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Systematic review and meta-analysis

Automated guided vehicles with a mounted serial manipulator: A systematic literature review

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ABSTRACT

Automated Guided Vehicles (AGVs) have become a vital part of the automation sector and a key component of a new industrial revolution that promises to: i. automate the entire manufacturing process, ii. increase productivity rates, iii. develop safer workplaces, while iv. maximising profits and reducing running costs for businesses. However, several concerns arise in the face of this very promising revolution. A major issue is how to ensure that AGVs function effectively and safely during interactions with humans. Another one concerns the ethical desirability of pervasive, continuous, and multidimensional couplings (or interactions) between humans and robots. Generally speaking, automated systems, in virtue of their vast sensing capabilities, may pose privacy challenges to their users. This is because such systems can seamlessly gather information about people' behaviors, without people's consent or awareness. To tackle the important issues abovementioned, we performed a systematic literature review [SLR] on AGVs with mounted serial manipulators. We used as an input 282 papers published in the relevant scientific literature. We analysed these papers and selected 50 papers based on certain criteria to find out trends, algorithms, performance metrics used, as well as potential ethical concerns raised by the deployment of AGVs in the industry. Our findings suggest that corporations can effectively rely on AGVs with mounted manipulators as an efficient and safe solution to production challenges.

1. Introduction/background

Automated Guided Vehicles (AGVs) are a versatile and increasingly crucial form of industrial automation used in many production systems worldwide [1]. The industry has used AGVs for load transportation and material handling since the 1950s [2]. The technology is therefore well-developed and readily available to large companies and enterprises of various sizes [3].

The VDI 2510 standard guidelines cited by [2] describes an AGV as a floor-supported, self-propelled mode of transportation controlled automatically and guided by a non-contact guiding system. In other words, an AGV is a machine that moves on the ground and that has its own internal control that can work autonomously without human intervention. Fig. 1 displays an example of such a machine. Naturally, there are several types of AGVs (such as LGVs [Laser-guided Vehicles], SGVs [Self-guided Vehicles], and AGCs [Automated Guided Carts]) developed by the industry, each of which with a specific purpose and aim.

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Fig. 1. Autonomous Ground Vehicle (AGV) [4].

Fig. 2. Autonomous Ground Vehicle (AGV) with mounted serial manipulator [6].

In warehouses, AGVs are typically combined with serial manipulators-as shown in Fig. 2- for more effective object handling, higher production rates (hence, less operational time), and more flexible collaboration with human labour. So, we can say that an AVG with a mounted serial manipulator is a type of robot that consists of a fixed base, and consecutive links that are connected together by joints, to which are typically appended different end-effectors that vary in accordance to the purposes and goals to be performed or achieved by the robot itself [5].

As noted by [7], the rapid development of e-commerce and express delivery, led to an increased demand for AGVs. This determined more research toward the application of such systems in the industry [8], which -in turn- demanded the creation of international guidelines and safety standards to regulate humans' interactions with such machines [9], [10], [7], [11].

The development of these guidelines and safety standards can be framed and understood in the more general context of current trends of automation and data exchange in manufacturing technologies known as *Industry 4.0* [12], which promises to radically change the manufacturing industry in the next decade or so [13] and which is characterised by what is known as 'Smart Manufacturing'. Smart Manufacturing is a form of manufacturing that 'employs computer-integrated manufacturing, high levels of adaptability, rapid design changes, digital information technology, and more flexible technical workforce training' [14] with the intent of increasing productivity and optimising logistics and supply chains [12]. The idea of Smart Manufacturing fits nicely into the concept of a smart factory, a working place with inter operable systems, multi-scale dynamic modelling and simulation, intelligent automation, strong cyber security, and networked sensors that is envisaged by many as the future of the industry [15].

AGVs may play a significant role in this forthcoming industrial revolution. It is therefore worth briefly explaining their functioning in terms of the algorithms that characterise them. To date, there are diverse algorithms and controlling techniques for AGVs and many more are still being researched. The existing algorithms are generally classified in two main categories: a. *position based control* and b. *image based control* [16]. Both these categories share the same goal (optimizing an AGV's pose); however, they differ in the way in which such a goal is achieved.

Position based control algorithms require (to function properly) only information about the desired pose. Hence, the robot moves from its current pose to the desired pose by continuously reducing the error between its current pose and the target pose. Crucially, it does so by using translation and rotation motion control inputs [16].

Image based control algorithms are instead based on epipolar geometry and typically combine outputs from two (or more) cameras to construct a 3D scene of the environment surrounding the AGV itself. The information obtained from the cameras is subsequently used to calculate the geometric mappings between the current view and the desired view. In particular, the desired motion is achieved by reducing the error control vector between the image features from the current view and the features in an image previously taken at that particular pose. The Epipolar control law [16], [17], is used for the navigation of the vehicle using a feedback control law where the inputs are the coordinates of the epipoles. Furthermore, the Neural Extended Kalman Filter (NEKF), is used for estimating pose and to improve the process model [18].

These control techniques and algorithms can be used to evaluate, assess, and rank the performance of AGVs. This raises the question of which of them are better (or more applicable) than others (if any, at all).

As techniques and algorithms continue to pop up at a fast speed in the AGV industry, indicating that there are still open gaps in the literature [19], it is difficult to give a definite answer to this research question. Nevertheless, one can list a series of problems affecting current AGVs, which future algorithms may contribute to solve. These include:

- control/positioning problem; [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37]
- safety; [38], [39], [40], [41], [42], [43], [44], [45], [46], [47]
- socioeconomic impacts on job security and productivity; [48], [49], [50], [51], [52], [53], [54], [55], [56], [57]
- ethical issues regarding AGV use. [9], [58], [59], [10], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69], [70]

To contribute to the solution of some of these problems, in this study we aim to:

- assess the impact of adopting AGVs with mounted serial manipulators;
- show whether AGVs are a reliable and efficient technology for warehouse automation;
- identify how researchers have improved the accuracy of control strategies;
- discuss and evaluate various methods used by researchers to enhance the safety of these systems as well as to avoid collision with humans;
- analyse some of the most important ethical issues concerning the use of AGVs presented this far by researchers in the field.

In other words, in this work, we would like to address the following research questions (Table 1):

Table 1
Research Questions.

1.	Can industrial corporations depend on AGVs with mounted manipulators as a reliable and robust solution for efficient warehouses automation?
1a.	In tasks which require human-robot intervention, does collision handling (detection, localization, classification, and reaction) ensure human safety while allowing workers to achieve high productivity?
1b.	Does AGVs achieve optimal trajectory planning with model predictive control (MPC)?
1c.	Are there any potential societal benefits from incorporating ethical considerations in the usage of AGVs?

The study is therefore organized as follows.

