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ELM-based control system applications: A bibliometric analysis and review

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Abstract

This study conducts a bibliometric analysis of the extreme learning machine (ELM) research, with a particular emphasis on ELM-based control systems and applications. The objective of this study is to identify research trends, collaboration opportunities, and challenges in ELM applications. The analysis comprises the identification and retrieval of 3,174 articles from Scopus between 2018 and 2023. VOSviewer 1.6.20 is used for data interpretation, identifying six distinct keyword clusters and revealing both well-established research areas and emerging fields with significant potential for future exploration. Key research trends indicate a shift towards advanced or hybrid approaches, with recent interest in integrating optimization techniques. In the analysis, opportunities for collaboration with leading researchers are also highlighted. The findings emphasize the wide range of applications for ELM in improving the robustness of control systems while also highlighting important issues that need to be addressed. Finally, this study provides valuable insights into the current state and future directions of ELM research, especially ELM-based control systems.

Keywords: extreme learning machine; control system; bibliometric analysis; ELM application.

I. Introduction

Extreme learning machine (ELM) was first declared by Huang *et al.* [1] in 2006, and it was compiled from a single hidden layer feedforward network (SLFN), whose application was divided into classification and regression. ELM has found extensive applications in control systems due to its capacity to enhance system robustness, especially in scenarios involving disturbances, model uncertainties, and defect detection. Its fast learning capabilities and adaptability make it suitable for real-time control applications where traditional methods may fall short. As modern control systems evolve, incorporating advanced techniques like ELM becomes increasingly vital for achieving higher efficiency and reliability.

Analysing the growing number of scientific articles in a research field is crucial and essential work for researchers in the age of information development. Bibliometrics is the application of information science principles to analyse books, journals, and other publications, relying on mathematical statistics [2]. There are the following features of bibliometric analysis in comparison to conventional literature evaluations or summaries: By utilizing professional software and high-performance computers, bibliometric methods analyse tens of thousands of documents in a

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comprehensive database to provide a comprehensive network picture of a research topic (e.g. ELM). Bibliometric methods quantitatively assess the impact of a research field, a group of researchers, and a specific publication by analysing citations. In a given research field, the classical literature and research hotspots can be effectively identified or captured. In this study, ELM's explored topics, research trends, and collaboration opportunities are aimed to be analyzed through bibliometric analysis. A bibliometric analysis was conducted using the literature from the Scopus database, with papers published over a 5-year period from 2018 to 2023 being selected. The selected keyword for this study was "extreme learning machine." The literature and key research areas within a specific field can be efficiently captured or identified.

Recently, ELM integration with control systems has been developed. ELM has been applied to increase efficiency in many control applications such as permanent magnet linear motor (PMLM) [3], welding monitoring and control [4], steer-by-wire vehicles [5], hypersonic vehicle (HV) [6], and brushless DC servo motor [7]. Fast non-singular terminal sliding mode (FNTSM) in [3] uses ELM as an estimator. In addition to ensuring finite time error convergence and high robustness, the proposed control strategy does not necessitate prior knowledge of system parameters since ELM has been employed to predict equivalent control during the design process. The next work, an intelligence modeling and control framework based on the ELM technique and novel model-free adaptive control (MFAC) has been presented in [4] to monitor and control weld penetration utilizing keyhole visual signals, ELM provides precise feedback information with speed of calculation, which is faster and better prediction accuracy than back propagation neural network (BPNN). Furthermore, the FNTSM control strategy for steer-by-wire (SbW) vehicles was designed with ELM as an estimator for estimating the equivalent control and produced the excellent performance of the proposed control strategies for different steering maneuvers proposed in [5]. Moreover, the sliding mode control (SMC) scheme combined with the ELM-based neural network disturbance observer (NNDO) in [6] is able to accurately predict unknown interference signals by establishing appropriate adaptive laws and the hypersonic vehicle's learning speed. In other work presented in [7], ELM super twisting repetitive control (ELMSTRC) has outstanding results compared to conventional methods for a brushless DC servo motor on periodic signals. Several sources of the literature highlight the superiority of the ELM method to several contemporary estimations and compensation not only in terms of classification accuracy but also in terms of efficacy. Another computational approach, known as reinforcement learning, demonstrates significant intelligence and broad applicability in control and optimization domains. Nevertheless, ELM also offers the benefits of straightforward structure, rapid learning capability, and strong generalization. ELM was selected to be combined with a control system because it improves prediction accuracy, increases robustness, generates a small root mean square error, improves tracking performance, and provides high precision.

Based on our knowledge, no specific reference exploring the bibliometric analysis of ELM, with a particular emphasis on ELM-based control systems and their applications, could be found. Therefore, in this study, a bibliometric analysis of ELM research works from 2018 to 2023 is aimed at identifying research trends, collaboration opportunities, and challenges in ELM applications. The main contributions of this study are summarized as follows:

- Identify established and emerging research areas within the ELM domain.
- Determine the most frequently used keywords and recent trends in ELM research.
- Analyze potential collaborations with leading researchers in the field of ELM.
- Describe ELM's applications in control systems and the challenges they pose.

The remaining sections of this paper are structured as follows: In Section II, the methodology is outlined, which encompasses the analytical tool and data source employed in this investigation. Section III presents the results and discusses them, including explored topics, research trends, and collaboration opportunities. Section IV discusses the applications of an ELM-based control system. Section V highlights ELM's future outlook and challenges. Finally, a conclusion is provided in Section VI.

