Kalman Filters in IoT: A Bibliometric Analysis

Khaled Obaideen, Mohammad AlShabi, and Stephen Andrew Gadsden

Abstract This bibliometric analysis focuses on the evolution and trends of the Kalman Filters (KFs) studies in the Internet of Things (IoT) from the year 2009 to 2023. This being a data-intensive study, it uses the information from major academic databases, which it adapts to explore key terms, publication patterns, and the interdisciplinary nature of the research. The paper comes out with a sharp increase of the research in 2015, which corresponds to growing of the research interest to the application of KFs for IoT. Key points of the study accentuate the role of KFs in IoT, especially in respect of the betterment of the systems for indoor positioning, global positioning, and sensor data fusion. This software proves the KFs are in the spotlight in IoT by helping to improve localization accuracy and data processing. The research highlights progress in filtering methods, for example, extended and unscented Kalman filters, evidently to improve state estimation and predictive analytics in dynamic contexts. Furthermore, KFs research scope includes novel areas such as machine learning and deep learning, which indicates the possibility of using this technology as a tool for advancing IoT. The rapid growth of technology in this area also presents challenges, a part of those are the data privacy and security problems in complex IoT environments. The paper emphasizes the major part KFs are playing in driving IoT technology and also stresses the type of interdisciplinary studies that are needed to navigate the changing landscape of IoT applications.

Keywords Kalman filters · Internet of Things · IoT · Bibliometric

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1 Introduction

The Internet of Things (IoT) ecosystem, a network interconnecting physical objects with digital intelligence, is evolving rapidly, driven by advancements in sensor technology and data analytics [1–3]. Central to this transformation is the application of Kalman Filters (KFs), a powerful algorithm used for data prediction and analysis in dynamic systems [4–18]. This paper aims to conduct a bibliometric analysis of the use of KFs within the IoT domain, highlighting its pivotal role in enhancing IoT systems' efficiency, accuracy, and reliability. The incorporation of KFs in IoT represents a critical juncture in the evolution of smart systems [19–22]. By enabling more accurate data prediction and noise reduction in sensor outputs, KFs significantly enhance IoT devices' performance.Thisleapincapabilityhasprofoundimplications, revolutionizing industries like autonomous vehicles, healthcare monitoring, and smart cities. In these domains, the precision and dependability offered by KFs translate into safer autonomous navigation, more accurate health tracking, and smarter, more responsive urban environments.

Academically, the study of KFs within IoT marks a vibrant and rapidly expanding field of inquiry. This exploration extends beyond mere technical enhancement; it embodies a paradigm shift in our understanding and utilization of IoT systems. This field challenges existing technological boundaries, fostering innovations in sensor fusion, real-time data analysis, and predictive modelling. It is an exploration that pushes IoT from a network of connected devices to an intelligent, self-optimizing system capable of unprecedented levels of autonomy and accuracy.

As of 2023, the integration of KFs in IoT has witnessed considerable growth and diversification, yet a comprehensive understanding of their full potential within IoT remains a complex puzzle. This study addresses this gap by offering a detailed bibliometric analysis of KFs in IoT. This analysis will not only map out the current state of research but also identify key trends, challenges, and future directions.

This research sits at a crucial intersection, aiming to provide a holistic view of the challenges and opportunities presented by the integration of KFs in IoT. A significant debate in this area revolves around the practical and ethical implications of advanced data processing in IoT. As IoT devices become more sophisticated and autonomous, questions arise regarding data privacy, security, and the ethical use of predictive data.

Importantly, this paper emphasizes the need for a comprehensive understanding of KFs' role in the IoT landscape. It examines the current state of research, assesses progress, and identifies areas requiring further investigation. In doing so, the paper adds to the broader dialogue on the future of IoT, offering valuable insights for researchers, policymakers, and industry practitioners.

2 Methodology

The methodology employed in this study is a meticulously crafted fusion of advanced bibliometric and data analysis techniques, specifically tailored to garner both quantitative and qualitative insights into the use of KFs in the IoT. This approach, as depicted in Fig. 1, aligns with the best practices in bibliometric research [23–29], ensuring a multi-faceted examination of KFs' role in augmenting IoT systems.

The primary data source for this research was the Scopus database, selected for its comprehensive collection of scholarly articles. Precise search queries were developed, focusing on terms related to "Kalman Filters," "IoT," and their interplay. These queries, detailed in Fig. 1, were designed to selectively extract publications that accurately depict the integration of KFs in IoT. The timeline of this study extends from the inception of these technologies to the end of 2023, offering a wide-ranging historical and contemporary perspective.

