Collision-Free Robotic Manipulation: A Review and Bibliometric Analysis

Abstract

This study presents a comprehensive review and bibliometric analysis of collision-free robotic manipulation, a key area for ensuring safety and optimizing efficiency in advanced robotics. A data set was collected from the Web of Science Core Collection (2014-2024) and subjected to analysis, with 169 articles, with the aim of identifying emerging trends, key contributions and global collaboration patterns. The results demonstrate a steady increase in scientific output and identify four research clusters: collision avoidance in robotic systems, trajectory planning and optimization, reinforcement learning and autonomous planning, and collaborative robotics and safety. These clusters illustrate the convergence of advanced techniques such as trajectory planning, optimization algorithms and autonomous learning. This highlights their influence on both industrial applications and collaborative environments. This study provides a comprehensive overview of the research landscape, facilitating a deeper understanding of the field and fostering interdisciplinary collaboration.

Keywords: Bibliometric analysis, Collision avoidance, Robotic manipulation, Trajectory planning, Autonomous systems

1. Introduction

The development of robotic systems capable of collision-free manipulation has gained importance in recent decades, driven by the need to automate complex tasks in diverse environments such as industry Touzani et al. (2022), medicine Zhao et al. (2020), and space exploration Seddaoui and Saaj (2021). Collision-free handling is a multifaceted challenge that spans disciplines such as trajectory planning, environmental sensing, artificial intelligence, and controller design. Ensuring safe and efficient movement of robotic manipulators in environments shared with humans or other robots is a primary goal, with the potential to achieve higher levels of productivity and safety.

In the domain of collaborative robotics, the issue of collision avoidance in dynamic environments, particularly in scenarios where humans and robots share a workspace, is of paramount importance. To address this challenge, Safeea et al. (2019) have proposed a system that integrates off-line generated trajectories with real-time reactive adjustments. Using collaborative manipulators and common sensors, this system ensures safe movements in industrial applications. Based on this research, Liu and Wang (2021) introduced a system that uses contextual awareness and depth sensors to dynamically adjust trajectories in human-robot collaboration, highlighting significant improvements in response time and efficiency. In a complementary approach, Dennis Mronga and Kirchner (2020) proposed a constraint-based framework for human-robot collision avoidance that has proven highly effective in ensuring safe and efficient interactions in a shared workspace. By incorporating predefined constraints directly into the motion planning process, their method allows robots to proactively anticipate and avoid potential collisions while maintaining optimal task execution. At the same time, Zhang et al. (2021) developed a collision avoidance scheme for dual-redundant manipulators based on neural networks that optimizes cooperative tasks by resolving redundancies and ensuring safe performance in constrained spaces.These studies underline the importance of hybrid and learning-based methodologies to improve the safety and adaptability of robotic systems.

Additionally, the optimization of pick-and-place robotic systems has been widely studied to improve the efficiency of assembly lines and industrial processes. Daoud et al. (2014) analyzed and compared three metaheuristic: Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA), and showed that ACO outperformed the other techniques in terms of efficiency and response times in pick-and-place tasks. Complementary, Bourbonnais et al. (2015) proposed a minimum-time path planning method for a five-bar parallel robot using cubic splines and optimization algorithms to maximize accuracy and minimize cycle times. These approaches highlight the role of metaheuristic algorithms and optimization methods in improving productivity in industrial applications.

In the field of agricultural automation, Lin et al. (2021) tackled the problem of collision-free path planning for fruit-picking robots using deep learning through recurrent reinforcement. This approach enabled a trade-off between efficiency and robustness in unstructured environments.

Finally, studies related to path planning and fuzzy logic have provided a solid foundation for the development of hybrid methods in robotics. Hentout et al. (2023) provided a comprehensive review of fuzzy logic-based approaches to collision-free path planning, highlighting their ability to cope with uncertainty in complex systems. In a more practical approach, Jose and Pratihar (2016) explored task allocation and path planning in multi-robot systems using heuristic methods, demonstrating the effectiveness of combinations such as genetic algorithms and A* to ensure safety and efficiency in collaborative environments.

Además de los avances teóricos, múltiples estudios han demostrado aplicaciones prácticas de la manipulación libre de colisiones en entornos reales. Por ejemplo, Secil and Ozkan (2023) proponen un método de planificación de trayectorias sin colisiones específicamente diseñado para manipuladores industriales que operan en presencia de humanos, destacando su aplicabilidad en escenarios colaborativos donde la seguridad es prioritaria. Por otro lado, Bence Tipary and Erdős (2021) presentan una metodología integral para operaciones de pick-and-place en entornos industriales altamente restringidos, abordando la manipulación de piezas con geometrías complejas en células de ensamblaje congestionadas. En medicina, se han desarrollado estrategias avanzadas de planificación de trayectorias y prevención de colisiones aplicadas a la cirugía asistida por robot. Por ejemplo, Yong Jin Cho and Kim (2016) propusieron un método de planificación para end-effectors que evita colisiones durante procedimientos quirúrgicos robotizados, destacando su aplicabilidad en entornos clínicos restringidos. Más recientemente, Li et al. (2023) desarrollaron una técnica de evitación activa de colisiones para robots continuos multisegmentados teleoperados, orientados a la cirugía mínimamente invasiva, con validación experimental en escenarios clínicos simulados. Finalmente, en el ámbito de la automatización industrial, Zbiss et al. (2022) propusieron un algoritmo eficiente para la planificación colaborativa sin colisiones en tareas de pintado de automóviles con múltiples robots industriales. Estas investigaciones refuerzan la conexión entre las contribuciones académicas y su impacto tangible en entornos complejos y dinámicos.

This article aims to provide a comprehensive review of the most relevant approaches in the field of collision-free manipulation. It is accompanied by a bibliometric analysis, which aims to contextualize the impact and evolution of the field. Key aspects such as the predominant algorithms, the most common applications, and emerging research areas are addressed. The ambition of the article is to serve as a useful tool for researchers and practitioners interested in contributing to the development of safer and more efficient robotic systems.

1.1. Methodology and Article Structure

The development of this article was carried out in two main phases. First, a comprehensive research and bibliometric analysis of the field of robotic manipulation was carried out, followed by the formulation of the state of the art, which was based on the results derived from this analysis. In the initial phase of the analysis, key trends, recurring themes and the most influential articles within the field were identified. In the subsequent phase, the state of the art was formulated, structuring the information obtained according to the thematic groups that had been identified. This section provides a conceptual framework that contextualizes the advances and challenges of the field, integrating the results of the bibliometric analysis with the most relevant theoretical and practical contributions, and includes a detailed analysis of the most important articles, providing a guide for researchers interested in exploring the key contributions in the field, among other noteworthy developments.

The structure of the present article is as follows. The section 2 provides a comprehensive description of the methodologies employed for data collection and analysis, thus laying the groundwork for this study. Subsequently, section 3 presents the findings of the analysis, highlighting the most significant contributions from the main areas. Section 4 then discusses, through a co-occurrence analysis, keywords and the grouping of themes into four main clusters. Finally, section 5 presents the conclusions and recommendations for future research, detailing the challenges and opportunities presented by this interdisciplinary field.

2. Data Collection and Analysis Methods

This study employs a research methodology based on a comprehensive bibliometric analysis to examine the phenomenon of collision-free robotic manipulation. This structured, quantitative approach identifies the most relevant research papers, the most representative authors, the most influential academic journals, the most significant regions and the leading institutions within the field. By providing indispensable data on the collaborative dynamics and key performance indicators of the field, bibliometric analysis is positioned as a fundamental instrument for understanding the evolution and trends within this interdisciplinary domain.

As a well-established statistical tool, bibliometric analysis has proven to be an invaluable method for investigating the evolution of the quality and quantity of research in different fields. The methodology is widely applied in disciplines such as advanced robotics, automation and artificial intelligence, thus ensuring a systematic and data-driven assessment of the available literature. This approach allows mapping the landscape of collision-free robotic manipulation, identifying key contributions and trends, and enriching the current debate around this research topic.

2.1. Data collection

This disciplinary study employed a bibliometric approach to conduct a comprehensive analysis of the peer-reviewed literature on collision-free robotic manipulation, using the Web of Science Core Collection (WoSCC) database as the primary source of information.

La selección de Web of Science Core Collection (WoSCC) como única fuente de datos para este análisis bibliométrico se basa en su alta fiabilidad, su contenido cuidadosamente indexado y su compatibilidad con herramientas estándar como Bibliometrix y VOSviewer, que permiten realizar análisis reproducibles y rigurosos. Todas las revistas indexadas en WoSCC están incluidas en el Journal Citation Reports (JCR), lo que garantiza que los artículos proceden de publicaciones de alto impacto y relevancia científica. WoSCC ofrece metadatos enriquecidos, enlaces de citación completos y una cobertura especialmente sólida en ciencias exactas y naturales.

Aunque bases de datos como Scopus o IEEE Xplore podrían ampliar la cobertura temática en algunos sectores, la integración de múltiples fuentes puede introducir inconsistencias en nombres de autores, títulos, revistas e indicadores bibliométricos. Por ello, se optó por una única base de datos de alta calidad para asegurar la coherencia de los datos y la solidez metodológica del estudio Birkle et al. (2020).

The search was conducted on articles published between 1 January 2014 and 23 September 2024, ensuring the inclusion of relevant and recent work in this field. The data was downloaded in BibTeX format to facilitate bibliometric analysis and allow for a systematic assessment of emerging trends, key contributions and possible future research directions in the field.

Antes de establecer el proceso de búsqueda final, se realizaron varias búsquedas piloto con diferentes combinaciones de términos y operadores booleanos. Estas pruebas preliminares permitieron ajustar el vocabulario empleado, evaluar la sensibilidad y especificidad de cada combinación, y eliminar términos que generaban ambigüedad o recuperaban resultados fuera del alcance del estudio, como los relacionados con robótica móvil. Como resultado de este proceso iterativo, se definió una cadena que combinaba términos relacionados con la prevención de colisiones, la manipulación robótica y el pick-and-place, limitada a los campos de título y palabras clave asignadas por los autores, para garantizar una mayor precisión temática.

Esta estrategia se adoptó para asegurar una alta especificidad y evitar la inclusión de trabajos marginales. En áreas especializadas como la planificación de trayectorias sin colisión, los estudios relevantes suelen incluir los términos clave en estos campos. No obstante, se reconoce como limitación que esta decisión pudo excluir trabajos cuyo enfoque principal aparece únicamente en el resumen.

To ensure the quality and relevance of the collected literature, a meticulous search strategy was designed according to the following criteria:

- Articles had to contain one or more of the following keywords in their titles or keywords: *collision avoidance*, *collision-free* or *pick-and-place* in combination with *robot*, *manipulator* or *arm*. However, terms relating to *mobile robots*, *autonomous navigation* or *vehicle* were excluded.
- The selected articles had to have been published in English, in peer-reviewed journals and indexed in the WoSCC database.
- All articles published with the specified terms were included in the review, allowing the most recent and relevant advances in collision-free robotic manipulation to be collected.

La definición del conjunto de palabras clave y de los criterios de inclusión/exclusión fue revisada de manera colaborativa por los autores del estudio. Esta validación interna permitió afinar los términos utilizados, identificar sinónimos relevantes y excluir conceptos ambiguos, como los relacionados con sistemas móviles. El proceso fue iterativo y se apoyó en búsquedas exploratorias, asegurando que los términos empleados reflejaran con precisión el enfoque temático del estudio. Aunque no se conformó un panel externo formal, consideramos que la diversidad y especialización del equipo de investigación garantiza la solidez y pertinencia de la estrategia empleada.

This methodological approach allowed us to collate and analyze a substantial body of high-quality publications, thus providing a solid basis for investigating current trends, identifying the most influential contributions and guiding future research in this field. The preliminary search yielded a total of 1526 articles, which were subjected to a thorough evaluation process to determine their relevance and quality.

