the gaps between research and practice in UAV for construction safety. This paper is structured as follows. In the next section, the use of preferred reporting items for systematic reviews and meta-analysis (PRISMA) method to collect relevant publications is described. This is followed in the third section with an overview and analysis of these studies based on the publication year, journal title, country/region, lifecycle stage, and addressed health and safety issues. The fourth section presents a discussion from a thematic perspective, and finally, the conclusions are stated.

2. Research methodology

This study adopted the PRISMA method to document comprehensive knowledge. PRISMA method allows the researchers to (1) identify large databases with scientific and academic literature through keyword and search strategies, (2) screen inclusion and exclusion criteria, and (3) conduct an eligibility process in appraising the relevant literature to analyse the data from the studies [12]. Figure 1 demonstrates the main steps adopted in this research.

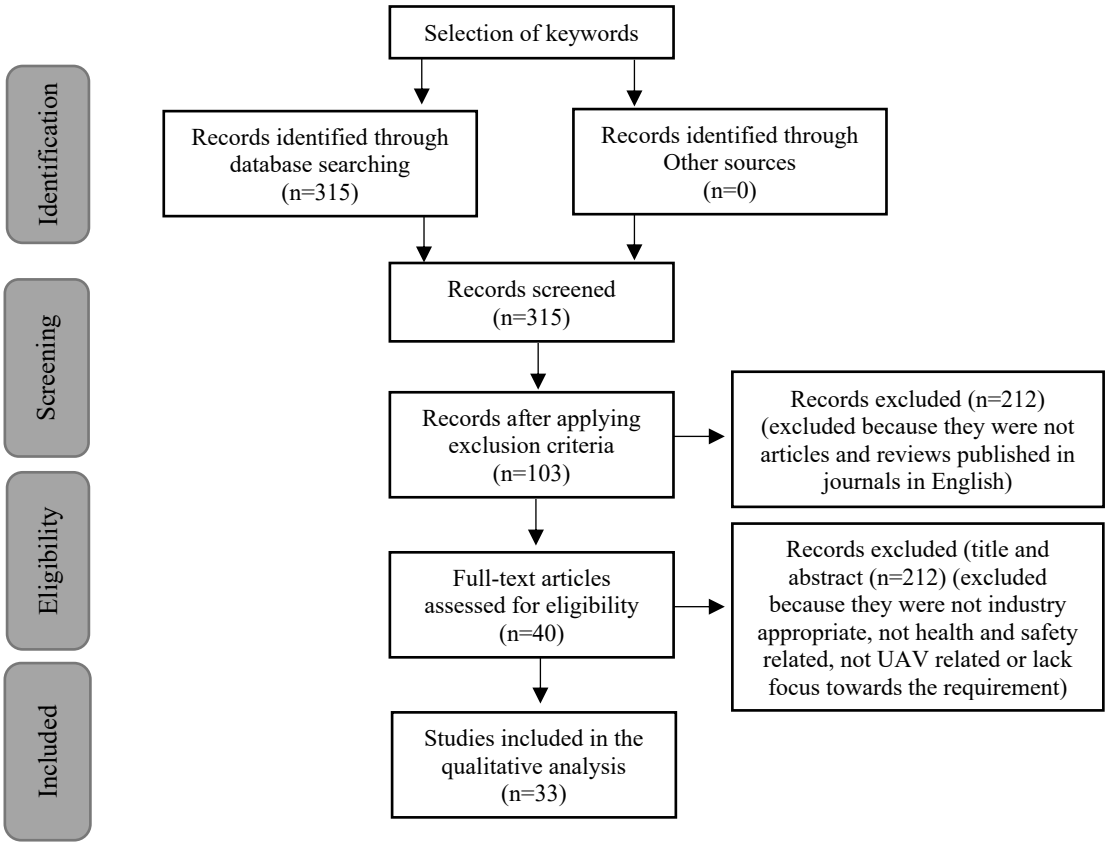

Figure 1. Research flowchart.