II. Materials and Methods

Bibliometric analysis has garnered considerable interest as a quantitative method for evaluating the growth and progress of a particular study topic [8]. Alan Pritchard developed the idea of bibliometric analysis in 1969 in order to predict the development of a certain topic. A visual representation of extensive data accompanied by a precise analysis is typically produced by computer programs with these unique features, such as VOSviewer, which is frequently used by researchers [9]. By using citations, refinements, resolution parameters, and keywords, bibliometrics aid in comprehending research traditions by framing relationships between related fields of study [10].

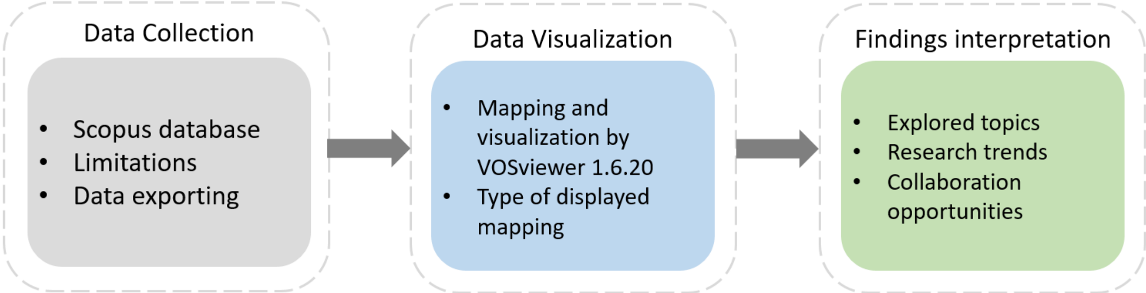

Figure 1. Stages of the conducted bibliometric analysis.

Bibliometric research is comprised of three primary phases, as illustrated in Figure 1 indicates the research process, which involved the following stages: i) the initial search for data sources, limitations, and data export; ii) the bibliometric analysis; and iii) the interpretation of the results. The data was retrieved from Scopus on October 3rd, 2023. To assess the advancements and contributions made in the field, the literature for the years 2018 through 2023 was identified by utilizing the advanced search options "title, abstract, and keywords". The selected keyword for this study was "extreme learning machine". The data was filtered from the journal article type and written in English. Finally, 3,174 publications were gathered and exported in CSV format. The data visualization was executed with VOSviewer 1.6.20. Visualizations have been used to support the data as these are so important for comprehending relationships and patterns. The study findings might serve as a starting point for future academic investigation into the potential applications of ELM.

While every effort has been made by the authors to eradicate errors, there are a few articles that are not pertinent to the subject, and a few articles may have been omitted because only one database was scanned to assess the development and themes. This may have contributed to the survey limitations.

III. Results and Discussions

Co-occurrence may involve keywords that are related to each other and pertain to the same topic but are not necessarily identical. In bibliometrics, the co-occurrence of author keywords is employed to uncover research focal points within a particular discipline. The keyword co-occurrence analysis was carried out by tallying keyword usage and ranking. Through keyword co-occurrence analysis and clustering discussions, it was identified that the main research areas in ELM studies revolve around application research associated with its methodologies, variations, and utilization in classification tasks. After data accumulation, VOSviewer was used to determine the classification criteria for the locations, which involved a minimum of 15 words per document. Then, 737 items were generated with 6 clusters, as seen in Figure 2, deducing various subareas on the topic of ELM. Based on the bibliometric analysis, it generates several clusters with their own respective application domains.

Cluster I (red color) contains 204 items focused on research related to ELM, its approaches, variants, and applications in classification. Cluster II (green color) produces 143 items, suggesting a strong emphasis on assessing the performance of predictive models and evaluating the accuracy of predictions. Cluster III (dark blue color) generates 133 items proposing an extensive amount of focus on accurate forecasting models, parameter optimization, and prediction. Cluster IV (yellow color) provides 86 items involving the diagnosis and early detection of diseases, as well as image processing techniques for medical images, and explores subjects like emotion recognition and remote sensing for applications related to healthcare, biomedicine, and image analysis. Cluster V (purple color) generates 86 items related to remote sensing, spectroscopy, and modeling in agriculture and environmental sciences. Cluster VI (light blue color) offers 85 items that emphasize various aspects of fault detection, control, and monitoring in a wide range of systems, including machinery, vehicles, and energy systems. Specific research hotspots have been chosen that require further attention according to cluster analysis performed to determine the co-occurrence of terms.

The keywords generated by cluster I produce the most items, as can be seen in Figure 2, representing ELM classification algorithms and methods. The related literature, including [11][12][13]. Study [11] presented the ELM technique and built an ensemble-based multi-label classification model in order to solve the classification problem of multi-label data. Reference [12] works, they modeled an efficient architecture for online data classifications by employing the principles of parallel algorithms and ELM theory. Research [14] conducted a new algorithm for learning using the majority voting algorithm,