Finally, a set of 169 documents stored in CSV format was obtained, once the above-mentioned selection process was completed. This set included a wide range of bibliometric data, such as titles, authors, years of publication, sources, abstracts, keywords, citations and references of the included bibliography. This data set formed the basis for a comprehensive analysis, providing a complete and accurate overview of the literature on optimal collision-free robotic manipulation. A flow chart (Figure 1) has been included to provide a visual representation of the step-by-step filtering process of the literature collection.

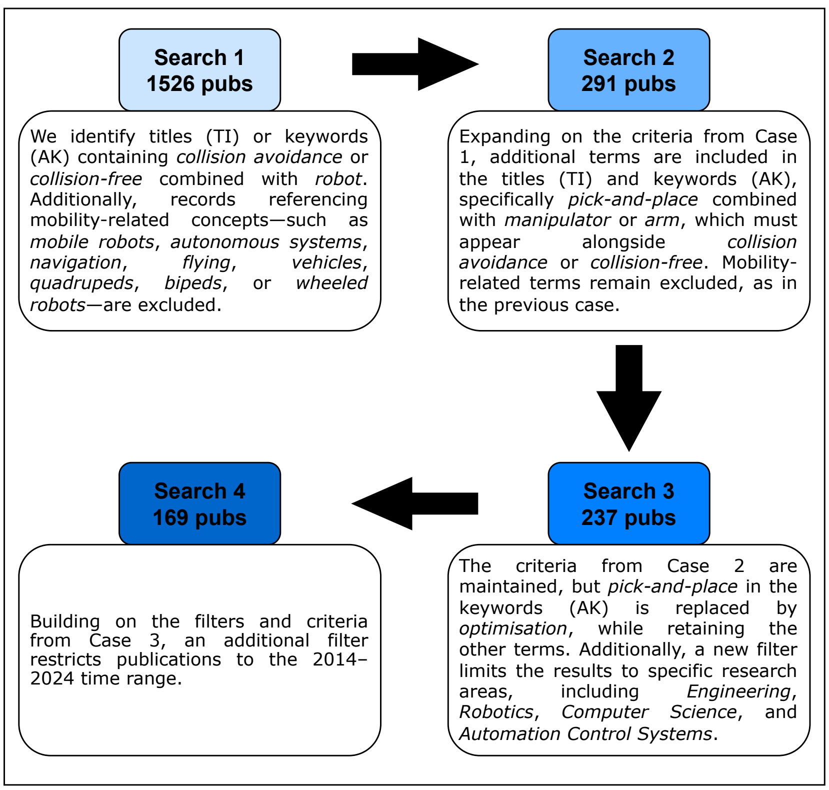

Figure 1: Flowchart of the filtering process.

Bibliometrics, defined as the quantitative study of bibliographic material Broadus (1987)Donthu et al. (2021), represents a pivotal methodology for the analysis of academic domains. Widely employed in disciplines such as medicine Azizan (2024b), economics and sociology, or physical activity Azizan and Fadzil (2024), bibliometrics facilitates the identification of subject dynamics through metrics including publication and citation counts by country, journal, author or institution, thereby offering valuable insights into prevailing scholarly trends.

In this study, R software (version 4.4.0) R (2024) was used as a bibliometric tool to facilitate data visualization using term maps and keyword co-occurrence networks. For this purpose, the definitive collection of relevant documents was downloaded from the WoSCC in BibTeX format, and the data were analyzed using packages such as *tidyverse* Wickham et al. (2019), *ggplot2* Wickham (2016), *bibliometrix* Aria and Cuccurullo (2017), *igraph* Csardi and Nepusz (2006) and *maps* Becker et al. (2021). This approach enabled a comprehensive analysis of collision-free robotic manipulation, providing representative visualizations of bibliographic trends and allowing in-depth exploration of metrics such as citations, co-authorship and keywords. The analytical process not only facilitated a deeper and more systematic understanding of the field, but also enabled the identification of relevant themes, emerging trends and research gaps, thus establishing a solid foundation for future research in this area.

The bibliographic analysis covers a data set with an average annual growth rate of 11.07% over the period studied. This corroborates the claim that there is a growing interest in the field of robotic manipulation. Publications come from 102 different sources, including journals and conferences. The average number of citations per article is 10.20, with an average of 2.06 citations per year. This is indicative of a remarkable academic impact.

In terms of academic collaboration, the authorship of the collection of articles considered corresponds to 601 researchers, with an average of 4.20 co-authors per article, which serves to illustrate the collaborative nature of this field of research. However, it is worth noting that only 13.61% of the articles included international co-authorship, indicating a tendency towards local or national collaborations. A total of 189 Keywords Plus and 610 Authors' Keywords were identified, which serves to illustrate the thematic diversity and terminological richness of the studies analyzed. Table 1 provides a summary of the above results and an overview of the current state of the literature review.

Table 1: Summary of the bibliographic collection (2014-2024).

Description	Results
Sources (Journals, Books, etc)	102
Documents	169
Annual Growth Rate (%)	11.07
Document Average Age	3.92
Average Citations per Doc	10.20
Average Citations per Year per Doc	2.06
References	4687
Document Types	
Article	113
Article; Early Access	3
Article; Proceedings Paper	1
Proceedings Paper	49
Review	3
Document Contents	
Keywords Plus (ID)	189
Author's Keywords (DE)	610
Authors	
Authors	601
Author Appearances	709
Authors of single-authored docs	1
Author Collaboration	
Single-authored docs	1
Documents per Author	0.28
Co-Authors per Documents	4.2
International co-authorship (%)	13.61

3. Results of the analysis

To better understand the historical development of the literature on collision-free robotic manipulation, the evolution of this field has been examined (Figure 2). Scientific production in this field started modestly in 2014 with seven publications, showing a gradual increase from 2015 onward. This growth remained steady in the following years, reaching a peak of 24 publications in 2021. Although there were slight fluctuations in the number of articles published in 2022 and 2023, with 22 and 19 articles respectively, a recovery is seen in 2024, with 20 articles published to date. This growth reflects the relevance of the topic, driven by the need for advanced solutions that optimize robotic manipulation in increasingly complex environments.

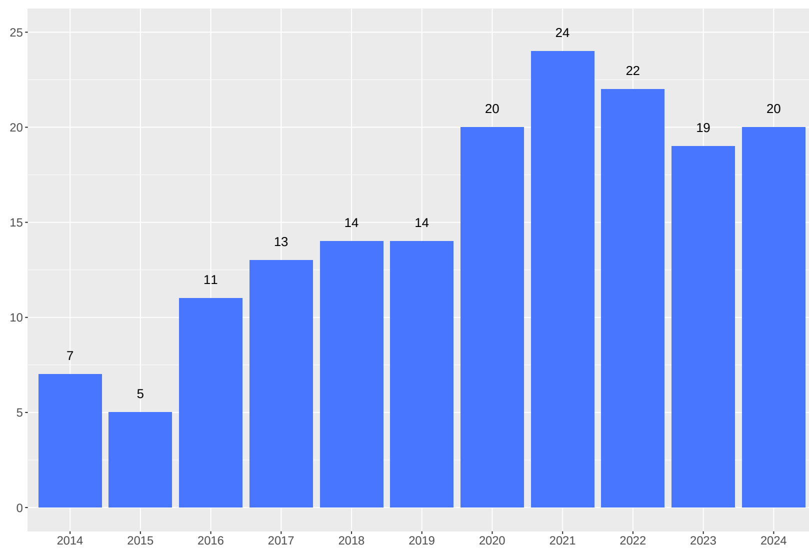

Figure 2: Evolution of the number of articles.

As shown in Figure 3 , which presents the historical evolution of the number of publications and cumulative citations related to collision-free robotic manipulation, it is possible to see a clear picture of the development of this field over time. Since 2014, a steady growth in the number of publications can be observed, reflecting a growing interest on the part of the scientific community, with the year 2021 representing a turning point, reaching an all-time high of 24 publications. This increase can be attributed to the consolidation of emerging technologies, such as 3D sensors and reinforcement learning algorithms, which have made it possible to overcome previous limitations in autonomous navigation and control. Although 2022 and 2023 see a slight decrease in the number of published articles, this trend does not reflect a decline in the impact of the field, as shown by the cumulative number of citations. On the contrary, sustained interest is evident in the citation figures, suggesting that more recent work is exerting a lasting influence on the academic community.

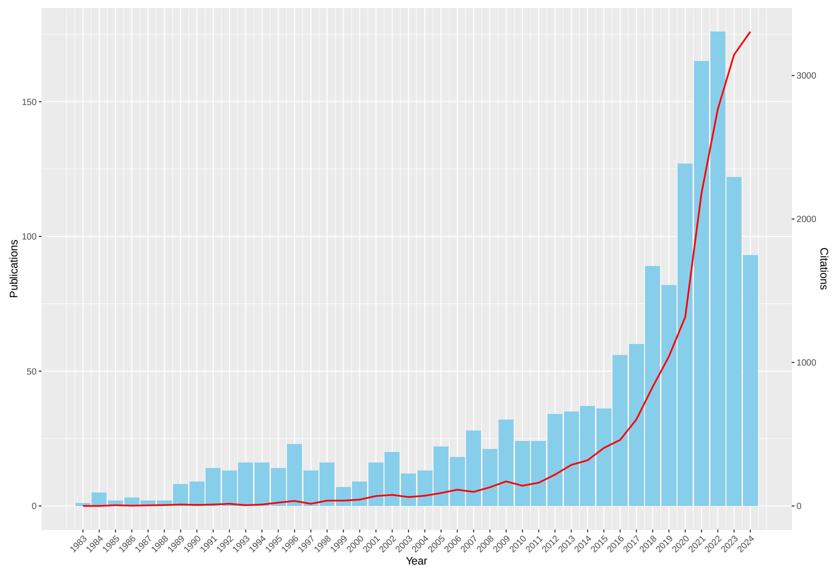

Figure 3: Times cited and publications over time.

The figure also highlights an interesting pattern: while publications have grown incrementally, the increase in cumulative citations is even more pronounced, indicating that articles published in this field tend to be widely referenced. This phenomenon can be attributed to the interdisciplinary nature of the topic, which encompasses key areas such as collaborative robotics, trajectory optimization and safety in shared environments, thus extending its relevance to both theoretical research and industrial and service applications.

The analysis of these results highlights the growing importance of collision-free robotic manipulation, underlining its role not only as an autonomous research domain, but also as a key component in the advancement of emerging technologies in automation and robotics. The trends identified reinforce the idea that this field will continue to be a primary focus of attention in the coming years, with direct ramifications for the improvement of autonomous and collaborative systems in increasingly intricate environments.

The following sections present the main results obtained from the bibliometric analysis.

3.1. Contribution of Leading Research Areas

The data analyzed, summarized in Figure 4 , reflects a balance between the main subject areas associated with the publications, highlighting *Computer Science* with 56 mentions, *Robotics* with 54, *Engineering* with 49, *Automation & Control Systems* with 38 and *Telecommunications* with 11. These results are evidence of the multidisciplinary nature of research in the field, where all these areas contribute significantly to the development of advanced solutions in automation, control and robotics. The interaction between fundamental disciplines such as computer science, engineering and systems control, together with more specific areas such as telecommunications, underlines the integrative approach of the research analyzed.