This study utilized a detailed bibliometric analysis on data from Scopus, employing R tools like Bibliometrix and Biblioshiny, alongside text mining with VOSviewer to uncover publication trends, citation patterns, thematic trends, and the geographical and institutional landscape of KFs research in the IoT. It provided

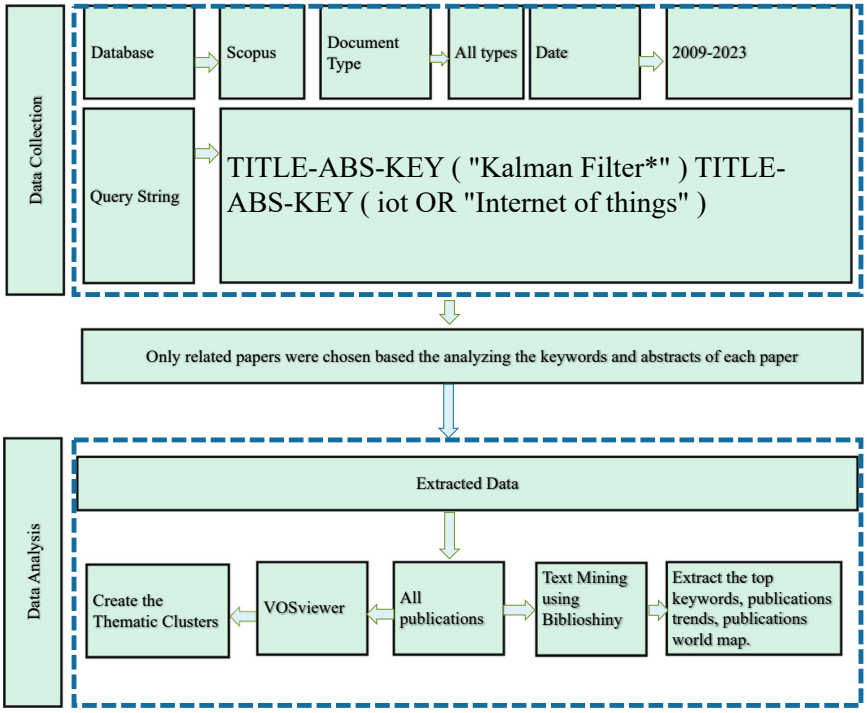

Fig. 1 Research methodology

insights into research trajectories, collaboration networks, and emerging innovations, using data visualization for clarity. The analysis extended to citation networks and keyword co-occurrence, revealing foundational works, influential researchers, and evolving research themes over time. Additionally, it explored the cross-disciplinary impact of KFs in IoT, highlighting interdisciplinary collaboration. This comprehensive methodology aimed to advance the understanding of KFs' application in IoT.

3 Results and Discussion

The Biblioshiny data offers, shown in Table 1, a detailed and comprehensive overview of the bibliometric landscape of KFs in the IoT. This analysis sheds light on key insights regarding the evolution, scope, and impact of this research area. Spanning from 2009 to 2023, the data captures a significant period in which KFs have been increasingly applied within IoT, highlighted by an impressive annual growth rate of 38.65%. This surge suggests that the expansion of the field is likely fuelled by ongoing technological advancements in IoT and the growing relevance of KFs in a variety of IoT applications.

With 369 sources and 593 documents included, the data reflects a broad and interdisciplinary nature of research, encompassing various academic and professional domains. This diversity emphasizes the topic's widespread interest and applicability. Additionally, the average age of the documents being 4.04 years, along with an average citation rate of 8.739 per document, signifies the recency and substantial influence of the research. This high citation rate particularly underscores the importance and impact of the work on KFs in IoT, marking these studies as frequently referenced and integral to ongoing research discussions.

The field has shown considerable evolution over the years, as indicated by the expansive timespan and consistent growth in the number of publications.

Earlier research likely set the foundation for the concepts and applications of KFs in IoT, while more recent studies have advanced these ideas, exploring new technologies, methodologies, and applications.

Table 1 Main information

Description	Results
Timespan	2009:2023
Sources (Journals, Books, etc.)	369
Documents	593
Annual Growth Rate %	38.65
Document Average Age	4.04
Average citations per doc	8.739

The diversity of sources and the range of keywords underscore the interdisciplinary nature of the research. It indicates collaboration across various fields like computer science, engineering, data analytics, and applied mathematics, which are essential in addressing the complex challenges and opportunities presented by IoT.

The bibliometric analysis based on the Biblioshiny data portrays a dynamic, rapidly growing, and impactful research field. KFs in IoT have attracted significant interest and contributions from the academic and research community, signifying their crucial role in advancing IoT technologies and applications. The trajectory of the field's growth indicates that it will likely remain a vibrant area of research activity and innovation.