- Section 2. PROTOCOL DEVELOPMENT: presents the methodology we have adopted in the study. In other words, it highlights the search process as well as the selection criteria that we used in this work.
- Section 3. RESULTS: systematically discusses the data we found and clusters them in ways that are useful to advance the discussion in the field.
- Section 4. DISCUSSION: Contextualises and critically analyses the results obtained in this study, by pointing out relevant (significant) gaps found in the literature.
- Section 5. CRITICAL REVIEW OF RESEARCH QUESTIONS: summarises our main results with respect to each of the research question we tackled in this study.
- Section 6. LIMITATIONS, THREATS TO VALIDITY, AND REVIEW ASSESSMENT: explores the major limitations and shortcomings threatening the validity of this study and its coherence.
- Section 7. CONCLUSION: summarises what we achieved, while describing possible, future research directions.

2. Protocol development

Systematic Literature Reviews (SLRs) represent formal approaches for discovering, objectively evaluating, and comprehensively assessing the scientific research performed on a specified issue or on a set of issues [71] [72]. SLRs therefore typically allow for the collection, extraction, synthesis, and critical analysis or interpretation of all the scholarly research conducted on a specific research topic [73,74], and are thus instrumental for providing optimal recommendations for practice and research [75,76].

In this SLR, our goal is to investigate the reliability of AGVs with mounted manipulators as a solution for industrial automation. In this context it is worth noting; however, that no SLR has been performed on this topic to date. This makes our work rather original.

The methodological protocol used in this study follows the guidelines of the “Preferred Reporting Items for Systematic Reviews and Meta Analyses” or (PRISMA) checklist [77], which is the benchmark adopted by researchers worldwide for conducting SLRs. The Prisma checklist used in this study is appended as Table 15 in the Appendix A.

Table 2
Keywords.

Industrial corporations
Automated guided vehicles
Mounted manipulators
Model predictive control
Navigation
Obstacle avoidance
Optimal control
Automation
Collaborative robots
Human-Robot interaction
Collision detection
Collision localization
Collision classification
Automation ethics
Machine ethics
Ethical robots
Ethical governance

2.1. Research questions

As noted above, we formulated one research question and three sub-questions. The sub-questions are instrumental because they provide unique perspectives as well as original insights for the main research question.

Our primary research question is:

RQ: Can industrial corporations depend on AGVs with mounted manipulators as a reliable and robust solution for efficient warehouses automation?

We then generated the following **sub-research questions**, as follows:

- **SRQ1:** In tasks which require human-robot intervention, does collision handling (detection, localization, classification, and reaction) ensure human safety while allowing workers to achieve high productivity?
- **SRQ2:** Does AGVs achieve optimal trajectory planning with model predictive control (MPC)?
- **SRQ3:** Are there any potential societal benefits from incorporating ethical considerations in the usage of AGVs?

We intend to answer our **RQ** by comparing and assessing the views of different authors with respect to the perceived efficiency of AGVs for operations in industrial settings. By answering **SRQ1**, we intend to delve into the safety concerns that may arise during human-robot interactions in the context of AGVs usage. In particular, we want to survey various authors' views on how collision handling aspects (such as detection, localization, classification, and reaction) may ensure safety for humans, while boosting their productivity and efficiency. With **SRQ2**, we intend to assess the usage of Model Predictive Control (MPC) as a trajectory planning algorithm for AGVs. We reflect on its optimality and performance compared to other trajectory planning strategies or algorithms. Finally, our response to **SRQ3** aims at providing a preliminary answer to whether it might be beneficial for society to develop legally binding (transnational) guidelines as well as ethical standards to regulate or normate the process of automation described in this study.

2.2. Literature search process

In this subsection, we carefully explain the procedure we undertook to finalise our reading log. Firstly, we extracted -from the above-mentioned research questions- several relevant keywords, which allowed us to further specify our research directions. The list of keywords we formulated is specified in Table 2. Subsequently, we searched for these keywords in five different databases (more on this in section 2.2.2 below) and recorded the total number of papers that this searched triggered for each keyword 3. Using Boolean operators ("OR" and "AND"), we then constructed our search queries (2.2.3). This was done to further increase the focus of our review. The search queries we formulated are listed in Table 4.

2.2.1. Keywords

As mentioned above, we used a set of keywords which we derived from the research questions we listed in section 2.1. We note that the keywords were carefully selected, following the best standards of the discipline, through several cross-collaborative interactions performed by all members of the research group.

2.2.2. Databases used

We then searched five databases with these keywords. The databases used for our searches are:

- **Google Scholar**
- **Springer Link**

Table 3
Keywords in Databases.

Searching Keyword	Google Scholar	Springer Link	IEEE Xplore	ACM Digital Library	Elsevier
Industrial corporations	2,230,000	271,835	5,211	102,373	200,951
Automated guided vehicles	131,000	31,931	1,291	641,783	10,278
Mounted manipulators	174,000	14,115	1684	139,367	86,945
Model predictive control	4,560,000	345,813	44,014	526,460	24,686
Navigation	6,400,000	240,982	86,814	64,001	674
Obstacle avoidance	1,090,000	45,822	12,465	251,847	656
Optimal control	6,050,000	1,354,656	117,743	427,147	16,329
Automation	4,850,000	442,075	350,929	150,798	1,606
Collaborative robots	245,000	21,709	4,125	149,248	23,762
Human-Robot interaction	193,000	12,634	15,243	400,215	56,929
Collision detection	2,450,000	108,029	8,345	232,456	159,598
Collision localization	210,000	28,724	1,358	63,130	86,943
Collision classification	880,000	54,313	899	219,516	62,506
Automation ethics	309,000	17,437	409	165,988	7,053
Machine ethics	3,240,000	94,697	418	316,277	48,196
Ethical robots	118,000	21,456	397	59,878	11,665
Ethical governance	2,200,000	69,945	99	105,072	23,432

Table 4
Search Queries - Results.

Boolean Operator	Google Scholar	Springer Link	IEEE Xplore	ACM Digital Library	Elsevier
(Industrial corporations) AND (Automated guided vehicles)	28,200	2,230	8	102,375	2,895
(Automated guided vehicles) AND (Mounted manipulators)	22,800	603	4	139,369	1,859
(Industrial corporations) AND (Automated guided vehicles) AND (Mounted manipulators)	19,200	366	0	27,165	432
(Model predictive control) AND (Automated guided vehicles OR Automation)	77,900	4684	451	283,140	57,163
(Navigation OR Obstacle avoidance) AND (Automated guided vehicles OR AGVs)	34,500	4,684	450	283,260	3727
(Model predictive control) AND (Navigation OR Optimal control)	3,630,000	143,180	0	545,232	567,415
(Collaborative robots) AND (Collision detection OR Obstacle avoidance)	28,800	2,174	210	92,033	2,706
(Collaborative robots) AND (Collision detection) AND (Collision localization) AND (Collision classification)	20,700	1,296	0	13,100	490
(Collaborative robots) AND (Human-robot interaction) AND (Automated guided vehicles OR AGVs)	11,300	322	2	131,890	1,530
(Human-robot interaction) AND (Collision detection OR Collision classification)	18,100	1,748	0	457,115	5,087
(Ethics) AND (Robots) AND (Legislation)	18,100	2,649	9	277	891
(AGVs) AND (Ethical governance)	716	99	0	92	5
(AGVs) AND (Ethical legislation)	810	90	0	8	8

- **IEEE Xplore**
- **ACM Digital Library**
- **Elsevier**

We note that these databases are widely used in robotics and control field. In addition, we remark that they are among the most widely used by researchers worldwide.