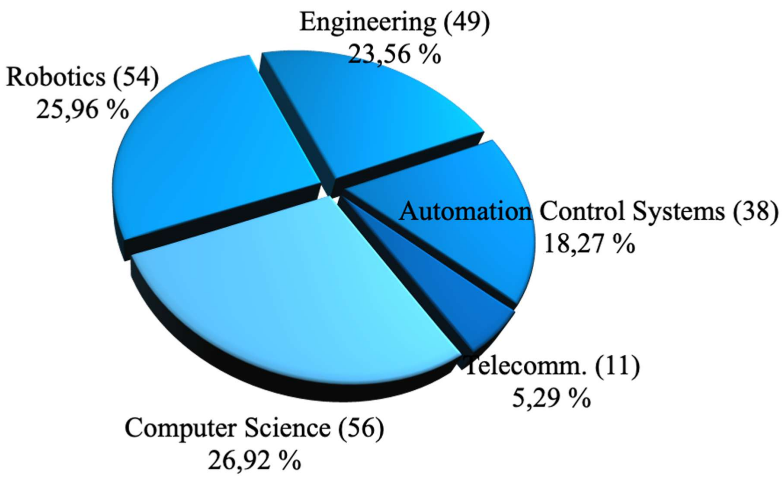

Figure 4: Most productive research areas.

The analysis shows that publications focus not only on pure robotics, but also on the intersection with other areas such as engineering, control systems and computer science. This highlights the interdisciplinary nature of research in these fields, reinforcing the importance of integrating diverse perspectives to advance the development of innovative solutions.

3.2. Contribution of Leading Journals

A review of the main sources of scientific production on robotic manipulation, summarized in Figure 5, reveals a substantial and diverse set of outstanding publications.

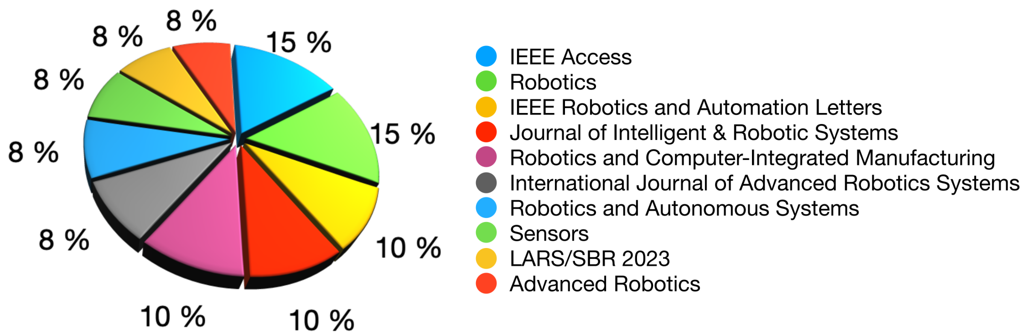

Figure 5: Top 10 most productive journals.

Among the main journals, *IEEE Access* and *Robotics* lead with 11 articles each, consolidating their position as fundamental references in the field. They are followed by *IEEE Robotics and Automation Letters*, *Journal of Intelligent & Robotic Systems*, and *Robotics and Computer-Integrated Manufacturing*, with 7 articles each, positioning themselves as key platforms for research dissemination. Meanwhile, *International Journal of Advanced Robotic Systems*, *Robotics and Autonomous Systems*, *Sensors*, *LARS/SBR 2023*, and *Advanced Robotics* have published 6 articles each, reflecting their important contribution to the advancement of academic knowledge in the field of robotic manipulation.

Of the 20 sources analyzed, several operate on an open access model with mandatory article processing charges (APCs). These include *IEEE Access*, *Robotics* (MDPI), *Sensors* (MDPI), *Applied Sciences* (MDPI), *Complex & Intelligent Systems* (Springer) and *International Journal of Advanced Robotic Systems* (SAGE). In contrast, *IEEE Robotics and Automation Letters* employs a hybrid model, whereby open access is allowed only for articles accompanied by article processing fees. Meanwhile, other sources, such as *Robotics and Computer-Integrated Manufacturing* or *Robotics and Autonomous Systems*, are characterized by a subscription or restricted access model.

Of the total number of sources, seven (35%) operate under an open access model with mandatory article processing charges (APC), one (5%) employs a hybrid model, and the remaining twelve (60%) operate under subscription or restricted access models. The data demonstrate the coexistence of traditional and emerging models of scientific dissemination, reflecting a gradual transition towards open access in the field of robotics. However, it is important to note that access restrictions remain a significant feature of a considerable proportion of publications.

The co-citation analysis of sources allows for the identification of collaboration patterns and thematic areas within the robotic manipulation literature. This approach demonstrates the existence of two main thematic communities, as illustrated in Figure 6 . The nodes represent journals or conferences, and the colors group the sources according to their frequency of co-citation. The first cluster, indicated in red, encompasses journals such as *IEEE Robotics and Automation Letters* and *International Journal of Robotics Research*, which are mainly associated with research in the field of robotic control and autonomy. The second cluster, represented in blue, comprises sources such as *Robotics and Autonomous Systems* and *Applied Sciences*, which are more oriented towards technological and interdisciplinary advances.

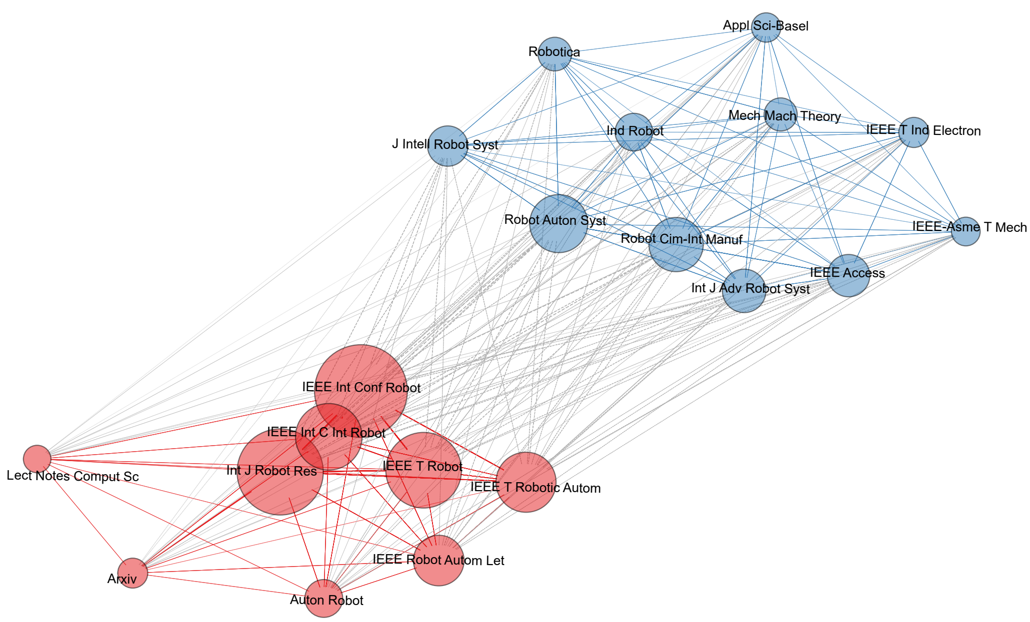

Figure 6: Journals co-citation network.

The size of the nodes in the figure is indicative of the relevance of each source within the network, thus indicating its impact on the academic community and its contribution to the advancement of shared knowledge. This analysis demonstrates that publications are not only grouped according to their thematic content, but also facilitate integration and specialization in different areas of robotics, thus consolidating a diverse and complementary academic ecosystem.

3.3. Contribution of Leading Countries/Regions

The analysis of contributions by country and region, as summarized in Table 2 , provides an overview of the distribution of scientific production in the field of robotic manipulation during the period analyzed. This section makes it possible to identify the extent of their international collaboration, represented by the Multinational Collaborative Publications Ratio (MCP Ratio).

Table 2: Productivity by country.

Countries	**No. of Articles**	**Freq (%)**	**SCP**	**MCP**	**MCP_Ratio**
China	69	41.07	64	5	0.073
Italy	15	8.93	12	3	0.200
USA	10	5.95	9	1	0.100
India	7	4.17	7	0	0.000
Germany	6	3.57	6	0	0.000
Korea	6	3.57	6	0	0.000
Brazil	5	2.98	4	1	0.200
Canada	5	2.98	4	1	0.200
Japan	5	2.98	5	0	0.000
France	4	2.38	3	1	0.250

Where:

- **Freq:** ratio between the number of items and the total number of items associated with the different countries.
- **SCP:** Single-country publications.
- **MCP:** Publications from various countries.
- **MCP_ratio:** MCP divided by articles.

China is the main contributor to the scientific literature on robotic manipulation, with 69 articles accounting for 41.07% of the total. Of these, 64 are single-country publications (SCP) and 5 are multinational collaborations (MCP). This gives a CCM ratio of 0.0725, suggesting a relatively low level of international collaboration. Italy is the second largest contributor with 15 papers (8.93%), distributed across 12 SCPs and 3 CCMs, giving a CCM ratio of 0.2, indicative of a higher level of international collaboration. The United States follows with 10 papers (5.95%), divided into 9 single-authored publications (SCP) and 1 multinational collaboration (MCC). The proportion of CCMs is 0.1. India, with seven papers (4.17%), has no international collaborations.

Similarly, Germany and Korea, with six and three publications, respectively, also show a paucity of international collaboration. At a more moderate level, Brazil, Canada, Japan and France have produced between four and five publications each. Notably, Brazil, Canada and France have MCP ratios of up to 0.25, indicating a higher propensity for international collaboration compared to other countries in the same group.

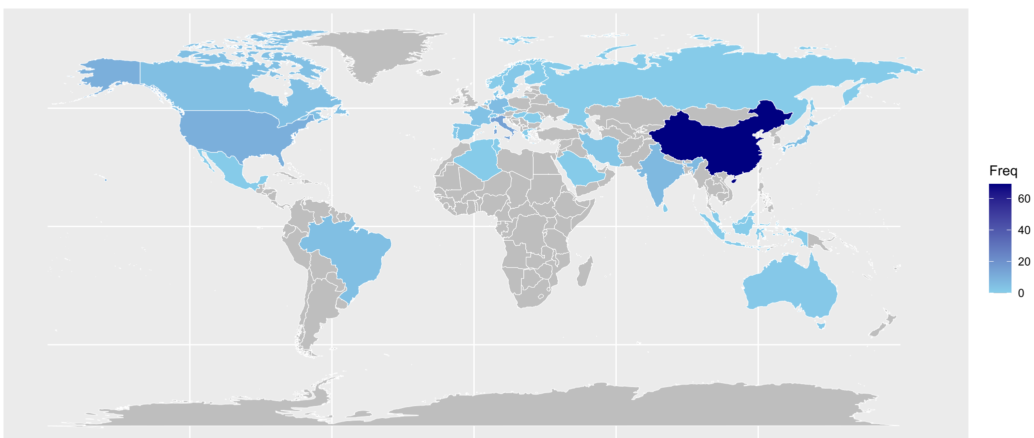

Figure 7: Map of country production

Figure 7 provides a visual representation of the diversity of scientific output and levels of collaboration, presenting a world map with the geographical distribution of contributing countries. The map clearly illustrates the concentration of output in specific regions and the global reach of international collaborations.

China has witnessed a substantial increase in its scientific output in recent years, consolidating its position as the most prolific contributor of publications indexed in the Science Citation Index (SCI) since 2018. According to Liu (2020), between 2010 and 2019, the number of SCI publications in China increased by 252%, from 137,000 in 2010 to 482,000 in 2019. This contrasts sharply with the 31% growth observed in the United States during the same period. This increase can be attributed to strategic policies such as the 'Double First Class Plan' and significant investment in research and innovation, which position China as a major contributor to the global scientific community. This development is indicative of China's dedication to consolidating its position as a leader in advanced research and technological development.