Moreover, the bibliometric data from Biblioshiny chronologically outlines the research progression on KFs in the IoT, showcasing a distinct trend of escalating academic interest and publication activity over the years, as shown in Fig. 2. From 2009 to 2014, there was a modest start in the publication numbers, with only one article in 2009, increasing gradually to seven by 2013. This period marked the early stages of research in this area, focusing on laying the foundational concepts and exploring initial applications of KFs in IoT. The number of publications in this phase indicates it was a time of preliminary exploration and theoretical development.

A significant shift occurred from 2015 onwards, as evidenced by a sharp increase in publication activity. The year 2015 alone saw a notable rise to 14 articles, doubling the previous year's output. This upward trajectory continued, reaching a peak of 99 articles in 2022 and maintaining a high count of 97 in 2023. This rapid growth signifies an expanding interest in the field, likely propelled by technological advancements in IoT and a growing recognition of the potential benefits of KFs in enhancing IoT applications.

The accelerated growth in this area can be attributed to several factors, including advancements in IoT technologies such as enhanced sensors, improved connectivity,

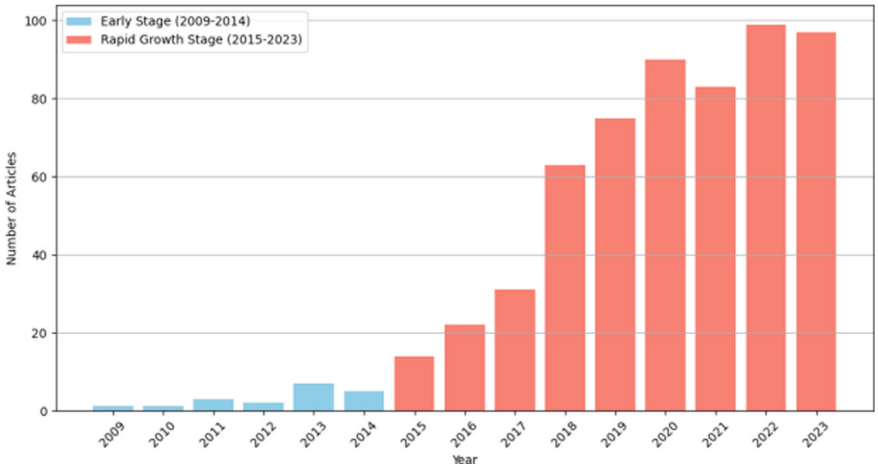

Fig. 2 Publication trend in IoT and KFs research

and more sophisticated data processing capabilities. These developments provided a conducive environment for applying KFs in increasingly complex and varied IoT scenarios. Additionally, the rising availability of data and the need for real-time processing and analytics in IoT systems likely drove more research into efficient algorithms like KFs.

Significant advancements in related fields like machine learning, artificial intelligence, and edge computing, particularly in the later years of this timeline, also played a crucial role. The integration of these technologies with IoT has potentially opened new avenues for research in KFs, particularly suited for predictive analytics and state estimation in dynamic environments, which are critical for smart IoT systems.

Despite the substantial growth in research, the field still faces challenges, including the complexity of IoT environments, the need for real-time processing, and concerns around data privacy and security. As IoT continues to evolve, there's a potential for KFs to be adapted or integrated with other emerging technologies to address these new challenges and applications.

The bibliometric data indicates a significant and sustained interest in the application of KFs in IoT. The field has transitioned from its early exploratory phase to a dynamic area of research, mirroring the growing complexity and capabilities of IoT systems. The consistently high number of publications in recent years suggests that this research area will remain a fertile ground for academic inquiry and technological innovation, likely having a considerable impact on the future of IoT applications.

As can be seen in Fig. 3, the VOSviewer analysis of the bibliometric data reveals insightful trends and focal areas in the research of KFs within the IoT. The clustering of keywords and their average publication years provide a nuanced understanding of the evolution and current state of research in this field.

- Dominance of IoT and KFs: The most weighted terms are "internet of things" and "kalman filters," highlighting the central focus of recent research. The average publication year of 2020 for IoT and 2019 for KFs indicates ongoing and increasing interest in this area. This suggests that the integration of KFs in IoT is a relatively recent trend, gaining momentum as IoT applications become more complex and data-driven.
- Emergence of Adaptive Filtering and Data Fusion: "Adaptive filtering" and "data fusion" are prominent, reflecting the focus on enhancing data accuracy and efficiency in IoT systems. The presence of terms like "big data" and "sensor data fusion" with publication years around 2019–2020 underlines the growing need for sophisticated data processing techniques in handling the vast amounts of data generated by IoT devices.
- Role of Artificial Intelligence and Machine Learning: The appearance of "artificial intelligence" and "machine learning" with an average publication year around 2020 suggests a burgeoning interest in the incorporation of AI and ML in enhancing the capabilities of KFs in IoT. This integration is likely focused on improving predictive accuracy and enabling more autonomous IoT systems.
- Application in Positioning and Navigation Systems: There is a clear trend in the application of KFs in "indoor positioning systems," "global positioning system,"