Subsequently, we recorded the number of hits that our searches generated for each of the five databases we used. This information is displayed in Table 3.

2.2.3. Search queries

We then applied Boolean operators (“OR” and “AND”) to our previously selected keywords, constructing our main search queries. We searched the databases we selected with our search queries. The search queries along with corresponding results (the hits we found) are listed in Table 4.

2.3. Inclusion and exclusion criteria

Through these preliminary searches we obtained a rather large amount of papers. To achieve more focus in our study; hence, to standardize our searches and findings - following the best norms of our discipline- we pruned (redundant or irrelevant papers) from our original list. We did so, by applying a set of specific inclusion and exclusion criteria, which we formulated upfront.

Table 5
Paper selection according to IC and EC.

Source	Initial Selection	Relevant	IC1	IC2	IC3	IC4	IC5	EC1	EC2
Google Scholar	3911126	123	96	5	122	107	123	59	34
Springer Link	164125	43	29	19	43	43	43	22	5
IEEE Xplore	1134	58	48	16	57	32	58	18	11
ACM Digital Library	2075056	26	8	23	26	26	26	16	8
Elsevier Database	664208	32	27	22	32	32	32	20	4

We used the following *inclusion* criteria:

1. The paper is not older than **15** years.
   This is because we discovered that after 2008 there was a peak in papers related to this topic. So, we decided to survey papers from 2007 onwards.
2. The paper is not limited by specific geographical locations; hence, it may come from any part of the globe.
   There was no need for limiting our review to any geographic location.
3. The paper is written in English
   This is because research nowadays is primarily conducted in English and all the leading journals accept only papers written in English
4. The paper has as a target audience researchers in the field -among others- those interested in control, navigation, and in human-robot collaboration- as well as corporations (such as Amazon, Yandex).
   This is because the final users of our review could potentially be all researchers in the field as well as companies investing in this technology for warehouse management.
5. The paper relates to Automated Guided Vehicles deployed in warehouses or for indoor activities.
   This is to limit the scope of our review; so to exclude all other potentially relevant AGVs (such as waterborne AGVs, for instance).

We further applied the following *exclusion* criteria:

1. Non peer-reviewed articles and grey literature were excluded.
   This was done to ensure high standards.
2. Duplicates in databases were removed.
   Some papers appeared in more than one database. So, we excluded duplicates based on the chronological order of the searches we performed.

The procedure through which we applied inclusion/exclusion criteria is detailed in Table 5. We subsequently produced a PRISMA Flow Chart Diagram (Fig. 3) to detail graphically for the reader the search process that led to the formation of our final reading log.

Table 5 details the selection process that led to the formulation of our final literature log.

The initial number of papers obtained through preliminary searches is modified through the application of inclusion/exclusion criteria 2.3. In addition, duplicates are removed.

The final literature log for this study consists of 50 papers. The PRISMA flow diagram shown in Fig. 3 summarises this procedure graphically for the reader.

2.4. Quality assessment

We then assessed the reliability of our findings, by reviewing the overall quality of the studies we included in the reading log. To this end, we formulated five questions, which we used as benchmarks for our analysis.

For each of the questions we formulated we assigned a numeric value (0, 0.5, or 1). This was done to give a quantitative measure of quality to the studies we reviewed. All the team members involved in this research took part in the evaluation process, and so we are fairly confident that the values we obtained (as described further below) are fair and scientifically sound.

The list of questions we generated is as follows:

1. Did the paper clearly states its objectives along with the research questions?
   - 1 point if the paper stated its objectives along with the research questions.
   - 0.5 if the objectives were stated ambiguously or vaguely.
   - 0 was assigned if the objectives were not stated or the research questions were hard to determine.
2. Did the paper performs a comparative analysis and offers detailed explanations and/or discussion?
   - 1 point if the paper performed a comparative analysis and offered detailed explanations and/or discussion.
   - 0.5 if the paper offered weak comparative analyses that lacked justification.
   - 0 if the paper did not provide comparative analysis at all.
3. Did the paper provides a verification procedure?
   - 1 point if the paper verified its approach with hardware implementation.
   - 0.5 if the paper only performed a simulation.

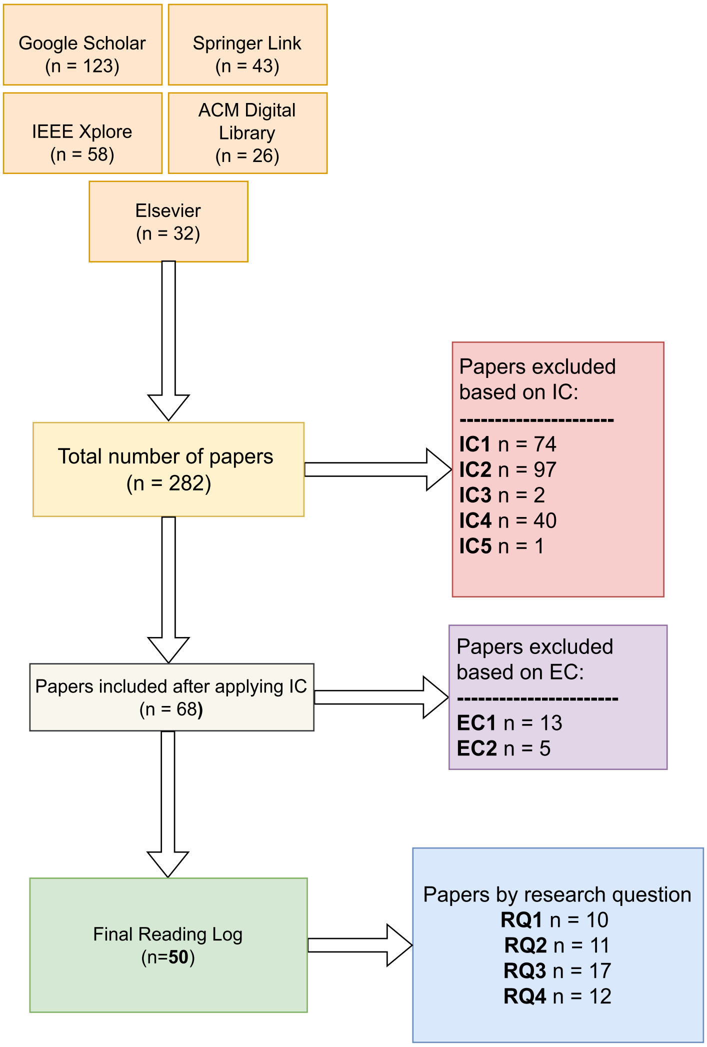

Fig. 3. PRISMA Flow Chart Diagram.