2.1. Search strategy

The systematic literature review was undertaken in April 2021 according to PRISMA guidelines. The keywords selected to identify the related articles were in three categories as (1) UAV and other known names, (2) keywords related to health and safety ((both spelt out and abbreviated), and (3) Construction 4.0 and construction-related terms. Accordingly, the set of keywords and Boolean operators selected for the search strings were (TITLE-ABS-KEY ("industry 4.0" OR "construction 4.0" OR "unmanned aerial vehicles" OR "UAV" OR "unmanned aerial system" OR "remotely piloted vehicles" OR "drone") AND TITLE-ABS-KEY ("construction industry" OR "construction") AND TITLE-ABS-KEY ("occupational health and safety" OR "occupational safety and health" OR "health and safety" OR "safety and health" OR "Safety" OR "Health")).

Generally, it is recommended to use more than one database to conduct a systematic literature review to improve the coverage of the included studies [13]. However, many similar studies [13-17] have been conducted only on the Scopus database since it is recognised as the most extensive database for peer-reviewed abstracts. Thus, only the Scopus database was used in this research because it is found to have a broader range, accuracy, and ease of retrieving articles compared to similar literature databases such as Web of Science and Google Scholar [13, 15].

2.2. Eligibility criteria

The study included only articles and reviews published in journals in English because journal articles usually provide more comprehensive and higher-quality information than other types of publications [16]. Conference papers are usually of lower quality and less mature than journal articles, and thus, they were not included in the study [16, 17]. Accordingly, conference papers, conference reviews and book chapters, book series, trade journal notes, and articles written in languages other than English

were not included. By applying these limitations, 103 publications were generated that were further scrutinised.

3. Research methodology

3.1. Analysis of publications by year

Figure 2 demonstrates an upward trend in the UAV applications in construction industry safety studies. Since article screening for this study was done in April 2021, relevant articles until April 2021 were included in the study.

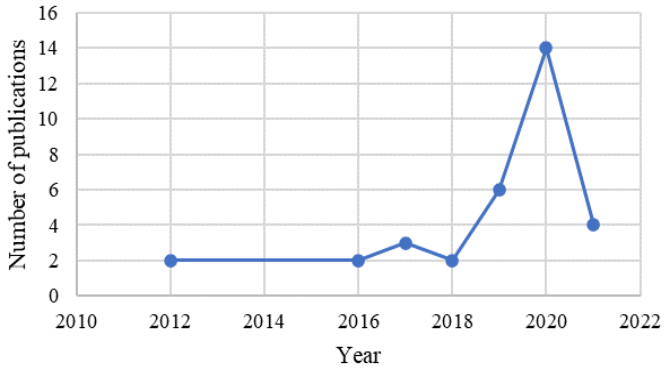

Figure 2. Publications by year.

It is substantiated from Figure 2 that UAV is a relatively new concept, with the first relevant article only published in 2012. The graph implies that much less attention was given to the technology and its application to improve safety in the industry prior to 2012 and between the periods 2012-2016. However, a slight increase is visible after 2016, demonstrating an improved awareness of UAV use for construction safety in academia and industry. From 2018, a substantial increase occurred, leading to fourteen publications in 2020. Although only three publications were included in the graph for 2021, it must be noted that since the article identification was carried out early in 2021, most of the articles published in 2021 were not considered. However, the graph does demonstrate that the use of UAV to enhance safety in the construction industry is emerging, and more applications and advancements would be expected in the future.

3.2. Analysis of publications by the country

Research on UAV applications for construction safety occurred in seventeen countries, and these are illustrated in Figure 3. However, it should be noted that we did limit our search to only include journals written in English, which would have affected this finding.

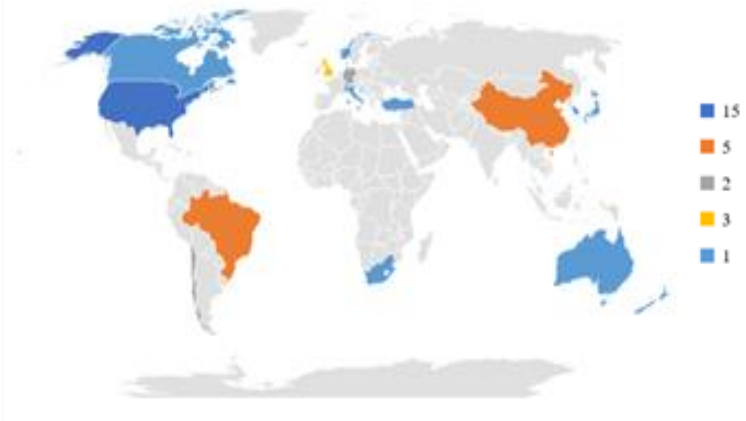

Figure 3. Publications by the country.