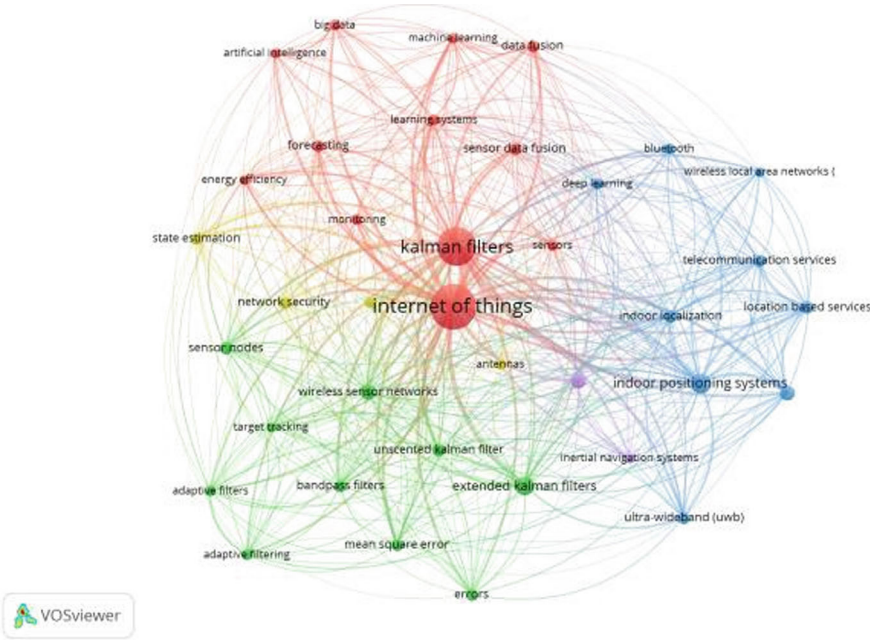

Fig. 3 Thematic clusters of the top index words

and "inertial navigation systems." The recent average publication years (around 2020) for these terms indicate active and ongoing research. This could be attributed to the critical role of KFs in enhancing the accuracy and reliability of positioning and navigation systems, which are integral to many IoT applications.

- Focus on Network Security and Energy Efficiency: The emphasis on "network security" and "energy efficiency" (average publication years 2020) reflects the growing awareness of the need for secure and sustainable IoT solutions. As IoT networks expand, ensuring data security and optimizing energy usage become paramount.
- Trends in Sensor Technology: Terms like "sensors," "sensor nodes," and "wireless sensor networks" with earlier average publication years (around 2018–2019) suggest that the foundational work in sensor technology has matured, setting the stage for more advanced applications, such as those involving KFs.
- Emerging Technologies: The emergence of "deep learning" and "ultra- wideband (UWB)" technologies in recent years (average publication year 2021) points to the exploration of new methodologies and technologies to further enhance the capabilities of IoT systems using KFs.
- Challenges and Errors in KF Applications: The presence of "errors" and "mean square error" as significant terms reflects ongoing challenges in optimizing the performance of KFs. Researchers are likely focusing on reducing errors and improving the accuracy of state estimation in dynamic environments.

This bibliometric analysis reveals a dynamic and rapidly evolving research landscape. The integration of KFs in IoT is heavily influenced by advancements in AI, ML, sensor technology, and data processing. The focus on applications in positioning systems, network security, and energy efficiency highlights the practical implications of this research. The continuous evolution of IoT necessitates ongoing research, particularly in addressing challenges related to data accuracy, system reliability, and security.

4 Conclusion

This bibliometric analysis aimed to thoroughly examine the progression and expansion of research on KFs in the IoT, uncovering a distinct and growing trajectory since 2009, with a notable surge from 2015 onwards. This increase in scholarly attention, spurred by significant advancements in IoT technologies such as sophisticated sensors, improved connectivity, and advanced data processing, highlights the critical role of KFs in enhancing IoT applications, particularly in real-time data processing and predictive analytics. The convergence of KFs with machine learning and artificial intelligence opens new research avenues within IoT. Despite its contributions, the study acknowledges limitations due to its bibliometric focus, suggesting future research should explore the practical applications and challenges of KFs in IoT, alongside the integration of emerging technologies like 5G and advanced AI algorithms. Addressing challenges such as data privacy and the complexities of IoT environments is vital. Overall, the analysis significantly enhances our understanding of KFs in IoT, emphasizing the field's vibrant, interdisciplinary nature and its potential for ground breaking advancements.

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