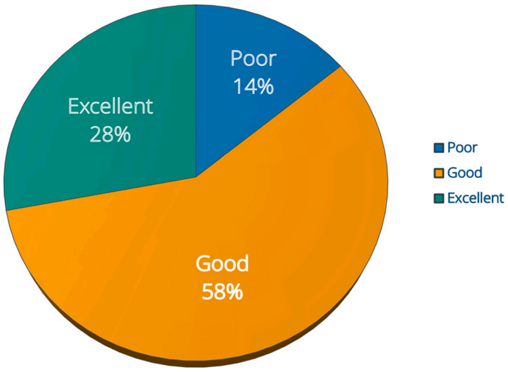

Fig. 4. Quality Assessment - Percentages II.

  - 0 if the paper did not provide experimental evaluation in any form.
4. Did the study clearly states the evaluation metrics used and did it critically evaluate all its results?
   - 1 point if the study clearly stated the evaluation metrics used, and if all the results presented were critically evaluated.
   - 0.5 if the study did not evaluate all its results and if the metrics used were not made available.

Table 6
Quality Assessment - Scores.

Paper	QA1	QA2	QA3	QA4	QA5	Total	Rank
Raju et al. [48]	1	0.5	0.5	1	1	4	Good
Henesey et al. [49]	1	0.5	0.5	1	1	4	Good
Berman et al. [50]	1	1	0.5	0.5	1	4	Good
Yim et al. [51]	1	1	1	1	1	5	Excellent
Silva et al. [52]	1	1	0.5	1	1	4.5	Excellent
Shah et al. [53]	1	0.5	0.5	0.5	0.5	3	Good
Cronin et al. [54]	1	1	0.5	1	1	4.5	Excellent
Llopis-Albert et al. [55]	1	1	0.5	1	1	4.5	Excellent
Theunissen et al. [56]	1	0	0.5	1	1	3.5	Good
Riazi et al. [57]	1	0.5	1	1	0.5	4	Good
Popov et al. [38]	1	1	1	1	0.5	4.5	Excellent
Popov et al. [39]	1	0.5	1	0.5	1	4	Good
Popov et al. [40]	1	1	1	1	1	5	Excellent
Popov et al. [41]	0.5	0.5	1	1	1	4	Good
Haddadin et al. [42]	1	0.5	1	0.5	0.5	3.5	Good
Popov et al. [43]	1	0.5	1	1	1	4.5	Excellent
Haddadin et al. [44]	1	0	1	0	1	3	Good
Mikhel et al. [45]	1	0.5	1	0.5	1	4	Good
Lee et al. [46]	1	0.5	1	0.5	1	4	Good
Ragaglia et al. [47]	1	0.5	1	1	0.5	4	Good
Chen et al. [20]	1	1	1	1	0.5	4.5	Excellent
Yin et al. [21]	1	1	0.5	1	0.5	4	Good
Qi et al. [22]	1	1	0.5	1	0.5	4	Good
Xu et al. [23]	1	0.5	0.5	1	1	4	Good
Li et al. [24]	1	1	1	1	1	5	Excellent
Mikumo et al. [25]	1	0	0	0	1	2	Poor
Wu et al. [26]	1	0	1	1	0.5	3.5	Good
Witczak et al. [27]	1	1	0.5	1	1	4.5	Excellent
Kim et al. [28]	1	1	0.5	1	1	4.5	Excellent
Sánchez et al. [29]	1	0	0.5	0.5	0.5	2.5	Good
Wang et al. [30]	1	1	0.5	1	1	4.5	Excellent
Choi et al. [31]	1	1	0.5	0.5	1	4	Good
Shang et al. [32]	1	0	0.5	0.5	1	3	Good
Yu et al. [33]	1	0	1	1	1	4	Good
Weng et al. [34]	1	1	0.5	1	1	4.5	Excellent
Yap et al. [35]	1	0	1	1	1	4	Good
Beal et al. [36]	1	1	1	1	1	5	Excellent
Shin et al. [37]	1	0	1	1	0.5	3.5	Good
Vanderelst et al. [9]	1	0	0.5	1	1	3.5	Good
Dogan et al. [58]	1	0	0.5	1	1	3.5	Good
Dodig Crnkovic et al. [59]	1	0	0	0	1	2	Poor
Heron et al. [10]	1	0	0	0	1	2	Poor
Yijia et al. [60]	1	0.5	0.5	0.5	1	3.5	Good
Lutz et al. [61]	1	1	0	0	1	3	Good
Flathmann et al. [62]	1	0	0.5	0	1	2.5	Good
Munteanu et al. [63]	1	0	0	0	1	2	Poor
Dignum et al. [64]	1	0	0	0	1	2	Poor
Björk et al. [65]	1	0	0.5	0	0.5	2	Poor
McBride et al. [66]	1	0	0.5	0	1	2.5	Good
Schiff et al. [67]	1	0	0	0	1	2	Poor

  - 0 if no evaluation was provided.
5. Is the conclusion clear and sound (based on evidence)?
   - 1 point if the conclusion was clear and sound and directly followed the stated results.
   - 0.5 if the conclusion was only partially supported by the results.
   - 0 if the conclusion did not follow the results or if it was overstated.

Table 6 shows the numeric values we assigned to each of these questions for each paper we included in the reading log.

The results of our qualitative analysis can be seen in Table 7. Only a few papers fell short of the high standards we set.

Fig. 4 shows visually for the reader the percentage (in terms of quality: that is, excellent, good, poor) of the papers we included in our reading log.

We note that the average quality of the papers we selected was 3.66 out of 5. We should also note that the majority of papers included in our literature log (over 95%) was either of good or of excellent quality. We can therefore infer that the findings obtained for our SLR are reliable and scientifically sound.

Table 7
Quality Assessment - Percentages.