A comprehensive investigation of the diffusion of scientific contributions in the field of collision-free robotic manipulation on a European scale is presented in Figure 8 . In this illustration, Italy, Germany and France stand out as the most prolific countries, reflecting their leadership in research and development of advanced robotic technologies. Italy, with 15 publications, stands out for its capacity for international collaboration, as demonstrated by the high proportion of multinational co-authored publications. In contrast, Germany and France show a more local focus, with a high volume of publications from their institutions, but with a lower proportion of international collaborations. It is clear that other European countries, such as Spain, the Netherlands and Sweden, also contribute actively to the field, albeit with a more modest volume of publications.

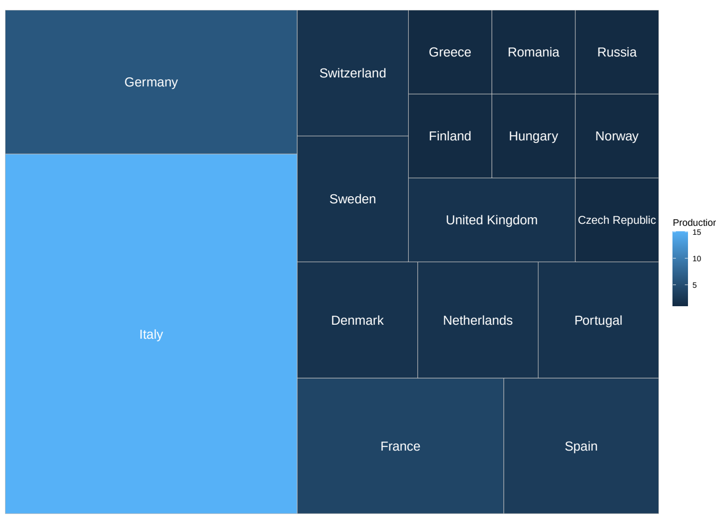

Figure 8: Map of European countries production

The distribution illustrated in the figure highlights Europe's central position in the field of advanced robotics research. Despite variations in the volume and focus of research, the region as a whole demonstrates a strong commitment to the advancement of safe, collaborative and autonomous technologies, essential elements for industrial and service applications in complex environments.

3.4. Contribution of Leading Institutions

The analysis of institutional contributions in the field of robotic manipulation reveals a number of interesting patterns in terms of the number of publications and cumulative citations received. The data not only allows us to assess the amount of scientific output, but also the relative impact of institutions, providing a more complete representation of their influence within the academic community.

In terms of the number of publications, institutions such as *Harbin Institute of Technology* and *Shanghai Jiao Tong University* are at the forefront, with six and four articles respectively. However, their impact in terms of total citations (27) is relatively modest compared to other institutions. In contrast, *Tsinghua University*, despite having a smaller number of publications (3), has a significantly higher average impact per publication, as shown by its 62 total citations. It is also worth noting that the *Indian Institute of Technology* has only two publications, but has accumulated 105 citations, which puts it at the top in total impact. Similarly, *South China University of Technology* has only two publications, but has achieved 68 citations, reflecting a high relative influence.

Table 3: Most productive institutions.

Institutions	**No. of Articles**	**No. of Total Citations**	**Citation Rate per Article**
Harbin Institute of Technology	6	27	4.50
Shanghai Jiao Tong University	4	27	6.75
Tsinghua University	3	62	20.67
East China University of Science and Technology	3	40	13.33
University of Tehran	3	15	5.00
Miguel Hernández University	3	13	4.33
University of Padova	3	12	4.00
Indian Institute Of Technology	2	105	52.50
South China University of Technology	2	68	34.00
National University of Defense Technology	2	42	21.00

This analysis, shown in Table 3 , reveals an interesting trend: while some institutions distinguish themselves by the volume of their publications, others distinguish themselves by the impact and quality of their contributions.

3.5. Contribution of Leading Authors

The analysis of the top authors in the field of robotic manipulation identifies those researchers whose output and citation reflect their significant impact on the discipline. As indicated in Table 4 , *Wang Xuewu* is the most prolific author, having published four papers that have been cited a total of 41 times. This places him among the most influential researchers in the field. Other prominent researchers include *Zhou Xin*, *Anvari Zolfa*, *Ataei Parnyan* and *Masouleh Mehdi Tale*, each of whom has published three articles and received between 15 and 20 citations. This evidence corroborates the remarkable contributions they have made in terms of quality and impact.

In terms of average impact, *Wang Lihui* and *Lu Huimin*, who have each published two articles and received a considerable number of citations (142 and 42, respectively), deserve special attention. This suggests that their research is highly relevant. The data illustrate the diversity of scope and influence of individual contributions within the field, reflecting a combination of research productivity and impact.

Table 4: Authors' documents and citations.

Author	**Documents**	**No. of Citations**	**Citation Rate per Document**
Lihui Wang	2	142	71.00
Huimin Lu	2	42	21.00
Junchong Ma	2	42	21.00
Xuewu Wang	4	41	10.25
Xin Zhou	3	20	6.67
Zolfa Anvari	3	15	5.00
Parnyan Ataei	3	15	5.00
Mehdi Tale Masouleh	3	15	5.00

The analysis based on the fractCount indicator and the number of published articles provides a more detailed view of the role of authors in scientific collaborations. As indicated in Table 5 , authors such as *Anvari Zolfa*, *Ataei Parnyan* and *Masouleh Mehdi Tale* have a fractCount of 1.0 with three articles each, suggesting that they have assumed the role of lead author in all their publications. Similarly, *Wang Lihui* and *Zhang Tie* have a fractCount of 1.0 with two articles, which serves to reinforce their status as lead contributors in a relatively limited corpus of publications.

In contrast, authors such as *Kwon Hyock-Ju* and *Lobbezoo Andrew* have a fractCount of 0.833 with two articles, indicating that they have collaborated on articles where they shared authorial leadership. *Wang Xuewu*, with four articles and a fractCount of 0.726, exemplifies high productivity with a more pronounced collaborative approach. Finally, *Yang Guocai*, with three articles and a fractCount of 0.7, provides further evidence to support the claim that he is a collaborative author in shared projects.

Table 5: Most productive authors by fractional counting.

Author	**FractCount**	**Documents**
Zolfa Anvari	1.0000	3
Parnyan Ataei	1.0000	3
Mehdi Tale Masouleh	1.0000	3
Lihui Wang	1.0000	2
Tie Zhang	1.0000	2
Xiaotian Yang	1.0000	1
Hyock-Ju Kwon	0.8333	2
Andrew Lobbezoo	0.8333	2
Xuewu Wang	0.7261	4
Guocai Yang	0.7000	3

This analysis, based on the fractal count paradigm, makes it possible to identify not only the productivity of authors, but also their degree of prominence in the field of research. Unlike the full-count paradigm, in which each co-author is assigned a weight of 1, the fractional count assigns a weight proportional to the number of co-authors, thus offering a more nuanced view of individual contribution in collaborative publications Perianes-Rodriguez et al. (2016).

Analysis of cumulative citations per author provides insight into the influence of the most prominent researchers in the field of robotic manipulation, as summarized in Table 6 . *Lihui Wang* is the most cited author, with a total of 142 citations, illustrating the relevance and impact of his contributions within the scientific community. *Francis Bourbonnais*, *Pascal Bigras*, and *Ilian A. Bonev* are then cited 98 times each, reinforcing their status as key references in their respective fields of study. *Jose Kelin* and *Dilip Kumar Prathihar* rank with 93 citations each, demonstrating their notable influence in specific areas of research. Similarly, authors *Guichao Lin*, *Lixue Zhu*, *Jinhui Li*, and *Xiangjun Zou* have each received 74 citations, illustrating the considerable impact of their contributions to the advancement of knowledge in their respective fields.

Table 6: Authors with the highest citations.

Author	**Citations**
Lihui Wang	142
Francis Bourbonnais	98
Pascal Bigras	98
Ilian A Bonev	98
Kelin Jose	93
Dilip Kumar Prathar	93
Guichao Lin	74
Lixue Zhu	74
Jinhui Li	74
Xiangjun Zou	74

The results demonstrate a balanced distribution of academic recognition among the leading researchers, underlining the diversity of approaches and the quality of contributions that have driven the field forward. Local citation analysis, which quantifies the frequency with which an author has been cited by other researchers within the same analyzed set, reveals an even distribution of citations among the leading authors in the specific field of robotic manipulation. As indicated in Table 7 , *Richard Bearee*, *Pedro Neto*, *Mohammad Safeea*, *Bernard Schmidt*, and *Lihui Wang* have each been cited four times locally, highlighting their importance within the scientific community represented in the analyzed corpus.

On a more modest level, authors such as *Martin Ruskowski*, *Lionel Amodeo*, *Hicham Chehade*, *Slim Daoud*, and *Nigora Gafur* have accumulated two local citations each, indicating a meaningful contribution to the field, albeit with more limited recognition within the same group. The data show that many leading researchers are recognized by their peers in a comparable way.

Table 7: Most locally cited authors.

Author	Local Citations
Richard Bearee	4
Pedro Neto	4
Mohammad Safeea	4
Bernard Schmidt	4
Lihui Wang	4
Martin Ruskowski	2
Lionel Amodeo	2
Hicham Chehade	2
Slim Daoud	2
Nigora Gafur	2

Figure 9 illustrates the output of the most prominent authors over time, providing a comprehensive representation of their contributions and the influence of their publications. This is demonstrated by the number of articles produced and citations per year.

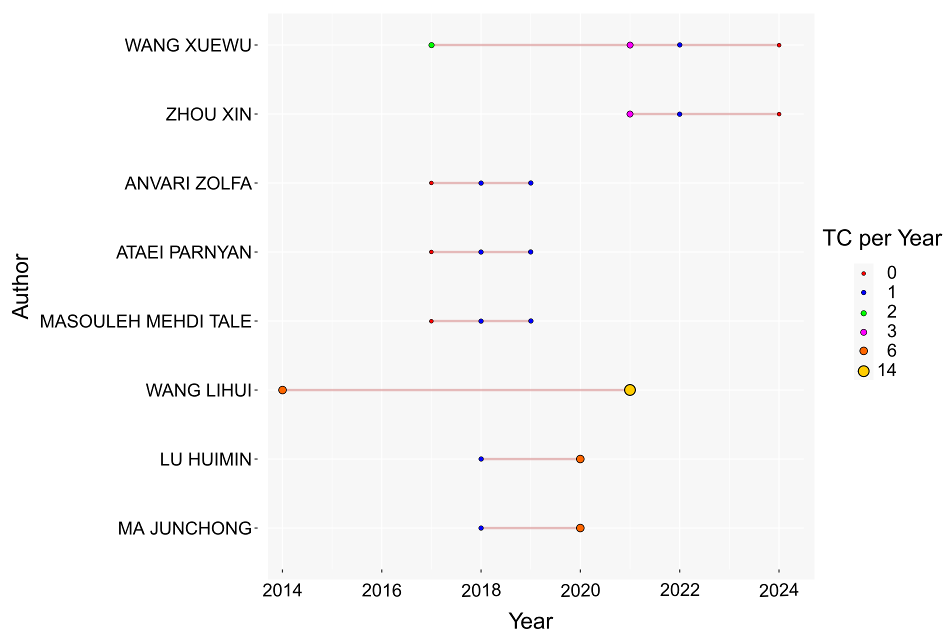

Figure 9: Top Authors' Production over the Time.

3.6. Contribution of Leading Articles

The analysis of the most cited articles provides insight into the most influential contributions in the field of robotic manipulation, as summarized in Table 7 . The article Bourbonnais et al. (2015), published in *IEEE-ASME Transactions on Mechatronics*, is the most cited article in the field of robotic manipulation, with a total of 98 citations and an average of 9.80 citations per year. Jose and Pratihar (2016) in *Robotics and Autonomous Systems* is the second most cited article, with a total of 93 citations and an average of 10.33 citations per year. These figures demonstrate the enduring influence of his work within the scientific community.