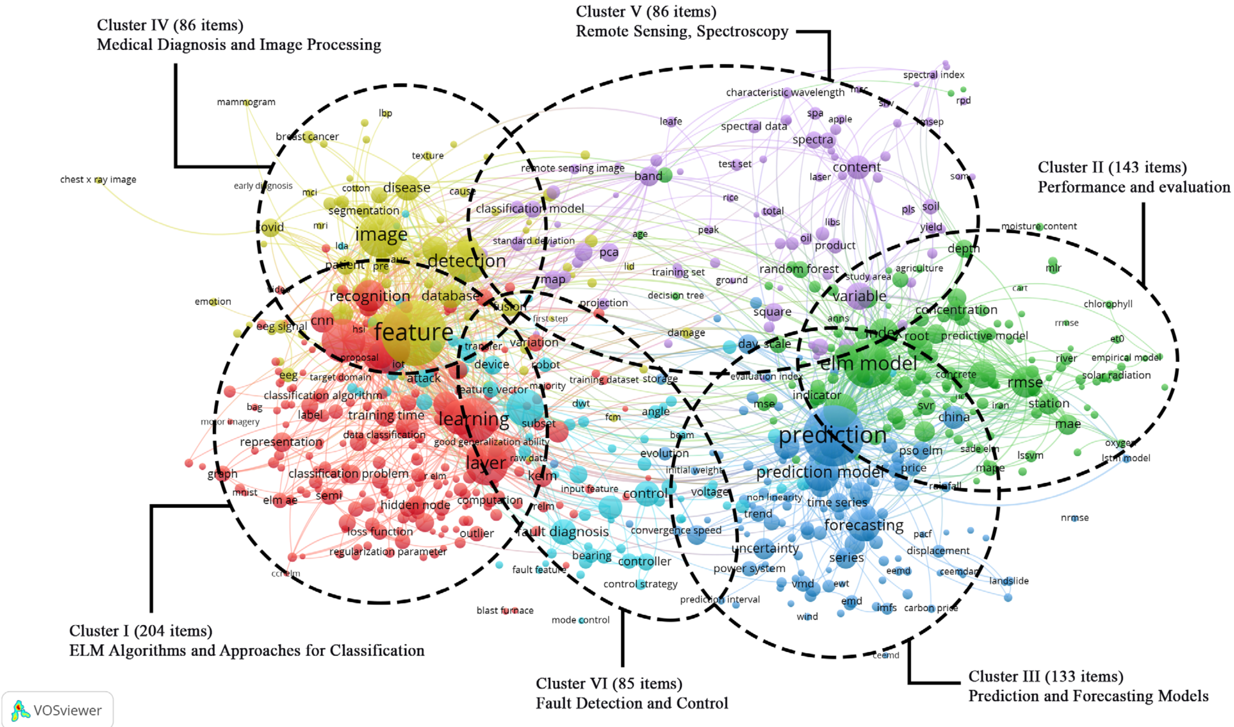

Figure 2. Clusters of keywords and keywords corresponding to their respective research centers.

constrained voting CV-ELM. The CV-ELM can not only increase the utilization efficiency of the hidden node in the ELM but also achieve a higher rate of precision.

Meanwhile, keywords in cluster II indicate a strong emphasis on assessing the performance of predictive models and evaluating the precision of predictions in various applications. Some works addressing this cluster are found in [15][16][17]. Literature [15], the equilibrium optimizer-coupled ELM (EO-ELM) was conducted to validate the performance of the remaining models. In terms of average performance, the EO-ELM model outperformed particle swarm optimization ELM (PSO-ELM) and particle swarm optimization-artificial neural network (PSO-ANN). Literature [16] used a combination of the improved sparrow search algorithm (ISSA), ELM, and Sobol methods, the influence degree of structural material parameters of roller compacted concrete (RCC) dams safety evaluation indices is analyzed. Reference [17] proposed an ELM network employing the Chaos Red Fox optimization algorithm (CRFOA) to estimate the frictionless shear strength of fiber reinforced polymer (FRP)-reinforced concrete columns.

Cluster III's keywords indicate a strong emphasis on accurate forecasting models, parameter optimization, and prediction performance in the context of energy and power systems. The relevant research consists of [18][19][20]. For instance, a novel predictive model known as Bagging-ABC-ELM that incorporates three distinct algorithms: the bagging algorithm, the artificial bee colony (ABC) algorithm, and the ELM algorithm is suggested by [19]. Using Raman spectroscopy technology, the model attempts to predict the blood glucose concentration. Study [18] introduced the fuzzy adaptive particle swarm optimization (PSO)-ELM model, which rapidly attained a higher degree of precision in solving the randomly generated weight matrix of the input layer and the threshold matrix of the hidden layer at the initial stage of the ELM, resulting in poor prediction accuracy. Research [20] combined the fuzzy c-means (FCM), whale optimization algorithm (WOA), and Gaussian mixture model (GMM) became the FCM-WOA-ELM-GMM method for wind power forecasting and uncertainty analysis. The model employs meteorological data to classify a training sample set, which is subsequently clustered using the FCM algorithm.

Keywords in cluster IV point out the diagnosis and early detection of diseases such as breast cancer, epilepsy, and COVID, as well as image processing techniques for medical images like mammograms, magnetic resonance imaging (MRI), electrocardiogram (ECG), and electroencephalogram (EEG) signals, and hyperspectral imaging. Several works addressing this cluster are presented in [21][22][23]. For instance, a two-phase hybrid method, feature weighting (FW) Harris Hawks Optimization optimized by PSO ELM (PHHO-ELM), based on feature weighting, optimization, and machine learning, was proposed by [21] for breast cancer detection. Study [22] examined the use of fMRI-based functional connectivity (FC) measures, including the Pearson correlation coefficient (PCC), maximal information coefficient (MIC), and extended maximal information coefficient (eMIC), in conjunction with ELM for the classification of Alzheimer's disease (AD). Work [23] proposed a novel biological ensemble ELM (BE-ELM) approach to ELM ensemble learning that seeks to simplify the learning procedure and enhance the generalization performance of an ensemble extreme learning machine.

In the cluster V, keywords likely represent research related to remote sensing, spectroscopy, and modeling. Some related works are found in [24][25][26]. Study [24] assessed active interference activity prediction in cognitive radar, an online sequential OS-ELM-based technique with interference frequency and angle prediction models. Reference [25] suggests assessing ELM to map burned regions and contrasting them with other widely used machine-learning methods. Literature [26] utilizing a minimal number of climatic variables to investigate the use of ELM for the precise prediction of daily soil temperatures (ST), including maximum and minimum air temperatures, relative humidity, and day of the year (DOY) as a proxy for the temporal component.