Researchers in the United States of America (USA) has taken the lead in authoring publications focusing on improving construction safety with UAV. They represented 39% of all publications in the area. Authors in China and Brazil were next in authoring and contributing to the research area, with five publications each. When author location by continent was concerned, North America has the highest number of publications, followed by Europe with three publications from the United Kingdom (UK). Both Asia and South America have seven publications each, with China and Brazil as the highest contributors in each continent, respectively. Africa only has one publication, while it is worth noting that only one article each was found on the use of UAV to improve construction safety within the Australian context. Accordingly, it can be assumed that UAV are more established in some parts of the world but is still an emerging technology in the rest. However, it must be noted that the findings are limited to the publications screened with inclusion and exclusion criteria.

3.3. Analysis of publications by the journal

The articles on the research on UAV use in the context of safety in construction sites were found in twenty-three journals, as demonstrated in Figure 4.

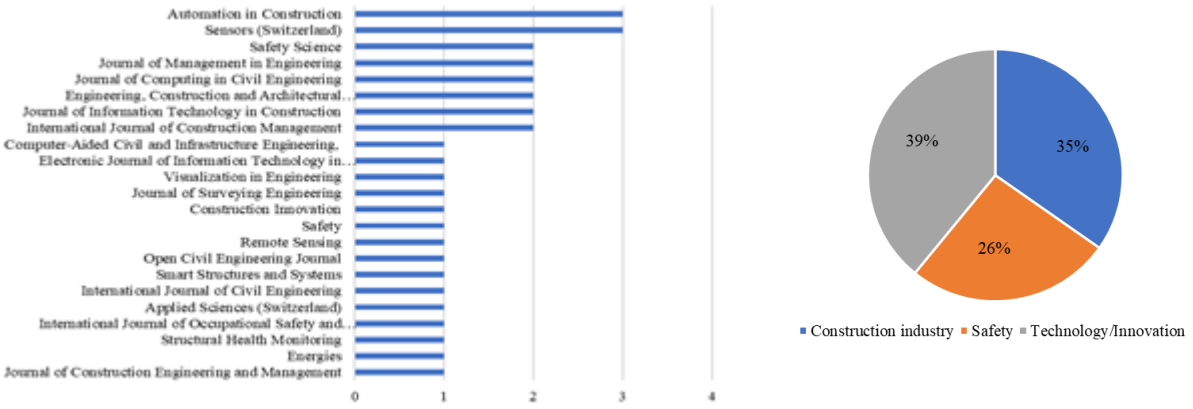

Figure 4. Publications by the journal.

The Journals 'Sensors (Switzerland)' and 'Automation in Construction' were identified as the preferred publication avenues for the research on UAV for construction safety. 'Engineering, Construction and Architectural Management', 'Journal of Computing in Civil Engineering', 'Journal of Management in Engineering', "International Journal of Construction Management', 'Journal of Information Technology in Construction' and 'Safety Science' were the next preferred journals with two studies each. It was identified that the studies focused on this research were published in journals under three categories: (1) journals related to the construction industry, (2) journals related to health and safety and (3) journals related to information technology and innovation. Interestingly, most of the studies on UAV for construction safety were in journals concentrating on information technology and innovation (39%).

3.4. Analysis of publications by the research method

The studies included in this research were analysed by the research method adopted by the researchers, and the findings are shown in Figure 5.

Among the research methods utilised in the use of UAV for construction safety studies, prototype development and experiments were revealed as the most commonly adopted. For instance, Meng, Peng, Zhou, Zhang, Lu, Baumann and Du [18] developed a prototype system to detect and warn an excavator is positioned too close to a pipe in pipeline construction. Similarly, Guo, Xu and Li [19] developed a technique for vehicle detection. At the same time, Kim, Lee and Kamat [20] and Kim, Liu, Lee and Kamat [21] prototyped a system to predict and monitor the proximity of a worker and a

heavy vehicle. Moreover, prototypes were also developed for automated data acquisition [22] and safety assessments [23, 24].