The most recent articles demonstrate the continuing impact of Lin et al. (2021), with 74 cumulative citations in *Computers and Electronics in Agriculture*, representing an average of 18.50 citations per year. This serves to illustrate the sustained relevance of the work over a relatively short period of time. Similarly, Liu and Wang (2021) has 69 citations and an average of 17.25 citations per year, cementing its position as one of the most relevant studies in current research. Other notable publications include Schmidt and Wang (2014) in the *Journal of Manufacturing Systems*, which has been cited 73 times and averages 6.64 citations per year, and Safeea et al. (2019) in *Robotics and Autonomous Systems*, which has been cited 58 times with an average of 9.67 citations per year. These articles, along with other notable articles, demonstrate a synthesis of historical and recent contributions that have significantly advanced the field. Table 8 provides a detailed summary of these leading articles.

Table 8: Most cited articles and their yearly citation averages.

Article	**No. of cites**	**No. of cites per Year**
Bourbonnais et al. (2015)	98	9.80
Jose and Pratihar (2016)	93	10.33
Lin et al. (2021)	74	18.50
Schmidt and Wang (2014)	73	6.64
Liu and Wang (2021)	69	17.25
Safeea et al. (2019)	58	9.67
Zhang et al. (2021)	47	11.75
Wu et al. (2016)	42	4.67
Tan et al. (2015)	36	3.60
Ma et al. (2020)	35	7.00

The Local Citation Score (LCS) and Global Citation Score (GCS) analyses provide valuable information on the influence of articles within and outside the collection analyzed. As illustrated in Table 9, the article Schmidt and Wang (2014), published in *Journal of Manufacturing Systems*, exhibits a remarkable LCS of 4 and a considerable GCS of 73, thus demonstrating a substantial impact within the selected literature and on a global scale. Similarly, Safeea et al. (2019) in *Robotics and Autonomous Systems* records an LCS of 4 and a GCS of 58, thus confirming its importance in both metrics. Other studies, such as Daoud et al. (2014) published in the *Journal of Intelligent Manufacturing*, achieved an LCS of 2 and a GCS of 33. In contrast, the most cited article in this field is Jose and Pratihar (2016), which has a GCS of 93. More recent work, such as Gafur et al. (2022), indicates an initial growth in recognition, as evidenced by an LCS of 2 and a GCS of 5.

Table 9: Most cited articles and their yearly citation averages.

Article	**LCS**	**GCS**
Schmidt and Wang (2014)	4	73
Safeea et al. (2019)	4	58
Daoud et al. (2014)	2	33
Ouyang and Zhang (2015)	2	9
Gafur et al. (2022)	2	5
Jose and Pratihar (2016)	1	93
Nagavarapu et al. (2016)	1	12
Deplano (2020)	1	8
Lobbezoo et al. (2021)	1	20
Boschetti et al. (2022)	1	4

This analysis demonstrates the relationship between local and global impact, illustrating how some articles are considered landmarks within the collection analyzed, while others gain greater visibility in the global scientific community.

3.7. Keywords and Terms Insights

An examination of the keywords used in the analyzed papers, as illustrated in Figure 10, clarifies the central themes and most relevant trends in the field of robotic manipulation.

Figure 10: Author keywords word cloud

The most prominent terms, such as *collision*, *avoidance*, *planning*, *robot*, and *control*, reflect a predominant focus on planning and control of safe trajectories for collision avoidance. In addition, keywords such as *optimization*, *trajectory*, and *path* underline the importance of efficiency and precision in the design of robotic systems. In contrast, terms related to *collaboration*, *learning*, and *robotics* in general indicate a growing interest in the integration of sophisticated technologies to address complex challenges within this field.

4. Discussion

4.1. Keywords Co-occurrence and Analysis

The bibliometric technique of keyword co-occurrence analysis allows identifying conceptual relationships between terms and grouping them into thematic clusters representing relevant research areas Lozano et al. (2019). Using R software as a tool, a network was constructed based on the density of connections between keywords, thus facilitating the identification of clustering patterns and recurrent themes within the field of robotics, shown in

Figure 11 . A minimum threshold of five occurrences for each keyword was used in the analysis, resulting in a total of 20 main keywords distributed in four clearly delimited thematic clusters. The nodes in the network represent keywords, the size of the node indicates the frequency of occurrence and the proximity between nodes reflects the strength of the associations between them.

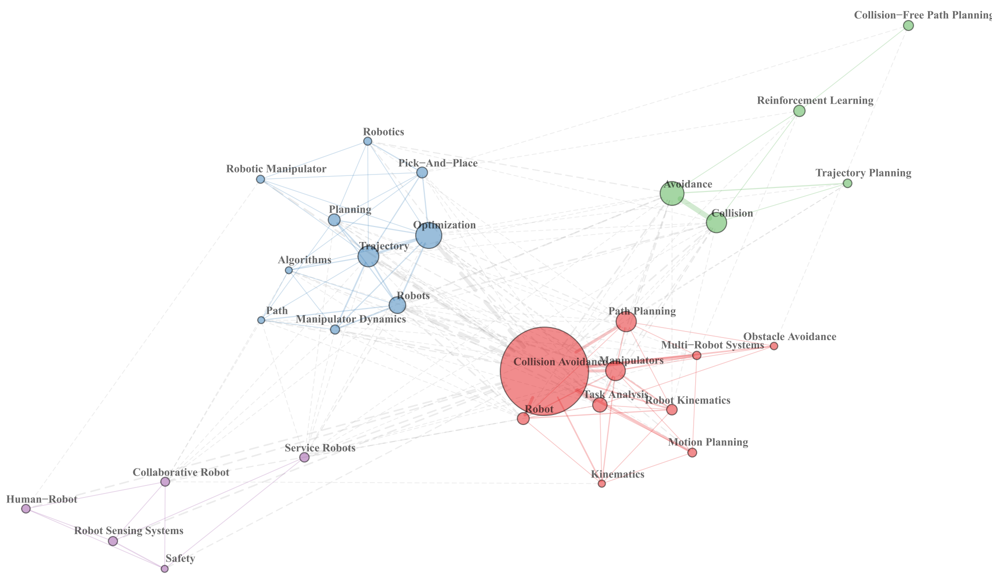

Figure 11: Network of Keywords co-occurrences

The keyword network clarifies the interrelationship between concepts such as *optimization*, *trajectory planning*, *autonomous learning* and *collaborative robotics*, thus providing an overview of the most prominent research areas. The groupings cover a wide range of topics, including collision avoidance, manipulator optimization, reinforcement learning and safety in collaborative robotics. This approach not only identifies the main topics, but also clarifies how they are interconnected, thus providing insight into the technological and practical challenges inherent in robotics.

The main keywords associated with each cluster were subjected to an in-depth examination (Figure 12), and the clusters were designated according to their predominant characteristics and the recurring themes that emerged. This analysis provides an overall framework for elucidating the predominant trends and developments in the field of robotics research.

Cluster 1 Collision avoidance in robotic systems	Cluster 2 Optimisation and trajectory planning for manipulators	Cluster 3 Reinforcement learning and autonomous planning	Cluster 4 Collaborative robotics and safety
Collision Avoidance	Optimization	Reinforcement Learning	Collaborative Robot
Robot	Planning	Collision-free Path Planning	Human-Robot
Path Planning	Algorithms	Trajectory Planning	Safety
Obstacle Avoidance	Robotic Manipulator	Avoidance	Robot Sensing Systems
Multi-Robot Systems	Trajectory	Collision	Service Robots

Figure 12: Clusters distributions and keywords.

Based on the analysis, the following articles have been defined as the most relevant within each research group, reflecting the key contributions in their respective thematic areas. Cluster 1, focused on collision avoidance in robotic systems, includes fundamental references such as Schmidt and Wang (2014), Liu and Wang (2021), Zhang et al. (2021), Tan et al. (2015), and Daoud et al. (2014). Cluster 2, centered on optimization and trajectory planning for manipulators, highlights works by Bourbonnais et al. (2015), Seddaoui and Saaj (2021), Hamer et al. (2018), Liu et al. (2018), and Wen and Pagilla (2023), which explore efficient motion planning strategies. Cluster 3, covering reinforcement learning and autonomous planning, features notable contributions such as Jose and Pratihar (2016), Lin et al. (2021), Moccia et al. (2020), Shi et al. (2019), and Hentout et al. (2023), emphasizing intelligent decision-making in robotic applications. Finally, Cluster 4, related to collaborative robotics and safety, includes relevant studies by Safeea et al. (2019), Wang et al. (2018), Wang et al. (2020), Scimmi et al. (2019), Borrell et al. (2020), and Maurtua et al. (2017), which address the challenges of human-robot interaction and safety measures in shared workspaces.

To investigate the temporal evolution of the identified clusters further, a burst detection analysis was performed. This technique identifies periods during which keywords experienced a significant increase in frequency, indicating a peak in interest in specific topics. In addition to the time span, the analysis quantifies the strength of the burst, reflecting the intensity of the keyword's importance during its active period. Figure 13 shows the results of this analysis, presenting both the time spans and the intensity of the bursts for each keyword.

Para investigar más a fondo la evolución temporal de los clústeres identificados, se realizó un análisis de detección de ráfagas (bursts). Esta técnica identifica los periodos durante los cuales las keywords experimentaron un aumento significativo de su frecuencia, lo que indica un pico de interés en temas específicos. Además del lapso de tiempo, el análisis cuantifica la fuerza de la ráfaga (burst), que refleja la intensidad de la importancia de la palabra clave durante su periodo activo. La Figura 13 muestra los resultados de este análisis, presentando tanto los intervalos de tiempo como la intensidad de las ráfagas para cada palabra clave.

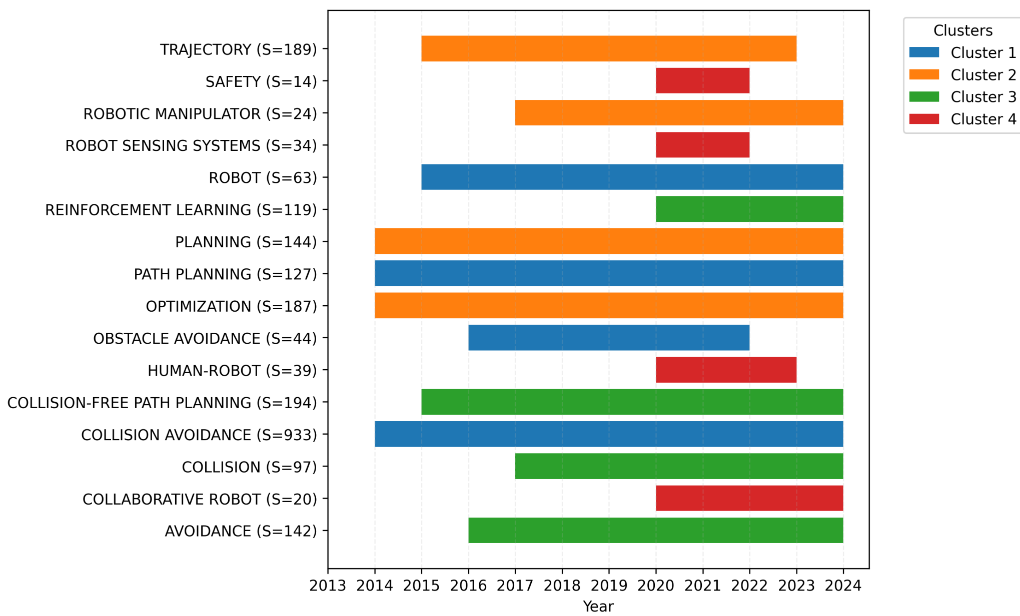

Figure 13: Temporal evolution of keywords based on burst detection analysis. The S value indicates the strength of the burst, and the colour of each bar indicates the *cluster* to which the keyword belongs.