Lastly, keywords in cluster VI likely focus on various aspects of fault detection, control, and monitoring in a wide range of systems, including machinery, vehicles, and energy systems. Some works addressing this cluster are found in [27][28][29]. Reference [27], a hybrid resampling-based improved ELM (HRIELM) is conducted to address the issue of imbalanced fault pattern data that arises during the diagnosis of chiller faults. Reference [28], an OS-ELM environmental parameter identifier-based distributed lateral and longitudinal finite-time sliding mode tracking controller was implemented to address the issue of ambiguous environment parameters in vehicle platoon lane-changing control. Study [29] presented a novel semiactive suspension control scheme with improved ELM for simultaneously improving vehicle comfort and performance.

According to the bibliometric analysis of ELM research from 2018 to 2023, keyword mapping in Figure 2 has resulted in the formation of six distinct clusters. Cluster 1 contains the most keywords, indicating a well-established and extensively researched area. In contrast, Cluster 6 (fault detection and control) marginally has smaller keywords than the other two, suggesting it is an emerging field with significant potential for future research and publication. The limited number of keywords in Cluster 6 highlights unexplored or under-researched topics within the ELM domain, offering opportunities for novel contributions and impactful studies. Therefore, targeting publications based on the keywords in Cluster 6 could position researchers at the forefront of pioneering advancements in this nascent area.

By examining ongoing research trends, as seen in Figure 3, it is possible to analyze research challenges. This pattern is evident in the relevancy and quantity of

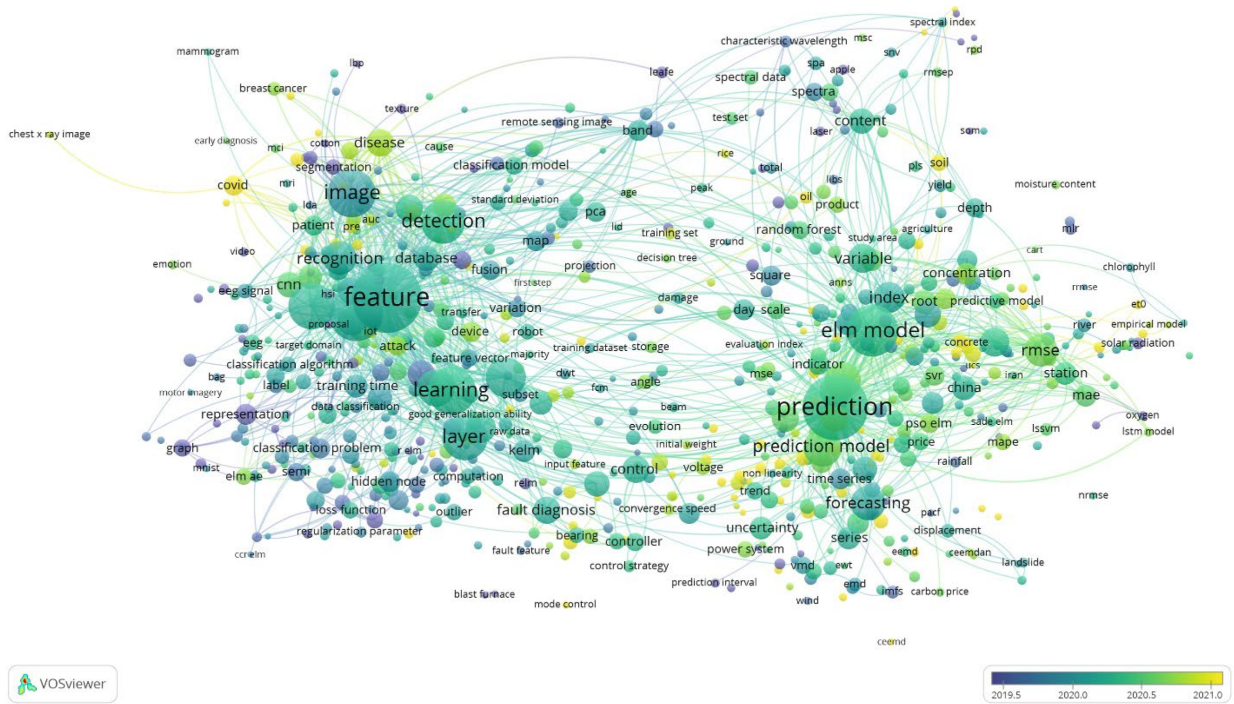

Figure 3. Keywords on the ELM research in overlay visualization.