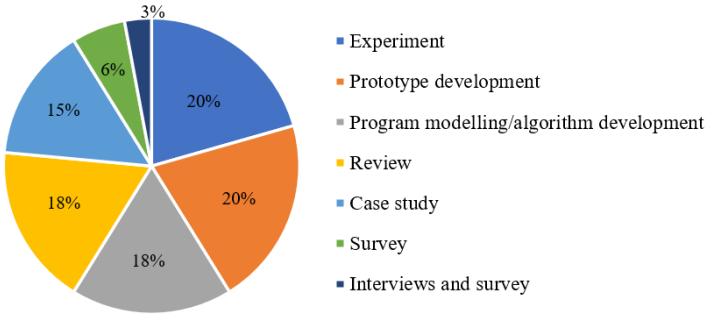

Figure 5. Publications by the research method.

Experiments were also a prominent research method, with researchers quantifying the effectiveness of UAV in construction safety with user studies [11, 25] and field tests [26]. Program modelling/algorithm development was the next most prominent research method, with researchers designing numerous applications to utilise UAV for safety in construction sites, while case studies have facilitated the research to explore its applications. Surveys and interviews were adopted to obtain the perceptions and perspectives of many construction workers on the use of UAV for safety. Although six out of the thirty-three publications have adopted literature review as the research method, they were (1) to assess the use of emerging technology to improve construction safety and (2) the applications of UAV in the construction industry separately. Thus, it is worth highlighting that the use of UAV for construction safety was not the focus in these publications.

3.5. Analysis of publications by the life cycle stage

Figure 6 demonstrates the stages of the construction life cycle in which UAV are adopted to improve safety.

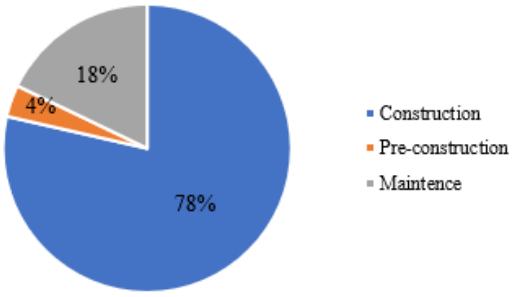

Figure 6. Publications by the life cycle stage focused.

Of the twenty-seven papers (six papers out of thirty-three articles on reviews are excluded), 78% of the studies focus on the application of UAV for construction safety during the construction stage of the project. Among this research, most of the studies were designed to identify or visualise hazards through inspections [7, 9, 25-28].

Structural health monitoring conducted during the maintenance stage was also recognised as a significant application of UAV within the context of safety. However, crack identification was the most common application [23, 29], while research on infrastructure focused on maintaining bridges with UAV [24, 30]. In contrast, the study by Jiang, Zhou, Ding, Zhou and Ning [31] was the only one on the hoist site mapping and layout planning with UAV to improve safety at the design/planning stage. The results imply more research could be carried out to evaluate UAV's use at different stages of the project life cycle, specifically at the design and maintenance stages of the project.

3.6. Analysis of publications by the nature of the projects

The construction sector for which UAV were adopted to enhance safety was analysed as presented in Figure 7.

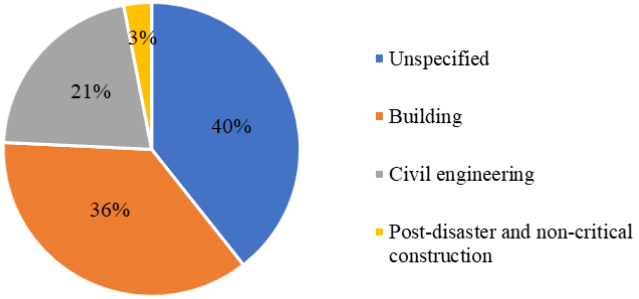

Figure 7. Publications by the construction sector focused.

Thirteen out of thirty-three (40%) of the articles have not specified a specific construction sector, and upon reading these articles, it is apparent the findings of such research can be used to enhance safety in all construction types. However, it has to be noted that reviews are also included in this category. Studies on building construction projects (36%) are the next most common scenario when safety improvements with UAV are concerned. Although these studies do not explicitly indicate the nature of the building, a study by Martinez, Gheisari and Alarcón [5] specifically focuses on high-rise buildings, while Jiang, Zhou, Ding, Zhou and Ning [31] researched safety positioning and planning the hoists using UAV. Among the studies on the application of UAV to improve safety in civil engineering construction (7 out of 33), a significant portion (29%) focuses on bridges [24, 30].