4.2. Cluster 1: Collision avoidance in robotic systems

This grouping addresses one of the most critical issues in the field of robotics: the ability of robotic systems to avoid collisions in dynamic environments. The associated keywords, such as *Collision Avoidance*, *Robot*, *Path Planning*, *Obstacle Avoidance*, *Multi-robot Systems*, reflect a focus on the development of strategies and technologies that ensure operational safety and efficiency in various robotic applications.

Este grupo agrupa la investigación centrada en métodos y planificadores locales para evitar colisiones en entornos dinámicos. Entre las tecnologías más comunes figuran el uso de campos potenciales artificiales, las estrategias de control basadas en sensores (como LiDAR, visión o proximidad) y las arquitecturas de control predictivo. En particular, destacan los sistemas de control basados en la lógica difusa o los algoritmos de prevención de obstáculos en tiempo real, que permiten adaptar el movimiento del robot en función del entorno percibido. Algunos estudios combinan técnicas clásicas con elementos de aprendizaje supervisado para mejorar la precisión de la detección de colisiones en contextos colaborativos. La principal ventaja de estas tecnologías es su rápida respuesta ante obstáculos inesperados, lo que las hace especialmente útiles en entornos dinámicos. Sin embargo, suelen tener limitaciones en cuanto a la planificación global y corren el riesgo de comportamientos subóptimos.

This group has been identified as comprising two main sub-topics, which are of particular importance within the field of robotics. The first sub-theme is *collision-free path planning.* This field of study is concerned with the development of algorithms that allow robots to calculate and adjust their trajectories in real time, with the aim of avoiding fixed or moving obstacles. For example, in Zhang et al. (2021) an advanced algorithm is proposed to solve inverse kinematics and collision avoidance problems in manipulators operating in dynamic environments, demonstrating significant improvements in the safety and adaptability of robotic systems in complex conditions. This is a crucial aspect to consider in industrial and autonomous environments, where robots interact with machinery or humans. The second sub-theme, *coordination in multi-robot systems*, addresses the interaction between several robots operating in a shared workspace. In Sukhovey and Gubankov (2020), a method is proposed to avoid collisions between industrial robot end-effector in overlapping work areas, without the need for prior obstacle information or additional sensors. The aim is to minimize the potential for conflict and improve collaboration in the context of complex tasks, such as assembly or logistics.

Cluster 1 is closely related to cluster 3 (*Reinforcement learning and autonomous planning*), as a considerable number of the models used for collision avoidance can be improved with autonomous learning algorithms. As an example, reinforcement learning allows robots to optimize their trajectories and decision-making processes in evolving environments. An illustrative example is Hong et al. (2024), where a methodology for integrating reinforcement learning into motion planning is presented. This approach enables redundant robots to avoid collisions and improve their performance in dynamic environments.

This cluster has a significant impact on both theoretical and practical aspects of robotics. From a theoretical point of view, it fosters the development of models that integrate dynamic planning, perception and control. In practice, the contributions of this cluster have major consequences for fields such as industrial production lines. Borrell et al. (2024) demonstrates how safe and efficient path planning can significantly improve productivity and safety in automated industrial environments, and highlights the importance of Cluster 1 in the implementation of practical solutions.

4.3. Cluster 2: Optimization and trajectory planning for manipulators

This group focuses on optimization and trajectory planning for robotic manipulators, fundamental areas in the design of efficient and accurate systems. The associated keywords, such as *optimization*, *planning*, *algorithms*, *robotic manipulators* or *trajectory*, highlight the interest in developing advanced techniques to maximize the accuracy, efficiency and performance of these systems. This is particularly relevant in applications such as industrial automation, where optimization of movements can reduce costs and operating times, and service robotics, where a high degree of adaptability and precision is required in complex tasks.

Los trabajos en este clúster destacan por su capacidad para generar trayectorias óptimas basadas en distintos criterios (como la seguridad, la eficiencia o la fluidez), y su flexibilidad para adaptarse a distintos tipos de manipuladores y entornos. Los métodos deterministas permiten obtener soluciones rápidas y repetibles, mientras que los algoritmos metaheurísticos destacan por su capacidad para explorar espacios complejos y no convexos. Sin embargo, los métodos clásicos pueden carecer de solidez en entornos dinámicos, mientras que los metaheurísticos requieren un mayor coste computacional y parámetros de ajuste no triviales. Por ello, cada vez son más los trabajos que combinan la planificación offline con la ejecución adaptativa en tiempo real o que integran algoritmos de optimización con aprendizaje profundo, buscando un equilibrio entre precisión, adaptabilidad y eficiencia.

The group can be divided into two primary sub-themes. The initial theme, *algorithmic optimization*, is concerned with the advancement of sophisticated algorithms that improve the efficiency of path planning, thereby reducing the time and resources required to complete specific tasks, such as assembly Batista et al. (2023) or pick-and-place Borrell et al. (2020), where accuracy is paramount. The second sub-theme, related to *manipulator dynamics and control*, is concerned with ensuring that planned trajectories are physically achievable. This takes into account aspects such as velocity, acceleration and mechanical limitations of the robotic manipulators. For example, Wen and Pagilla (2023) presents an innovative algorithm that allows manipulators to plan optimal trajectories in environments with specific constraints. The proposed approach ensures that trajectories satisfy both kinematic and dynamic constraints as well as the need for collision avoidance. Both sub-themes are fundamental to optimize the performance and adaptability of robotic systems in advanced industrial applications.

Dohmann et al. (2021) presents a distributed learning framework that allows multiple robots to dynamically estimate the properties of a manipulated object in a cooperative manner. This approach improves the adaptability and accuracy of real-time path planning, especially in changing environments. It is therefore appropriate to refer to this work when discussing the relationship between Cluster 2 and Cluster 3, as it demonstrates how learning techniques can optimize manipulator trajectories in dynamic environments.

This cluster has a significant impact on automation and Industry 4.0, facilitating the advancement of robotic manipulators that are both faster and more accurate. This, in turn, has the potential to generate cost savings and productivity improvements. From a theoretical point of view, it facilitates the advancement of optimization algorithms and dynamic models, thus establishing a solid foundation for the design of increasingly sophisticated and adaptable robotic system.

4.4. Cluster 3: Reinforcement learning and autonomous planning

This group explores the integration of reinforcement learning techniques with advanced autonomous planning methods to enable robots to adapt and improve their performance in dynamic and unstructured environments. Associated keywords such as *reinforcement learning*, *collision-free path planning*, *path planning*, *avoidance* and *collision* reflect the emphasis on the ability of autonomous systems to make optimal decisions in real time, thus improving their autonomy and efficiency.

Desde una perspectiva tecnológica, este clúster se centra en la aplicación de algoritmos de aprendizaje profundo por refuerzo (DRL) como DDPG, PPO y SAC, a menudo integrados con redes neuronales convolucionales o recurrentes para manejar datos sensoriales de alta dimensión y dependencias temporales. Estos enfoques ofrecen grandes ventajas, como la capacidad de adaptarse a entornos impredecibles, aprender políticas óptimas mediante la interacción y operar sin un modelo predefinido. Sin embargo, los métodos

DRL también plantean importantes retos. A menudo requieren grandes cantidades de datos de entrenamiento y recursos informáticos, y pueden adolecer de escasa generalizabilidad cuando se exponen a escenarios no encontrados durante el entrenamiento. En respuesta a estas limitaciones, han surgido enfoques híbridos que combinan el aprendizaje por refuerzo con la planificación clásica o el aprendizaje por imitación, proporcionando un marco más robusto y eficiente desde el punto de vista de las muestras. Esta convergencia tecnológica sitúa al Cluster 3 en la intersección del aprendizaje automático y el control del movimiento, permitiendo la creación de sistemas robóticos cada vez más autónomos, inteligentes y conscientes del contexto.

This cluster identifies two main sub-themes. The first is *reinforcement learning*, which encompasses the development of algorithms that facilitate robots learning from their environment through the use of rewards and penalties, thereby improving their ability to make optimal decisions in complex situations. Lobbezoo et al. (2021) provides a comprehensive review of the use of reinforcement learning for pick-and-place tasks in robotics. It discusses optimization methods, reward configurations and imitation learning, and highlights how these techniques improve the ability of robots to adapt and learn in complex environments. On the other hand, studies such as Xu et al. (2024) propose an algorithm that combines the artificial potential field with deep reinforcement learning to avoid collisions in robotic arms. This approach addresses the problem of local minima in trajectory planning and ensures safe and efficient execution of motions in dynamic environments. Una contribución destacada dentro de los enfoques híbridos es Khan et al. (2020), donde se propone un esquema de control que combina un algoritmo metaheurístico con redes neuronales recurrentes (RNN) para lograr la evitación de obstáculos y el control de seguimiento en manipuladores redundantes. Esta metodología permite al sistema aprender dinámicamente el comportamiento del entorno y generar trayectorias óptimas en tiempo real, integrando capacidades de predicción temporal con estrategias de optimización evolutiva. La arquitectura propuesta demuestra mejoras significativas en precisión y capacidad de adaptación frente a métodos clásicos, lo que refuerza la relevancia de incorporar modelos de aprendizaje profundo en la planificación autónoma y control avanzado de manipuladores robóticos. The second sub-theme, *autonomous collision-free planning*, integrates path planning algorithms with obstacle avoidance capabilities, thus ensuring safe and efficient robot motions even in dynamic scenarios. Works such as Zbiss et al. (2022), which presents an innovative approach for the automatic generation of collision-free trajectories in car painting processes. This algorithm integrates coverage planning and collision avoidance, thus ensuring safe and productive operations in dynamic contexts.

Cluster 3 is directly related to Cluster 1, as reinforcement learning allows the application of collision avoidance strategies in complex environments. Furthermore, these techniques are associated with Cluster 2, as they facilitate optimized path planning by adapting to dynamic constraints and improving performance. This clustering is distinguished by its ability to facilitate adaptation to unknown environments, which is particularly advantageous in contexts where such adaptation is necessary. It also stimulates innovation in learning and simulation algorithms, thus improving robotic performance and advancing autonomous systems and artificial intelligence.

4.5. Cluster 4: Collaborative robotics and safety

This cluster is concerned with the study of human-robot interaction and the implementation of safety measures in collaborative environments. The use of keywords such as *collaborative robot*, *human-robot interaction*, *safety*, *robotic sensing systems* and *service robots* indicates an overriding interest in ensuring the safe and efficient operation of robots in close proximity to humans. This topic is of vital importance in contexts where robots must be incorporated into shared environments without compromising safety and efficiency.

Este grupo se caracteriza por la integración de sistemas de percepción (por ejemplo, visión, sensores de pares de fuerzas, etc.) con estrategias de control que permiten una interacción física segura y adaptable entre robots y humanos. Estos sistemas ofrecen la ventaja de permitir una colaboración intuitiva, esencial en los espacios de trabajo compartidos. Los algoritmos de planificación colaborativa, los modelos de reconocimiento de intenciones y las arquitecturas de control conscientes de la seguridad contribuyen a mejorar la coexistencia entre humanos y robots. Sin embargo, sigue habiendo retos en cuanto a fiabilidad, tiempo de respuesta y adaptación específica al usuario. Asegurar la robustez en entornos impredecibles y garantizar la seguridad del usuario sin sobrecargar el rendimiento del robot es un delicado equilibrio. Además, la normalización de las métricas de seguridad y los protocolos de validación sigue siendo limitada, lo que dificulta la generalización entre distintas aplicaciones.