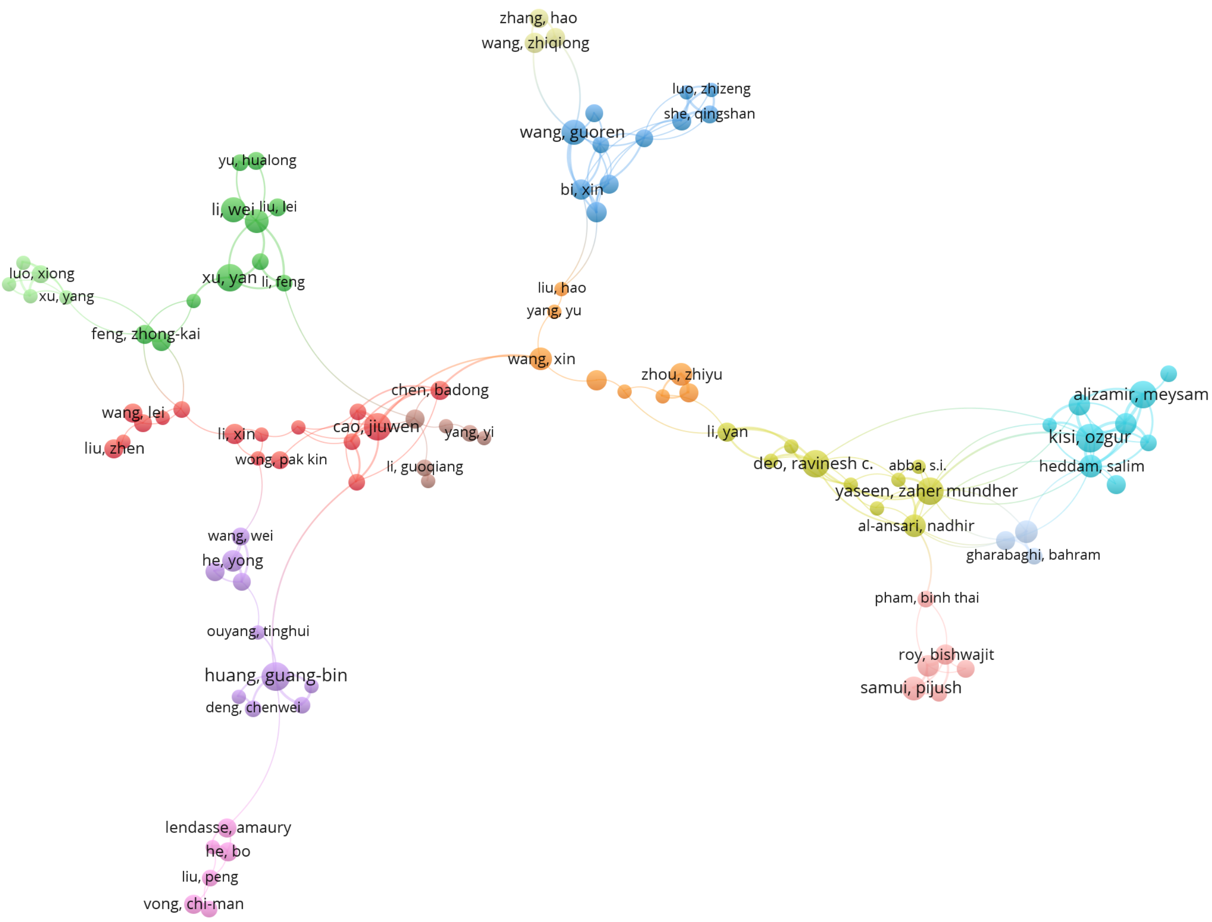

Figure 4. Authors' co-citation mapping.

keywords that researchers employ most frequently. In Figure 3, the linkage data between ELM research topic keywords from 2019 to 2021 is illustrated. The keywords linkage map was generated with VOSviewer. The software's features enable the interpretation of the map as Figure 3 by inputting the data obtained from Scopus. Keyword usage is indicated by the circle's scale. A larger circle indicates that a greater number of keywords are employed. The three most frequently used keywords, as indicated by the data, were "classification" (163 usages), "prediction" (1,407 usages), and "feature" (1,632 usages). These areas are central to ELM research and have received significant attention over the years. Conversely, "classical ELM" is the least frequently used keyword, with only 15 usages, suggesting a shift away from traditional methods towards more advanced or hybrid approaches.

When examined by year, the keywords in yellow are the most recent research keywords. One of the most recent research keywords is the "sparrow search algorithm (SSA)-ELM." SSA is a novel intelligent algorithm that has been developed to ascertain the weights and thresholds of the input layer and concealed layer in ELM. Reference [30], the SSA-ELM neural network model is a dependable model that is capable of accurately and comprehensively predicting the traffic safety factor. Literature [31], a method for finding faults in wind turbine bearings using CNN and SSA-ELM is suggested. This method can effectively extract fault features and groups and identify bearing data even when working conditions and speed change over time. It also applies well to other situations. Notably, one of the most recent research trends is the integration of the "sparrow search algorithm (SSA)" with ELM, highlighting an emerging interest in enhancing ELM performance through novel optimization techniques.

Figure 4 illustrates the authors' collaboration network. The picture depicts the 13 main clusters that consist of the closest collaborators and groups of authors who are primarily studying this issue. Table 1 displays information regarding the ten authors with the highest number of citations, as determined by the total number of publications in all countries. The quantity of citations is indicative of the author's influence on the research topic. The authors with the maximum number of citations are R. C. Deo, and Z. M. Yaseen, as indicated by the data in Table 1. R. C. Deo is a full professor of mathematics and a researcher of artificial intelligence and machine learning. His research interests encompass the fields of applied computation, deep learning, machine learning, and artificial intelligence. Z. M. Yaseen is an Assistant Professor at

King Fahd University of Petroleum and Minerals. His research interests relate to hydrology, water resources engineering, environmental engineering, civil engineering, and machine learning. R. C. Deo and Z. M. Yaseen, authored the review paper "An enhanced extreme learning machine model for river flow forecasting: state-of-the-art, practical applications in the water resource engineering area and future research directions," with a total of 573 citations. The paper presents a thorough review of the extreme learning machine (ELM) model, focusing on its application in river flow forecasting. It covers various hydrological process implementations and evaluates numerous studies from diverse perspectives. The enhanced ELM model shows exceptional performance in forecasting river flow. Additionally, the paper anticipates several key propositions to guide future research directions in this field. In terms of ELM research, there is an opportunity to collaborate with R. C. Deo and Z. M. Yaseen as both possess a high level of expertise in ELM, as demonstrated by the substantial number of citations to their articles.