Quality Level Score	Range	Count	Percentage
Poor	0 - 2	7	14%
Good	2 - 4	29	58%
Excellent	4 - 5	14	28%
Total	-	50	100%
Average	3.66	-	-

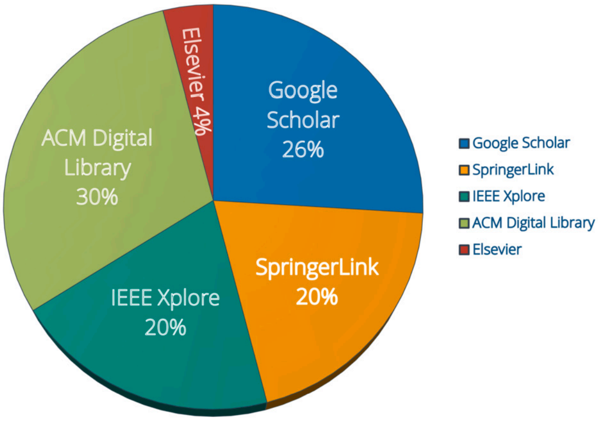

Fig. 5. Papers' distribution by databases.

3. Results

In this section, we categorized the results we gathered from the analysis of the papers we selected for inclusion in our final reading log. We used different statistical tools to organize our data in an informative manner and to give to our readers the possibility to fully grasp and understand the conclusions, as discussed in the sections below [section 4, section 5].

3.1. Search sources overview

We started our work of categorization by preliminary clustering the papers we included in our reading log in accordance with the databases used. In our study, as the reader may recall, we used five different databases (Elsevier, IEEE Xplore, Google Scholar, ACM Digital Library, and Springer Link).

Fig. 5 shows the distribution of our papers by databases. As noted above, if a paper was found in more than one database, it was assigned to the database where it was first found.

The majority of the papers were found on ACM Digital Library and on Google Scholar (these two databases accounted for 56 percent of the total papers). Elsevier was the least used database accounting for only 4 percent of the total number of papers relevant to the topic of interest of this SLR.

3.2. Preliminary classification

This section shows various ways of categorizing the publications included in our reading log. This preliminary analysis is of paramount importance because it may give our readers an idea about the quality and diversity of the papers we reviewed in the current study. Firstly, we classified all the papers we assessed by geographical distribution, where geographical distribution is understood as country of origin of the first author. This information is displayed in Fig. 6. We remark that the papers we selected originated from 26 different countries, with 9 papers from China, 6 papers from United Kingdom, Russia, and Sweden, and 5 from Italy and Korea. Most of the countries of origin are from Europe and North America, which may signal a higher interest in the area of mounted AGVs in developed countries. However, there is also a significant amount of papers coming from China and Russia, which shows interesting perspectives for advances in industrial automation in these fast developing nations.

Fig. 7 shows the distribution of our paper by year of publication. We note that the number of papers published in the past five years exceed by two times the number of papers published before that period. We attribute this increase in publication to recent technological developments and to recent interest in warehouse automation among business companies and corporations.

We also classified the papers included in our reading log based on the key topics or issues addressed in them. We deployed an unsupervised machine learning algorithm, called Self Organizing Maps, to perform a content-based clustering of the papers' key themes. Particularly, we used the *sklearn-som* Python package. Its implementation is based on the Kohonen Self Organizing Maps.

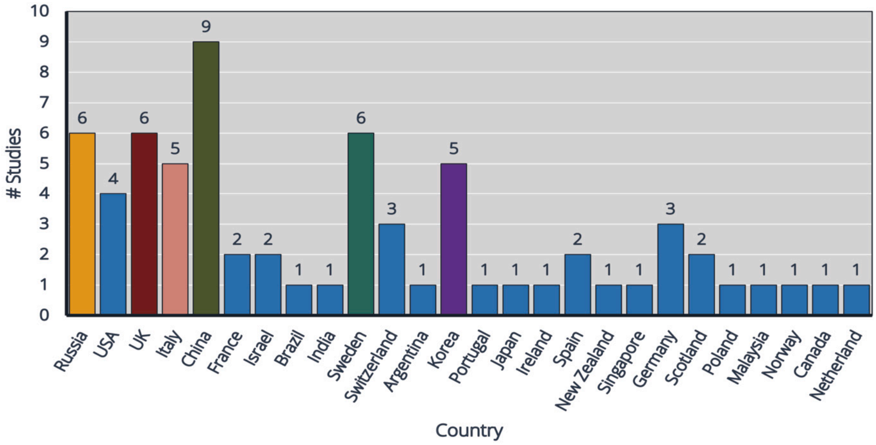

Fig. 6. Geographical distribution.

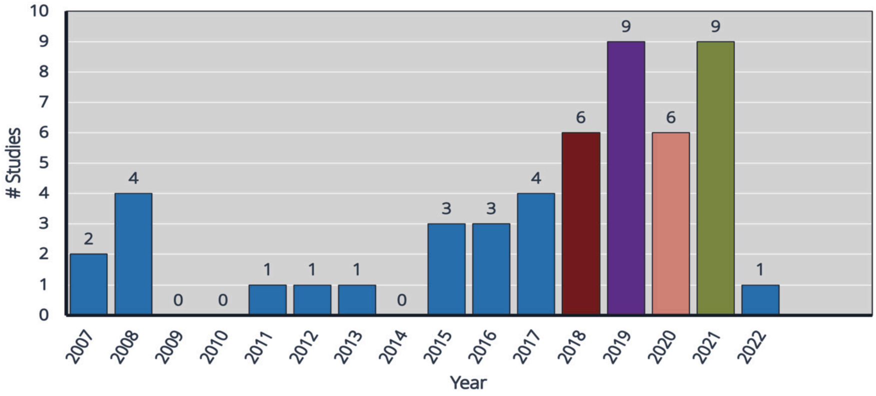

Fig. 7. Distribution by year of publication.

According to [78] this algorithm gives an excellent partitioning or clustering solution to problems that deal with large data sets. SOMs are neural networks that work by activating some neurons based on various patterns in input signals.

The clustering algorithm identified several key phrase clusters, which we further refined based on both cluster size and semantic redundancy, leading us to identify the following major clusters (Table 8).

- Model Predictive Control [MPC] [20–22]
- Human Safety during collaboration with robots [38–40]
- Ethics
- Evaluations of Impact On Industry

We must note that the four main key topics identified above significantly correlate to the research questions characterising our SLR. It is worth also noting that MPC has a significantly higher number of papers due to abundance in publications in the field of mobile robot control. Also, we must acknowledge that evaluation of performance and impact is a vital issue for researchers and corporations alike, which means that this topic is likely to attract more funds (hence more publications) by the industry in the near future.

Fig. 8 further highlights the trends within these topics. Notably, the number of papers which discuss the evaluation of AGVs performance and impact on the industry has doubled over the past five years. There is also an increase in the number of authors using model predictive control.

3.3. Further classification

Having preliminary clustered our findings, we then decided to more carefully analyse their significance for the field. To this end we summarised the metrics, algorithms, and methods (as well as their distribution) used in the studies we selected for inclusion in our reading log.

Performance metrics provide an objective means of evaluating the efficiency of a system. In this work a lot of the performance measures used were non-standard ones, which were tailored specifically to the researchers' needs. Consequently, the category "Others" displays custom designed performance measures as used in individual papers. Some metrics described here include make span, maximum lateness, tardiness, computational complexity, root-mean-square error etc. Accuracy was obviously a popular statistical

Table 8
Distribution by key topic.