Two main sub-themes emerge from this group. The first, *Human-robot interaction*, involves the design and development of technologies that enable robots to interpret and interact with humans safely and efficiently, thus optimizing cooperation in shared environments. Secil and Ozkan (2023) presents an innovative method for collision-free path planning for industrial robots, taking into account safe coexistence between humans and robots. The goal is to ensure that a safe distance is maintained between the robot and the human, thus allowing the robot tip to reach the target location through a smooth trajectory. This iterative method generates a random set of candidate waypoints for the robot tip at each iteration, and the point to follow is determined by solving an optimization problem. The objective function is formulated taking into account the distance between the human and the robot, as well as criteria for the robot tip to reach the target point with a smooth path. The second subtopic, *Robotic Sensing and Safety Systems*, will address the application of advanced sensing and control strategies to prevent accidents and ensure safety in industrial, medical and service applications, as in Wang et al. (2020). This paper presents a hybrid approach to collision avoidance and visual tracking tasks in the context of soft robotic manipulators. This method combines visual servo control strategies with contact detection and localization algorithms, allowing robots to adapt to dynamic environments and operate safely near humans or in shared spaces. Cluster 4 is closely related to Cluster 1, as collision detection and avoidance strategies are of vital importance in collaborative environments. It is also linked to Cluster 3, as it benefits from adaptive algorithms that optimize human-robot interaction through autonomous learning.

Además, recientes estudios bibliométricos centrados en sistemas de sensado aplicados a la salud han aportado perspectivas relevantes para el ámbito de la robótica colaborativa. Por ejemplo, en Azizan et al. (2024) presentan un análisis sobre sensores portátiles en el ámbito sanitario, en el que se destaca su papel en la toma de decisiones centrada en el usuario y en la automatización segura, aspectos que también son extrapolables a entornos industriales donde la interacción entre humanos y robots requiere niveles elevados de sensibilidad contextual y adaptabilidad. De forma complementaria, Azizan (2024a) analiza los retos y oportunidades de los sistemas basados en sensores para la prevención de caídas en personas mayores y subraya la importancia de un enfoque centrado en la seguridad del usuario. Ambos trabajos refuerzan la relevancia de incorporar métricas centradas en el usuario y estrategias basadas en sensores para garantizar la seguridad en la operación de los robots colaborativos en espacios compartidos.

The impact of these technologies is evident in industrial contexts, where collaborative robots (cobots) are transforming manufacturing processes by working alongside operators. A notable example is the work of Maurtua et al. (2017), which examines the potential of collaborative robots to improve productivity and quality in manufacturing by implementing strategies that prioritize safety, effective interaction and ergonomics in shared environments. The study concludes that effective integration of humans and robots not only serves to mitigate risks, but also optimizes efficiency and fosters a more collaborative and adaptive work environment. Moreover, these technologies are of considerable importance in the service sector, where assistive robots ensure the safe operation of machines and equipment in human environments.

4.6. Relaciones entre los clústeres temáticos

Los cuatro clústeres temáticos identificados en este estudio no representan líneas de investigación aisladas, sino un conjunto de enfoques interrelacionados que convergen hacia el desarrollo de sistemas robóticos cada vez más autónomos, eficientes y seguros. El Clúster 1 (Prevención de colisiones) y el Clúster 3 (Aprendizaje por refuerzo y planificación autónoma) están estrechamente vinculados, ya que los enfoques basados en aprendizaje mejoran notablemente la capacidad de los robots para evitar obstáculos en entornos dinámicos. El Clúster 2 (Optimización de trayectorias para manipuladores) complementa esta relación mediante algoritmos que, en muchos casos, se integran con modelos de aprendizaje del Clúster 3 para incrementar la adaptabilidad y el rendimiento de la planificación de movimientos. Por su parte, el Clúster 4 (Robótica colaborativa y seguridad) guarda una conexión directa con el Clúster 1, dado que la seguridad en entornos compartidos requiere estrategias fiables de detección y prevención de colisiones. Además, el Clúster 4 se beneficia de los avances en control adaptativo y reconocimiento de intenciones desarrollados en el Clúster 3, especialmente en contextos de interacción humano-robot. Estas interrelaciones reflejan una tendencia creciente hacia enfoques híbridos y multidisciplinares que combinan percepción, aprendizaje, planificación e interacción física para abordar tareas robóticas cada vez más complejas en escenarios reales.

5. Conclusions

This bibliometric analysis has identified four key clusters that structure the field of collision-free robotic manipulation: collision avoidance, trajectory optimization, reinforcement learning, and collaborative robotics. These areas are fundamental for advancing safety, operational efficiency, and adaptability in dynamic and unstructured environments.

This strategy facilitates the identification of articles that have exerted significant historical influence on the field, as well as those that represent recent and emerging trends. Articles with the highest citation rates provide a substantial foundation for contemporary theories and applications, thus establishing themselves as fundamental references in the field of collaborative bimanual robotics, as seen in Table 8 and Table 9. In contrast, the articles with the highest number of citations per year reflect cutting-edge research that is attracting the attention of the scientific and professional community, standing out for their relevance to current problems and for proposing innovative approaches. The dual approach ensures comprehensive coverage, combining historical foundations with the most current lines of development, providing researchers and practitioners with a complete overview of advances in the field.

The work of Liu and Wang (2021), Zhang et al. (2021) and Daoud et al. (2014) belongs to the collision avoidance cluster and proposes innovative methods to ensure safety and adaptability in dynamic environments shared between humans and robots. Their approaches combine the use of sensors, advanced algorithms and optimization techniques to adjust trajectories in real time, enabling safer and more efficient interaction in collaborative spaces. Regarding trajectory optimization, Bourbonnais et al. (2015) has made important contributions by applying metaheuristic algorithms and optimization techniques to improve efficiency and accuracy in industrial tasks. In the field of reinforcement learning, Lin et al. (2021) addresses the challenges of agricultural automation in unstructured environments by using recurrent reinforcement learning, allowing robots to better adapt to changing conditions. On the other hand, Hentout et al. (2023) and Jose and Pratihar (2016) highlight hybrid approaches that combine fuzzy logic and heuristic methods to optimize path planning and task allocation in multi-robot systems, ensuring safe and efficient interactions. Finally, in the field of collaborative robotics, Safeea et al. (2019) integrates path planning with real-time adjustments to improve safety in human-robot interaction.

Furthermore, the analysis revealed China's significant contribution to scientific output. With a total of 69 articles published during the period under study, China accounted for 52.27% of the total number of publications, clearly leading in terms of volume. It was followed by Italy with 11.36% (15 articles) and the United States with 7.58% (10 articles). Other countries, such as India (5.30%) and Germany (4.55%), make notable contributions. This trend reflects not only China's strategic commitment to technological development, but also a growing investment in research and innovation. In addition, the predominance of single-country publications (SCP, 64 articles in the case of China) versus international collaborative publications (MCP, 5 articles) highlights the capacity of Chinese institutions to generate knowledge independently.

While this bibliometric study provides a comprehensive analysis of trends in collision-free robotic manipulation, several research gaps remain. Advances in collision avoidance through adaptation and reinforcement learning are increasingly relevant, requiring more data-efficient and adaptive algorithms for dynamic environments with minimal human intervention. Ensuring safe human-robot collaboration is also crucial, especially in the industrial and service sectors, and hybrid approaches integrating physical-based models and AI show potential for real-time collision avoidance. However, the integration of trajectory optimization techniques into real-time control remains challenging, and faster and more efficient methods are needed.

Además de resumir los resultados del análisis bibliométrico y temático, este artículo identifica varias áreas prometedoras para la investigación futura en el campo del control de robots sin colisiones. Entre ellas se incluye la aplicación de modelos de aprendizaje por refuerzo, que permiten a los robots aprender políticas de acción óptimas en entornos dinámicos basándose en la retroalimentación del entorno. La colaboración multiagente también se perfila como un área clave para abordar tareas complejas de forma distribuida, especialmente en sistemas industriales coordinados. Por último, la optimización en tiempo real mediante algoritmos adaptativos y aprendizaje profundo es una dirección esencial para obtener respuestas eficientes y seguras en escenarios que cambian rápidamente. Estas líneas representan una convergencia entre inteligencia artificial, control avanzado y robótica colaborativa que será crucial en los próximos años.

Aunque este artículo proporciona una revisión exhaustiva de los enfoques existentes en la manipulación robótica libre de colisiones, es importante señalar que la discusión sobre las lagunas de la investigación actual es algo limitada. Para investigaciones futuras, se sugiere profundizar en áreas como la exploración de metodologías híbridas que combinen enfoques basados en aprendizaje con técnicas de control tradicionales, el estudio del impacto de la incertidumbre del entorno en la planificación de trayectorias y la evaluación de la adaptabilidad de los sistemas robóticos en escenarios dinámicos y no estructurados. Además, se destaca la necesidad de investigar la aplicación de estos sistemas en contextos más allá de la fabricación, como la agricultura o la medicina, donde la interacción entre humanos y robots y la seguridad son aspectos fundamentales.

In addition, improving international collaboration and promoting open access to research is essential, given the concentration of scientific output in China and limited cross-border cooperation.The expansion of applications beyond industrial robotics to healthcare, assistive technologies and space exploration present new challenges requiring further research, and collision-free manipulation offers new opportunities for innovation and development.

Addressing these challenges will contribute to the development of more adaptable, safer and more efficient robotic systems, reinforcing the role of robotics in technological and societal transformation.

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Data Availability Statement

The bibliographic database used for this analysis is accessible through the following GitHub Repository. Within this repository are available the searches carried out and a platform that facilitates the formulation of personalized queries and the extraction of the data necessary for the personal analysis, in accordance with the established conditions of use.

Declaration of 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.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

Aria, M., Cuccurullo, C., 2017. bibliometrix: An r-tool for comprehensive science mapping analysis. Journal of Informetrics 11, 959–975. doi:10.1016/j.joi.2017.08.007.

Azizan, A., 2024a. Challenges and opportunities in sensor-based fall prevention for older adults: a bibliometric review. Journal of Enabling Technologies 18, 306–318. doi:10.1108/JET-02-2024-0011.

Azizan, A., 2024b. Mapping the muscle mass: A birds-eye view of sarcopenia research through bibliometric network analysis. International Journal of Disabilities Sports and Health Sciences 7, 134–143. doi:10.33438/ijdshs.1362539.

Azizan, A., Ahmed, W., Razak, A.H.A., 2024. Sensing health: a bibliometric analysis of wearable sensors in healthcare. Health and Technology 14, 15–34. doi:10.1007/s12553-023-00801-y.

Azizan, A., Fadzil, N.H.M., 2024. What stops us and what motivates us? a scoping review and bibliometric analysis of barriers and facilitators to physical activity. Ageing Research Reviews 99, 102384. doi:https://doi.org/10.1016/j.arr.2024.102384.

Batista, J.G., Ramalho, G.L.B., Torres, M.A., Oliveira, A.L., Ferreira, D.S., 2023. Collision avoidance for a selective compliance assembly robot arm manipulator using topological path planning. Applied Sciences 13, 11642. doi:10.3390/app132111642.

Becker, R.A., Wilks, A.R., Brownrigg, R., Minka, T.P., Deckmyn, A., 2021. maps: Draw geographical maps. URL: https://CRAN.R-project.org/package=maps. r package version 3.4.0.

Bence Tipary, A.K., Erdős, F.G., 2021. Planning and optimization of robotic pick-and-place operations in highly constrained industrial environments. Assembly Automation 41, 626–639. doi:10.1108/AA-07-2020-0099.

Birkle, C., Pendlebury, D.A., Schnell, J., Adams, J., 2020. Web of science as a data source for research on scientific and scholarly activity. Quantitative Science Studies 1, 363–376. doi:10.1162/qss_a_00018.

Borrell, J., Perez-Vidal, C., Segura, J.V., 2024. Optimization of the pick-and-place sequence of a bimanual collaborative robot in an industrial production line. International Journal of Advanced Manufacturing Technology 130, 4221–4234. doi:10.1007/s00170-023-12922-9.