IV. Application of ELM-based Control System

This section provides an additional summary of the discovery in Figure 2 that was previously identified through bibliometric analysis. Several ELM and control system-related studies are mentioned in the previous section. Using the ELM to estimate and compensate for uncertainty has numerous notable benefits [32]. First, the settings for the hidden layer can be picked at random. Second, unlike many conventional neural networks, an adaptive learning coefficient created using the Lyapunov approach is capable of updating output weights quickly. Finally, once the input nodes of the ELM have been identified, no prior knowledge of uncertainty is necessary. In this part, representative works with ELM and control in various domains are examined. Some of the ELM-based control systems are summarized in Table 2.

A. Robotics

The application of ELM algorithms in control systems has revolutionized the robotics field, offering rapid and efficient solutions for real-time decision-making and precision control. Applications in the realm of robotics, such as brushless DC servo motors [7], bicycle robot [33], robot manipulator [34][35][36][37][38][39][40], robot trajectory tracking [41], plant protection robot [42], multiple robots [43], nonaffine pure-feedback system [44], permanent magnetic synchronous motors (PMSM) systems [45], [46], free-floating space robots [47], inverted pendulum [48], and system robot [49].

Chuei and Zao. [7] provided ELM-based super-twisting repetitive control (ELMSTRC) operating on brushless DC servo motors to improve the precision tracking of periodic signals while minimizing chattering. Comparison studies demonstrate that the suggested ELMSTRC exhibits outstanding performance in tracking periodic signals, compensating for aperiodic disturbances, friction, and backlash while also showcasing robustness against system uncertainty. In the times ahead, there will be consideration given to utilizing enhanced error correction-based neural network control [50] to enhance the precision of tracking, speed of transitions, and the robustness itself.

Zheng *et al.* [45] proposed field-oriented feedback linearization controllers (FOFLCs) based on ELM estimators for permanent magnetic synchronous motors (PMSM) systems. Based on research by Zheng who proposed ELM-based control, real-time implementation of the methods is possible in addition to their enhancement of speed tracking performance. The findings demonstrate that the proposed control

Table 1.
Top 10 authors with the number of citations.

No.	Author	Number of citation	Affiliation	Scopus ID
1.	Deo, Ravinesh C.	1250	University of Southern Queensland	8630380500
2.	Yaseen, Zaher Mundher	989	King Fahd University of Petroleum and Minerals	56436206700
3.	Shariati, Mahdi	928	Duy Tan University	36769148300
4.	Trung, Nguyen Thoi	825	Van Lang University	24171745600
5.	Xu, Yan	726	Nanyang Technological University	-
6.	Kisi, Ozgur	681	Ilia State University (ISU)	6507051085
7.	Cao, Jiuwen	537	Hangzhou Dianzi University	35274436100
8.	Al-Ansari, Nadhir	535	Lulea Technical University Sweden	-
9.	Feng, Zhong-kai	526	Hohai University	48561032800
10.	Niu, Wen-jing	526	Changjiang Water Resources Commission	56709266000

method excels in tracking performance even amidst different types of uncertainties. Subsequent efforts will aim to enhance the performance of ELM-based control systems in terms of their robustness, tracking accuracy, and transient response.

Chen *et al.* [33] proposed robust integral terminal sliding mode control (ELM-ITSM) that was applied for a bicycle robot. Chen *et al.* used the ELM algorithm to estimate the combined uncertainty, the estimated value of the combined uncertainty through the ELM mechanism, which is an estimated value designed as input control compensation. Studies have demonstrated that the suggested control incorporates a feedback control input and an ELM estimator to counteract the impact of combined uncertainty. This ensures not only a smoother balance between reducing chattering and maintaining tracking accuracy but also enhances the control structure's robustness and simplicity of design.

Yang *et al.* [34] proposed an ELM-based adaptive control scheme for haptic identification on an uncertain robot manipulator. ELM is utilized to compensate for unidentified nonlinearities in the dynamics of the manipulator. Therefore, achieving an exact match with the reference model is possible following the initial iteration.

Another application of PMSM is developed by Vijay Amirtha Raj *et al.* [46] which is a speed drive system with a new optimized adaptive ELM neural network-based fuzzy PI controller. The responsiveness of the drive system confirms its effectiveness when compared to other methods found in existing literature studies. Additionally, thorough statistical analysis further supports the credibility of the conducted research. Reduced error values validate the efficacy of the developed model.

B. Energy and power systems

In the zone of energy and power systems, the integration of ELM techniques has ushered in a new era of adaptive and robust control, optimizing the efficiency and reliability of critical infrastructure. The application includes two interconnected power systems [51][52][53], microgrid [54][55], electric spring [56], hydrostatic tidal turbine (HTT) [57], smart grid [58], buck converter [59][60], wind power [61], and photovoltaic (PV) system [62][63].

The works by Jin *et al.* [51] examines the application of exogenous disturbances, denial-of-service (DoS) attacks, and nonlinear dynamics to the output feedback security control of a class of high-order nonlinear interconnected systems involving two interconnected power systems. The presented observers, filters, and controllers featuring adaptive gain function design effectively mitigate the effects of DoS attacks, nonlinear dynamics, and disturbances. Furthermore, despite the existence of DoS attacks and disturbances, the proposed adaptive observation and control schemes can ensure unidirectionally bounded stability outcomes. In the upcoming research, a study will delve deeper into examining the effects of DoS attack frequency and duration on system performance while taking into account the anti-attack condition.