Topics	Papers	Earliest Publication Date	Latest Publication Date	Number of Papers	Percentage of Papers
Model Predictive Control	[21], [23], [24], [25], [26], [27], [28], [29], [30], [31], [34], [36], [37],	2008	2022	13	26%
Human Safety during collaboration with robots	[38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [29],	2008	2021	11	22%
Ethics	[9], [58], [59], [10], [60], [61], [62], [63], [64], [65], [66],	2011	2021	11	22%
Evaluations of Impact On Industry	[48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [20], [21], [22], [27], [30], [33], [9], [58], [62], [63], [67],	2007	2021	23	42%

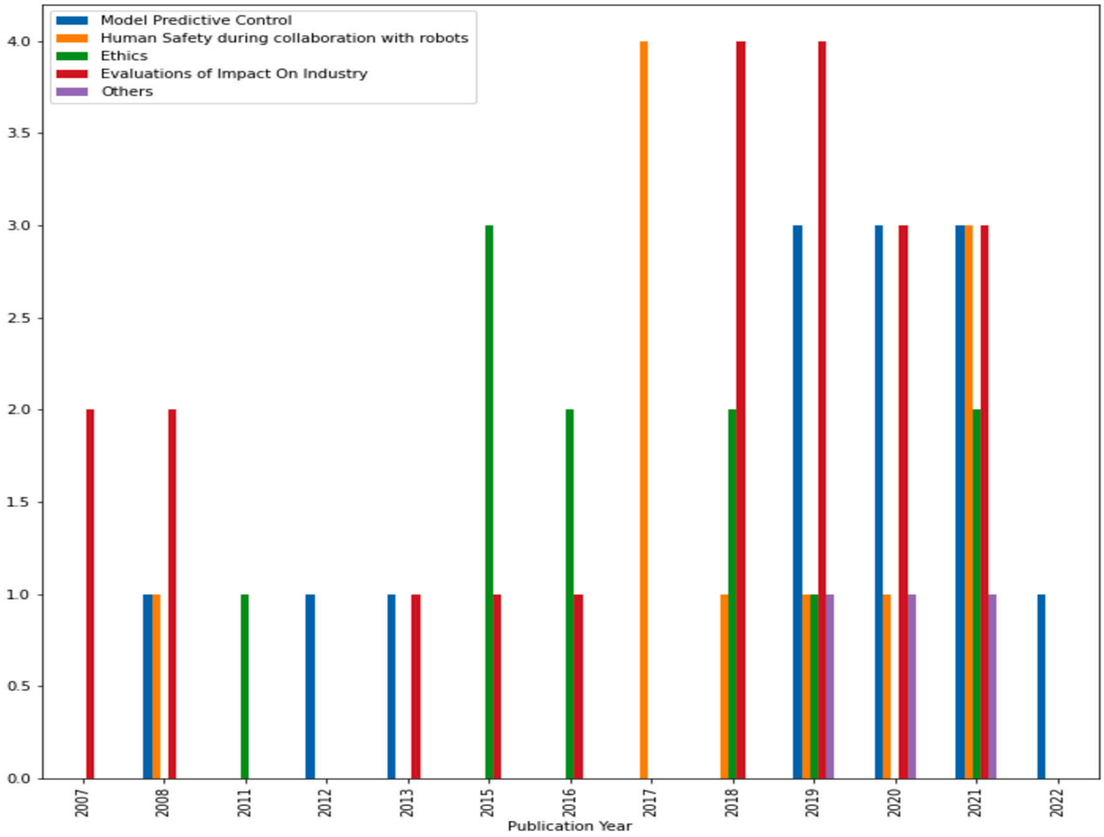

Fig. 8. Distribution of key topics by year.

metric, which was used to show the likelihood of a measurement or of a prediction to be true (or close to the accepted value) as expressed in Eq. (1).

$$Accuracy = \frac{T_p + T_n}{T_p + T_n + F_p + F_n} \tag{1}$$

Where:

- T_p: True Positives
- T_n: True Negatives
- F_p: False Positives
- F_n: False Negatives

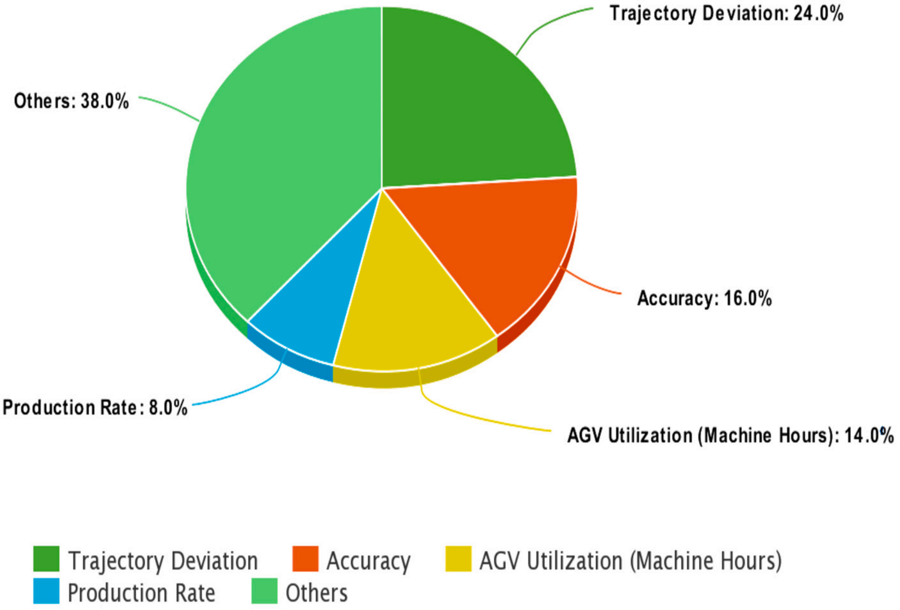

Fig. 9. Distribution of metrics used.

Table 9
Most used algorithms in the papers included in the reading log.

Algorithm	Quantity
Neural Network (NN)	6
Model Predictive Control (MPC)	16
PID Controller	4
Petri Net	2
Optimisation	7
Linear Quadratic Control	2

Equation (2) gives a more generalized formula to measure accuracy.

$$Accuracy = \frac{\textit{number of correct estimations}}{\textit{total number of estimations}} \tag{2}$$

Trajectory Deviation is the measure of how far the planned trajectory of the robot arm or path of the mobile robot varies from the actual path followed by the robot as expressed in Eq. (3).

$$Error = \textit{predicted trajectory} - \textit{Actual trajectory} \tag{3}$$

AGVs Utilization is the performance metric that measures how efficiently the AGVs is being put to use. According to [48] quantitatively evaluating utilization is difficult, but since it correlates significantly to idle time, this can be measured and used to estimate the utilization. Equation (4) expresses idle time in a quantitative measure.

$$\textit{Idle time} = \textit{Total work hours} - \textit{Hours machine in use} \tag{4}$$

Production rate is also used as a performance metric and is expressed as the ratio of the amount of units produced or service delivered to the time taken.