Borrell, J., Perez-Vidal, C., Segura Heras, J.V., Pérez-Hernández, J.J., 2020. Robotic pick-and-place time optimization: Application to footwear production. IEEE Access 8, 209428–209440. doi:10.1109/ACCESS.2020.3037145.

Boschetti, G., Gasparri, A., L'Afflitto, G., 2022. A distributed model predictive control scheme for cooperative active sensing in multi-robot systems. IFAC-PapersOnLine 55, 121–126. doi:10.1016/j.ifacol.2022.04.210.

Bourbonnais, F., Bigras, P., Bonev, I.A., 2015. Minimum-time trajectory planning and control of a pick-and-place five-bar parallel robot. IEEE/ASME Transactions on Mechatronics 20, 740–749. doi:10.1109/TMECH.2014.2318999.

Broadus, R.N., 1987. Toward a definition of "bibliometrics". Scientometrics 12, 373–379. doi:10.1007/BF02016680.

Csardi, G., Nepusz, T., 2006. The igraph software package for complex network research. InterJournal, Complex Systems 1695. URL: https://igraph.org.

Daoud, S., Chehade, H., Yalaoui, F., Amodeo, L., 2014. Efficient metaheuristics for pick and place robotic systems optimization. Journal of Intelligent Manufacturing 25, 27–41. doi:10.1007/s10845-012-0668-z.

Dennis Mronga, Tobias Knobloch, J.d.G.F., Kirchner, F., 2020. A constraint-based approach for human–robot collision avoidance. Advanced Robotics 34, 265–281. doi:10.1080/01691864.2020.1721322.

Deplano, D., 2020. Digital twin: Values, challenges and enablers from a modeling perspective. IEEE Access 8, 21980–22012. doi:10.1109/ACCESS.2020.2994472.

Dohmann, P.B.G., Lederer, A., Dißemond, M., Hirche, S., 2021. Distributed bayesian online learning for cooperative manipulation, in: 2021 60th IEEE Conference on Decision and Control (CDC), pp. 2888–2895. doi:10.1109/CDC45484.2021.9683772.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., Lim, W.M., 2021. How to conduct a bibliometric analysis: An overview and guidelines. Journal of Business Research 133, 285–296. doi:10.1016/j.jbusres.2021.04.070.

Gafur, N., Kanagalingam, G., Wagner, A., Ruskowski, M., 2022. Dynamic collision and deadlock avoidance for multiple robotic manipulators. IEEE Access 10, 55766–55781. doi:10.1109/ACCESS.2022.3176626.

Hamer, M., Widmer, L., Drandrea, R., 2018. Fast generation of collision-free trajectories for robot swarms using gpu acceleration. IEEE Access PP, 1–1. doi:10.1109/ACCESS.2018.2889533.

Hentout, A., Maoudj, A., Aouache, M., 2023. A review of the literature on fuzzy-logic approaches for collision-free path planning of manipulator robots. Artificial Intelligence Review 56, 3369–3444. doi:10.1007/s10462-022-10257-7.

Hong, T., Li, W., Huang, K., 2024. A reinforcement learning enhanced pseudo-inverse approach to self-collision avoidance of redundant robots. Frontiers in Neurorobotics 18, 1375309. doi:10.3389/fnbot.2024.1375309.

Jose, K., Pratihar, D.K., 2016. Task allocation and collision-free path planning of centralized multi-robots system for industrial plant inspection using heuristic methods. Robotics and Autonomous Systems 80, 34–42. doi:10.1016/j.robot.2016.02.003.

Khan, A.H., Li, S., Luo, X., 2020. Obstacle avoidance and tracking control of redundant robotic manipulator: An rnn-based metaheuristic approach. IEEE Transactions on Industrial Informatics 16, 4670–4680. doi:10.1109/TII.2019.2941916.

Li, J., Li, D., Liu, W., Zhang, H., Liu, H., 2023. Active collision avoidance for teleoperated multi-segment continuum robots toward minimally invasive surgery. The International Journal of Robotics Research 43. doi:10.1177/02783649231220955.

Lin, G., Zhu, L., Li, J., Zou, X., Tang, Y., 2021. Collision-free path planning for a guava-harvesting robot based on recurrent deep reinforcement learning. Computers and Electronics in Agriculture 188, 106350. doi:10.1016/j.compag.2021.106350.

Liu, H., Wang, L., 2021. Collision-free human-robot collaboration based on context awareness. Robotics and Computer-Integrated Manufacturing 67, 101997. doi:10.1016/j.rcim.2020.101997.

Liu, W., 2020. China's sci-indexed publications: Facts, feelings, and future directions. ECNU Review of Education 3, 562–569. doi:10.1177/2096531120933902.

Liu, Y., Yu, C., Sheng, J., Zhang, T., 2018. Self-collision avoidance trajectory planning and robust control of a dual-arm space robot. International Journal of Control, Automation and Systems 16, 2896–2905. doi:10.1007/s12555-017-0757-z.

Lobbezoo, A., Qian, Y., Kwon, H.J., 2021. Reinforcement learning for pick and place operations in robotics: A survey. Robotics 10, 105. doi:10.3390/robotics10030105.

Lozano, S., Calzada-Infante, L., Adenso-Díaz, B., García, S., 2019. Complex network analysis of keywords co-occurrence in the recent efficiency analysis literature. Scientometrics 120, 609–629. doi:10.1007/s11192-019-03132-w.

Ma, X., Zhao, J., Luo, Y., Zhou, J., 2020. A survey on cooperative control of multiple quadrotor uavs. Journal of Intelligent & Robotic Systems 98, 11–35. doi:10.1007/s10846-019-01106-x.

Maurtua, I., Ibarguren, A., Kildal, J., Susperregi, L., Sierra, B., 2017. Human–robot collaboration in industrial applications: Safety, interaction and trust. International Journal of Advanced Robotic Systems 14. doi:10.1177/1729881417716010.

Moccia, R., Iacono, C., Siciliano, B., Ficuciello, F., 2020. Vision-based dynamic virtual fixtures for tools collision avoidance in robotic surgery. IEEE Robotics and Automation Letters 5, 1650–1655. doi:10.1109/LRA.2020.2969941.

Nagavarapu, S.C., Vachhani, L., Sinha, A., 2016. Multi-robot graph exploration and map building with collision avoidance: A decentralized approach. Journal of Intelligent & Robotic Systems 83, 503–523. doi:10.1007/s10846-015-0309-9.

Ouyang, F., Zhang, T., 2015. Virtual velocity vector-based offline collision-free path planning of industrial robotic manipulator. International Journal of Advanced Robotic Systems 12, 1–12. doi:10.5772/60127.

Perianes-Rodriguez, A., Waltman, L., van Eck, N.J., 2016. Constructing bibliometric networks: A comparison between full and fractional counting. Journal of Informetrics 10, 1178–1195. doi:10.1016/j.joi.2016.10.006.

R, 2024. The r project for statistical computing. https://www.r-project.org/. Accessed: 2024-12-18.

Safeea, M., Neto, P., Bearee, R., 2019. On-line collision avoidance for collaborative robot manipulators by adjusting off-line generated paths: An industrial use case. Robotics and Autonomous Systems 119, 278–288. doi:10.1016/j.robot.2019.07.013.

Schmidt, B., Wang, L., 2014. Depth camera based collision avoidance via active robot control. Journal of Manufacturing Systems 33, 711–718. doi:10.1016/j.jmsy.2014.04.004.

Scimmi, L.S., Melchiorre, M., Mauro, S., Pastorelli, S.P., 2019. Implementing a vision-based collision avoidance algorithm on a ur3 robot, in: 2019 23rd International Conference on Mechatronics Technology (ICMT), pp. 1–6. doi:10.1109/ICMECT.2019.8932105.

Secil, S., Ozkan, M., 2023. A collision-free path planning method for industrial robot manipulators considering safe human–robot interaction. Intelligent Service Robotics 16, 323–359. doi:10.1007/s11370-023-00465-7.

Seddaoui, A., Saaj, C.M., 2021. Collision-free optimal trajectory generation for a space robot using genetic algorithm. Acta Astronautica 179, 311–321. doi:10.1016/j.actaastro.2020.11.001.

Shi, H., Chen, J., Pan, W., Hwang, K.S., Cho, Y.Y., 2019. Collision avoidance for redundant robots in position-based visual servoing. IEEE Systems Journal 13, 3479–3489. doi:10.1109/JSYST.2018.2865503.

Sukhovey, A., Gubankov, A., 2020. Collision avoidance method for end effectors of industrial robots with overlapping workspaces, in: 2020 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), pp. 1–5. doi:10.1109/ICIEAM48468.2020.9111919.

Tan, Y., Mao, Z., Qiao, J., 2015. Decentralized robust finite-time control of uncertain robot manipulators using integral sliding mode. IEEE Transactions on Control Systems Technology 23, 2383–2388. doi:10.1109/TCST.2014.2382578.

Touzani, H., Séguy, N., Hadj-Abdelkader, H., Suárez, R., Rosell, J., Palomo-Avellaneda, L., Bouchafa, S., 2022. Efficient industrial solution for robotic task sequencing problem with mutual collision avoidance & cycle time optimization. IEEE Robotics and Automation Letters 7, 2597–2604. doi:10.1109/LRA.2022.3142919.

Wang, Y., Sheng, Y., Wang, J., Zhang, W., 2018. Optimal collision-free robot trajectory generation based on time series prediction of human motion. IEEE Robotics and Automation Letters 3, 226–233. doi:10.1109/LRA.2017.2737486.

Wang, Y., Wang, H., Liu, Z., Chen, W., 2020. Visual servo-collision avoidance hybrid task by considering detection and localization of contact for a soft manipulator. IEEE/ASME Transactions on Mechatronics 25, 1310–1321. doi:10.1109/TMECH.2020.2974296.

Wen, Y., Pagilla, P., 2023. Path-constrained and collision-free optimal trajectory planning for robot manipulators. IEEE Transactions on Automation Science and Engineering 20, 763–774. doi:10.1109/TASE.2022.3169989.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Yutani, H., 2019. Welcome to the tidyverse. Journal of Open Source Software 4, 1686. doi:10.21105/joss.01686.

Wu, Y., Hu, Z., Du, Z., He, P., Zhang, W., 2016. Dynamic analysis and multi-objective optimization of a robotic mechanism for a forging manipulator. Mechanism and Machine Theory 105, 42–67. doi:10.1016/j.mechmachtheory.2016.09.005.

Xu, Q., Zhang, T., Zhou, K., Lin, Y., Ju, W., 2024. Active collision avoidance for robotic arm based on artificial potential field and deep reinforcement learning. Applied Sciences 14, 4936. doi:10.3390/app14114936.

Yong Jin Cho, J.W.P., Kim, J.H., 2016. End-effector path planning and collision avoidance for robot-assisted surgery. International Journal of Precision Engineering and Manufacturing 17, 1703–1709. doi:10.1007/s12541-016-0197-3.

Zbiss, K., Kacem, A., Santillo, M., Mohammadi, A., 2022. Automatic collision-free trajectory generation for collaborative robotic car-painting. IEEE Access 10, 9950–9959. doi:10.1109/ACCESS.2022.3144631.

Zhang, Z., Zheng, L., Chen, Z., Kong, L., Karimi, H.R., 2021. Mutual-collision-avoidance scheme synthesized by neural networks for dual redundant robot manipulators executing cooperative tasks. IEEE Transactions on Neural Networks and Learning Systems 32, 1052–1064. doi:10.1109/TNNLS.2020.2980038.

Zhao, H., Zhao, J., Duan, X., Gong, X., Bian, G., 2020. Research on collision avoidance control of multi-arm medical robot based on c-space. IEEE Access 8, 93219–93229. doi:10.1109/ACCESS.2020.2994304.