Rajput *et al.* [55] presented a microgrid system with renewable energy assistance using superconducting magnetic energy storage (SMES) storage. Microgrid performance evaluation utilizing an ELM-based PID controller is guaranteed to remain stable despite all uncertainty by means of the ELM control strategy. The ELM control strategies ensure system stability even when faced with various uncertainties. Future developments will entail integrating type-2 feedback linearization controllers (FLC) with advanced FLC techniques, such as fractional order sliding mode control, to enhance dynamic system stability, alongside the exploration of novel FLC methodologies.

Zhao *et al.* [56] introduced a hybrid approach to electric spring (ES) control, combining data-driven and analytical models. The imprecise analytical model establishes a fundamental guideline for generating system data. An ELM-based control model is suggested to formulate the ultimate control strategies. The findings indicate that ELM-based data-driven models outperform the analytical model in system prediction accuracy and control efficiency for ESs. According to statistical learning theory, the ELM model is dependable for prediction under specific circumstances. Future work will take into account the dynamic features of the environment, as well as the associated operating costs.

Reference [57], a hydrostatic tidal turbine (HTT) is devised and simulated, employing a hydrostatic transmission known for its increased reliability as a replacement for conventional fixed ratio gearbox transmissions. The dynamic model of the HTT is formulated by amalgamating the governing equations of all hydraulic machine components. A nonlinear observer is introduced to forecast turbine torque and tidal speeds in real time, utilizing the extreme learning machine (ELM) method. Subsequent efforts will concentrate on implementing the sensorless optimal power control on additional experimental platforms, which may include hardware-in-the-loop systems.

Lu *et al.* [60] proposed an approach for controlling the output voltage of buck converters that combines a PID controller and an ELM. They used the state space

Table 2.
Some recent applications of ELM-based control systems.

No.	Application	Reference
1.	Robotics	References in this category pertain to robotic technology, which encompasses the advancement of autonomous robotics, navigation algorithms, and industrial applications. Examples of such references are [3][7][33][34][35][36][37][38][39][40][41][42][43][44][45][46][47][48][49]
2.	Energy and power systems	References in this category provide information on the energy system, with a primary emphasis on energy efficiency and renewable energy sources. Examples of such references include [51][52][53][54][55][56][57][58][59][60][61][62][63]
3.	Transportation and vehicles	References in this category include studies of vehicle design, electric vehicle technology, and transport innovation. Several instances of such references include [5][6][28][29][32][64][65][66][67][68][69][70][71][72][73][74][75]
4.	Manufacturing technology	References in this category include new techniques and technologies in manufacturing, including automation and improved production efficiency [4][76][77][78][79][80][81][82] are notable examples of such references

averaging technique, and the mathematical model of a buck converter operating in continuous conduction mode (CCM) was created. The evidence indicates that the controller can adapt its parameters to handle external disturbances and nonlinear effects within a reasonable timeframe, demonstrating favorable dynamic attributes.

C. Transportation and vehicles

Within the domain of transportation and vehicles, the utilization of ELM methodologies has led to groundbreaking advancements in autonomous navigation and control, enhancing safety and efficiency in the ever-evolving automotive landscape. These applications are hypersonic vehicles (HV) [6], intelligent vehicle platoon [28][64], quarter-car test rig [29], aero engine [65], steer-by-wire (SbW) vehicles [5], [66][67], flight control [68], safe model learning [69], active driving safety car [70], autonomous robotic vehicle [71], electronic throttle [32][72], unmanned surface vehicle [73][74], and automotive engine idle [75].

Zhang *et al.* [5] introduced an active front steering (AFS)-based electronic stability control (ESC) strategy for SbW vehicles aimed at enhancing yaw stability and maneuverability. This strategy incorporates both the upper adaptive recursive integral terminal sliding mode (ARITSM) controller and the lower FNTSM controller based on the ELM estimator. The simulation outcomes have effectively demonstrated the effectiveness of the suggested control method during realistic steering maneuvers and when encountering sidewind disturbances. Subsequent efforts will focus on developing a vehicle stability control scheme based on sliding mode for SbW vehicles. This design aims to meet prescribed performance standards while addressing challenges related to rollover prevention and input saturation.

Literature [6], a new SMC scheme, integrated with an ELM-based NNDO, is suggested for achieving disturbance suppression control of HV. The ELM-based NNDO effectively estimates the unknown interference signal through the use of tailored adaptive laws and learning rates. Additionally, the employed direct feedback compensation (DFC) strategy entirely eliminates interference effects on the output, a fact supported by theoretical analysis and simulation results. The simulation outcomes confirm the effectiveness of the suggested ELM-based nonlinear estimator and anti-perturbation control method, particularly when considering prescribed performance standards. The next research endeavor involves devising controllers for more intricate models, such as those encompassing flexible dynamics or a six-degree-of-freedom model.

Reference [71], a two-layer extreme learning machine sliding mode (ELM-SMC) control technique is suggested by Wang *et al.* to ensure autonomous driving robotic vehicles can execute trajectory tracking control with outstanding precision. The goal of Wang *et al.* works is to address the issue of the manipulator's limited trajectory tracking control precision brought on by the change in the direction of the manipulator base. In comparison to alternative trajectory error-tracking control methods, the approach presented in this paper demonstrates distinct advantages and robustness.

Hu *et al.* [72] introduced an adaptive fixed-time trajectory tracking control strategy for electronic throttle valve (ETV) systems, employing an ELM-based approach. The proposed controller utilizes a full-order terminal sliding mode designed within a recursive fast terminal mode framework coupled with an ELM-based estimator to learn the rate of change bound information for lumped uncertainty. The excellent control performance has been confirmed. The forthcoming research will focus on devising adaptive fixed-time control strategies to address actuator/sensor malfunctions.