Fig. 9 highlights the distribution of the performance metrics in the papers we included in our reading log.

Table 9 lists the most used algorithms in the papers included in the reading log. We note that for vehicle optimal trajectory planning, Model Predictive Control (MPC) is widely used. Also, we remark that Neural Networks (NN) is mainly used for studying manipulator collision events. These algorithms are described in details in section 4.1 However, it is worth mentioning that some papers do combine multiple algorithms.

Fig. 10 shows the distribution of algorithms combinations. We must note that only **32 papers** used algorithms, while **18 papers** did not implement any algorithm at all.

Table 10 displays the implementation methods used in the papers included in our reading log. The table demonstrates that the majority of papers selected used simulation or both simulation and hardware verification. Fig. 11 presents the information shown in 10 in a graphical format, which is probably more appealing to our readers.

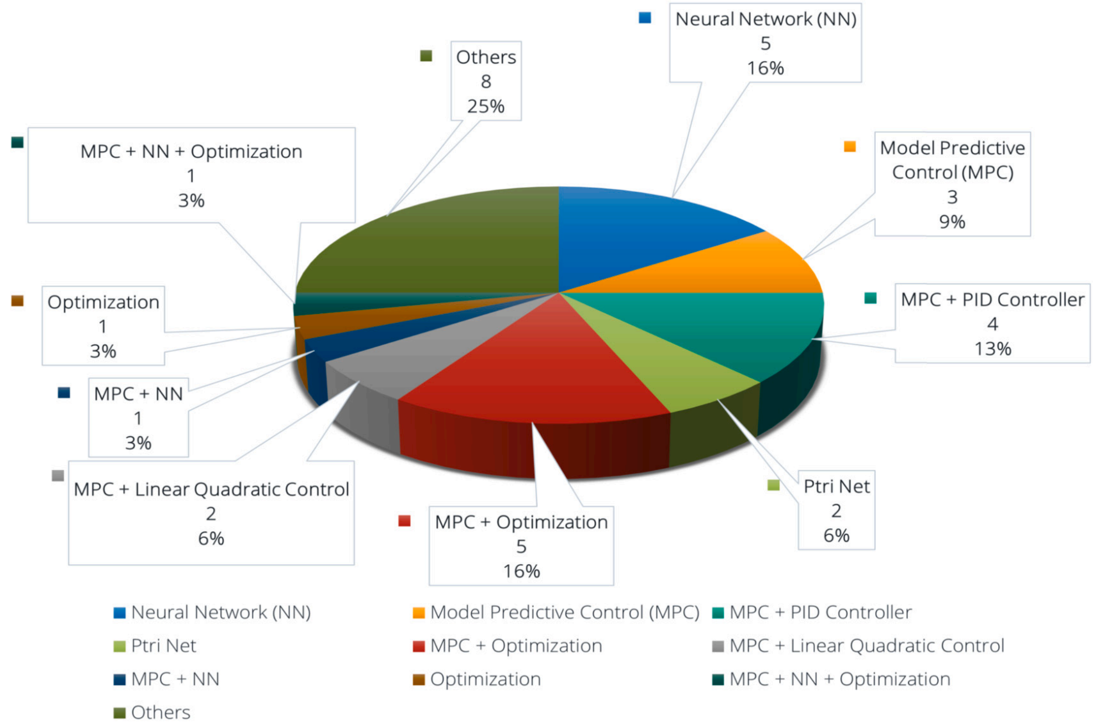

Fig. 10. Distribution of algorithms combinations.

Table 10
Implementation methods used.

Implementation	Count	Percentage
Simulation	18	36%
Hardware	4	8%
Both	17	34%
Neither	11	22%
Total	50	100%

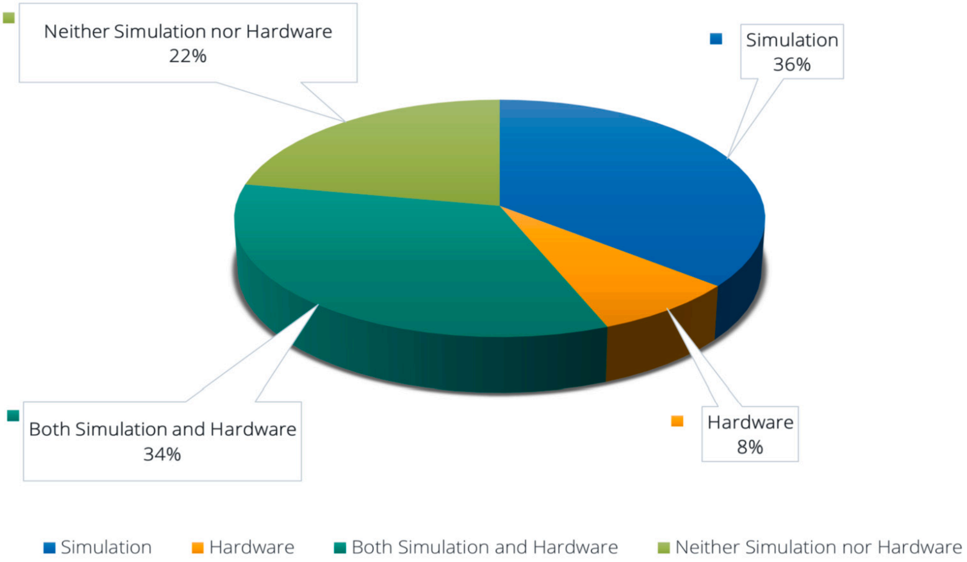

Fig. 11. Implementation methods used II.