In contrast, one study each on dam construction [32], road construction [33] and pipeline construction [18] were undertaken to evaluate the use of UAV for safety, while two studies within civil engineering focus on hazards with construction vehicles [19, 21]. Interestingly, Calantropio [34] studied the use of UAV for performing safety-related tasks at post-disaster and non-critical construction sites. Accordingly, the findings insinuate the versatility of UAV in safety management in construction.

3.7. Health and safety issues addressed in the publications

Figure 8 demonstrates the analysis of the publications based on the specific health and safety issues, which for the focus of the studies included in this research.

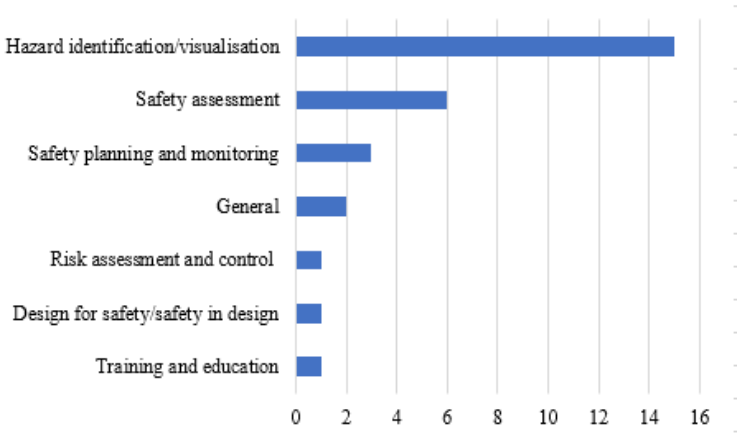

Figure 8: Publications by the health and safety issue focused.

Nearly half of the studies (45%) explored the use of UAV for hazard identification and visualisation, either to eliminate or reduce the risk or hazard. Out of these, 53% of the research looked at various aspects of safety issues using UAV for inspections. One study each was undertaken to evaluate the possibility of UAV use for hazard identification, including ground object detection in pipeline construction [18], direct visual operation support for workers to enhance awareness of the surroundings [35], vehicle detection in dense construction [19], proximity prediction [20] and proximity monitoring [21] between the worker and a truck.

Six out of thirty-three studies concentrated on the application of UAV for safety assessments. Herein, the opportunity to detect damages to improve safety was explored. The use of UAV for safety planning and monitoring was also a research avenue with a sizable number of studies (9%). However, less attention has been given to areas such as training and education as well as design for safety assessment and control. This indicates some opportunities for more studies on the viability of UAV for safety improvements in those contexts.

3.8. Limitations and research opportunities identified in the current research

Most of the research papers identified the sample size as a limitation [6, 9, 21, 35]. Accordingly, more research with larger samples was suggested to improve the generalisation ability of the work conducted. Furthermore, some safety aspects, such as weather conditions [36], and the interior building environment [22, 28], were not observed or included in the studies, which could potentially lead to future research. Similarly, research on program and prototype development to improve construction safety with UAV identified the dataset, program used or the environment as a limitation. Therefore, future studies could apply the findings to other settings to evaluate the generalisation [18, 19, 31]. Interestingly, Hamledari, Sajedi, McCabe and Fischer [27] identified that integrating technologies to improve safety in construction is another aspect that should be addressed in future studies.

4. Conclusions and further research

With emerging technologies, the construction industry has an opportunity to improve its efficiency, productivity, and safety. UAV is one new technology that could facilitate improvements to construction safety. This research was undertaken to investigate the current research status on UAV and construction safety. The analyses demonstrate that the use of UAV to improve construction safety is an emerging but expanding field. The significant increase in research undertaken in this arena since 2018 demonstrates it will play a significant role in the future. There are a considerable number of studies about the development of prototypes, algorithms, and programs to enhance construction safety with UAV. However, the research suggests more case studies, surveys, and interviews to establish the value of UAV in construction safety space. Although publications in this area would be expected to grow, the study identified a significant lack of research on the use of UAV other than for safety inspections to recognise hazards and safety issues, suggesting further research to be done in this context. Moreover, the research recognised potential future studies to be done in various contexts such as countries which facilitates a comparison of the applications. Also, it is worth acknowledging that to maximise the potential of UAV to improve construction safety, UAV can be complemented with other technologies. It should be noted that the publications analysed in this research were only from the Scopus database until April 2021 and were only those published in English, which are limitations of this study.

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