Jin *et al.* [74] devised a specified performance control approach based on nonlinear ELM estimators. The objective was to solve perturbation rejection and path-following issues that were implemented in models of unmanned marine systems. The simulation outcomes confirm the effectiveness of the suggested ELM-based nonlinear estimator and anti-perturbation control method, particularly when considering prescribed performance standards.

D. Manufacturing technology

The use of ELM algorithms has ushered in a new era of adaptable and flexible control systems in the field of manufacturing technology, optimizing production processes and ensuring precision within a constantly changing industry environment. Some of the manufacturing technology applications are variable polarity plasma arc welding (VPPAW) [4], doubly salient electromagnetic starter/generator (DSESG) [76], random vector functional link (RVFL) networks [77], excavation [78], multiple-input-multiple-output (MIMO) affine nonlinear dynamic systems [79], ground-granulated blast-furnace slag (GGBS) production process [80], arc welding of aluminum alloys [81], and extreme environment applications such as borehole magnetic field measurement [82].

Wu *et al.* [4] introduced an innovative framework for intelligence modeling and control that utilized model-free adaptive control (MFAC) and ELM techniques to oversee and regulate weld penetration via keyhole visual signal. Closed-loop experiments demonstrate that the MFAC system can control the VPPAW process by regulating the welding current and plasma gas flow rate simultaneously in order to maintain a constant full penetration despite varying initial heat input and heat transfer conditions.

Reference [76], the copper loss optimization control (CLOC) utilizing ELM was suggested for the angular position control (APC) active rectifier (AR) with optimized turn-OFF angles. A CLOC based on ELM is introduced to reduce copper loss. Future research endeavors will focus on analyzing temperature increases and iron loss using multiphysics simulations and experiments. The copper loss in the DSESG was minimized, leading to a decrease in heat generation. Building on the proposed approach, efforts will be directed towards optimizing both copper and iron losses. Furthermore, integration of the ELM-based model online with automated scanning and optimization will be pursued.

Li *et al.* [80] proposed a data-driven intelligent control approach using the improved online error minimized-ELM (IOEM-ELM) neural network for ground-granulated blast-furnace slag (GGBS) production process which has a comprehensive system with multiple operating modes, high uncertainty, high nonlinearity, and strong coupling. The simulation results indicate that the suggested approach effectively manages sudden changes in operating modes and minimizes network computation.

Zhang *et al.* [82] suggested and created a highly stable helium (He) lamp using a negative feedback excitation circuit based on the ELM-Hammerstein paradigm with a programmable metal–oxide semiconductor field-effect transistor (MOSFET) power amplifier and a digital PID feedback control system as its light source. In contrast to He-OPM using a laser light source, the sensitivity of He-OPM utilizing a discharge lamp was lower, yet it exhibited superior stability, especially in borehole environments at high temperatures. Consequently, this method is better suited for precise surveys and prolonged usage in sealed conditions.

V. Future Outlook and Challenge

It has been shown in Section IV that ELM-based controllers have been applied to various applications such as robotics, energy and power systems, transportation and vehicles, and manufacturing technology. Based on the comprehensive analysis of ELM, the proper recommendation of ELM can be listed as follows:

- Estimator: ELM can be utilized in real-time to estimate various disturbances, e.g. periodic or aperiodic disturbances, model nonlinearities, and model or parameter uncertainties, as presented in [3][5][6][7][33][45][72][74].
- Compensator: ELM can be used as a compensator to suppress various disturbances, friction, backlash, and unidentified nonlinearities to improve tracking performance and system robustness, as outlined in [7][33][34].
- Fault detector: ELM can be applied to recognize or detect if there are attacks (e.g. DoS) and faults (e.g. on sensors and actuators), as studied in [27][51][57][72].

Consequently, ELM finds extensive application in control systems owing to its capacity to enhance the system's robustness, particularly in situations involving disturbances, model uncertainties, and defect detections. Future versions of modern control methods, including sliding mode control, repetitive control, feedback linearization, model prediction control, iterative learning control, and optimal control, may incorporate ELM as a supplementary technique to achieve a more robust control system. However, the primary challenge associated with an ELM-based control system also lies in its need for significant real-time computational power, which is the ability to execute control algorithms and handle large amounts of data as an ELM input in real-time. Therefore, it is not solely on the execution of control algorithms.

VI. Conclusion

This bibliometric analysis of ELM research from 2018 to 2023 has identified significant trends, opportunities, and challenges in ELM applications, particularly in control systems. The keyword mapping resulted in six distinct clusters, with Cluster 1 (ELM algorithms and approaches for classification) being the most established and extensively researched area, while Cluster 6 (fault detection and control) emerged as a field with substantial potential for future exploration. The limited number of keywords in Cluster 6 indicates unexplored topics within the ELM domain, presenting opportunities for novel research contributions. The analysis of ongoing research trends revealed that "classification," "prediction," and "feature" are the most frequently used keywords, reflecting the focus and significant attention these areas have received. In contrast, "classical ELM" has seen minimal usage, suggesting a shift towards more advanced or hybrid approaches. A notable recent trend is the integration of the "sparrow search algorithm (SSA)" with ELM, highlighting an emerging interest in enhancing ELM performance through novel optimization techniques. Furthermore, the study identified opportunities for collaboration with leading researchers such as R. C. Deo and Z. M. Yaseen who have significant expertise in ELM. Future improvements to ELM in control systems could complement a variety of control methodologies such as sliding mode control, adaptive control, feedback linearization, model prediction control, iterative learning control, and optimal control, all aimed at establishing a more resilient control system. However, challenges such as the need for significant real-time computational power and the need to compute large real-time data remain prominent. Overall, this study provides valuable insights into the current state and future directions of ELM research, emphasizing the importance of addressing existing challenges and exploring emerging trends to advance the field further.

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Declarations

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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