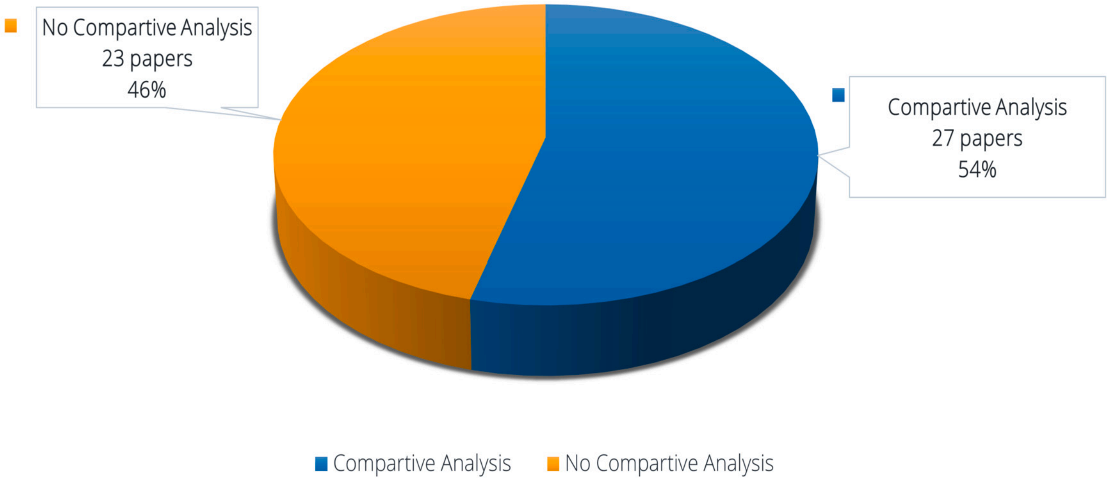

Fig. 12. Distribution of metrics used.

It is worth noting that a variety of hardware configurations have been implemented. For example, [20] applied their controller to a robot vehicle with Lidar and Up Board controller, while [26] used a robot with two distinct controllers: ARM LPC2210 as main controller for path tracking and DSP controller for image processing needed in the perception task. Furthermore, [24] used a robot with 2D lidar and mini pc intel (NUC). In addition, [31] used a B-POR to model a robot vehicle, in which a resistive touch was used to detect the ball position and Arduino Mega was used as a controller with VEST motor drivers. With respect to the simulation tools, most of the papers used ROS environment and Matlab.

Finally, Fig. 12 shows the percentage of papers that implemented comparative analysis vs the papers that did not. Comparative analysis tells us how a particular research performs, relative to benchmarks (either state-of-the-art or other papers) in that field. Fig. 10 demonstrate that more than half (54%) of the papers we selected contained a comparative analysis. This is good finding as it shows that the papers we reviewed compared their approach to that done by others, which is a sign of scientific accuracy and soundness, as replicability is one of the major pillars of scientific progress. In addition, we must note that a significant number of the papers that failed to implement comparative analysis were concerned with ethical reflections over the domain we investigated. Ethics typically does not perform comparative analysis, so this further confirms the soundness of our results.

4. Discussion

In this section, we contextualise our results and critically evaluate them, trying to point out interesting gaps in the literature.

4.1. Algorithms used in the papers

One of the most widely mentioned techniques in the papers we reviewed is Model Predictive Control (MPC). MPC uses a model of the system to make predictions about the system's future behavior. In other words, it selects optimal control signals that bring the system to a desired reference path. It can be utilized in multiple input and multiple output systems (MIMO). Also, it can incorporate constraints on input and output (such as maximum robot speed or maximum angular angle). One of the major limitations of MPC is the fact that is computationally expensive. However, due to increasing processing capabilities of micro controllers, this limitation can be overcome. Thus, due to its characteristics, Model Predictive Control ([20], [22], [23], [24], [25], [27], [28], [29], [30], [31], [34], [36], [37]) is nowadays widely used for vehicle trajectory planning.

Furthermore, another controller widely used in the papers we reviewed is Proportional Integrated Derivative controller (PID) [20], [22], [24], [26], [31]. This controller algorithm consists mainly of three part: proportional, integral, and derivative. The proportional part is responsible for the system's response speed and can be defined as a constant k_p multiplied by the error between current and desired state. The integral part, as the name suggests, integrates the error over a period of time (multiplied by integral coefficient k_i) until a steady state error becomes zero. The derivative part is the final part, which is associated with the rate of change of the error (multiplied by a derivative coefficient k_d) and typically leads to system's stability. One of the main limitations for PID is its tuning process, because there is no systematic way for doing it in a non-linear system.

Another control algorithm used in the papers we reviewed is Linear Quadratic Regulator (LQR) [31]. This algorithm uses a linear control law to minimise a quadratic loss function, which tries to reach the desired goal with minimum control input. However, this controller works with only linear systems and has a time complexity of $O(n^3)$. So, it can not deal with high dimensional states.

Neural networks are mainly used in studying manipulator collision events ([38], [40], [41], [42], [45], [46]). In [38], [40], it has been found that these networks typically achieve an accuracy greater than 98%. More details are presented in section 4.1.1.

Petri Net, which had minimal usage, appearing in [48], [51] was used for modeling and simulating AGVs taking into consideration design, management and control challenges, including the vehicles available and required buffer sizes, siding sizes, and vehicle dispatching algorithms. Petri Net provides a powerful mathematical tool to model the interaction of interacting subsystems and variables. As discussed by [48], the industry could benefit significantly from adopting it.

4.1.1. Human safety during collaboration with robots

Human safety within human-robot collaboration has obviously become a vital topic of research in the field. This is usually investigated by studying collision in order to detect the interaction, localize the point of contact, classify the collision, and -hence-choose the most appropriate reaction for the detected contact. There are multiple algorithms deployed in the papers we reviewed that tackle such issues. They can be roughly classified as follows:

- Neural Networks (NN) [38], [41], [45], [46], [47], which can be used in machine learning [79]. They are typically made up of three layers of neurons: an input layer, one to three hidden layers, and an output layer [80].
- Momentum Observer [44]
- SQP optimisation [39]
- Contact Particle Filter [40]

We note that the most used algorithm in this field is Neural Network (NN). This is because NN algorithms have been proven to achieve high accuracy in collision localization and classification processes. For example, in [38], by using a NN, collision detection was achieved with an accuracy of 99.2%, and collision point localization was estimated with an accuracy of 94.3%. However, some proposed algorithms encountered technical limitations. For instance, in [40] the NN algorithm managed to distinguish between hard and soft collisions; nevertheless it was unable to meaningfully discriminate between materials with similar stiffness properties (such as a human hand and a soft chair). In addition, the control strategy used in [42] did not enable the robot to find its way back for the desired trajectory after the collision.

4.1.2. Trajectory planning and control

Several algorithms in the studies we reviewed were concerned with trajectory planning and control tasks as implemented in AGVs. The most used algorithm proved to be model predictive control [20], [21], [22], due to its proven capacity to provide the optimal control law for the path trajectory of AGVs. This algorithm was also compared to other control algorithms that used: LQR, PID, optimisation, and neural networks, as in [24], [25], [26], [28], [29], [30], [31]. Our results show that MPC provides more accurate performances since it results in less deviations from the reference trajectory, as shown in Fig. 13. We not that the drawbacks of each algorithm will be discussed in the following paragraphs, relative to the performance of MPC.

In [20], [22], [24], researchers used one of the most classical controllers, which is PID (proportional integral derivative) controller; however, it showed higher deviation from the reference trajectory relative to MPC and its execution time was much slower.

In [31] a LQR linear quadratic regulator was used to ensure fast and safe delivery of goods using mobile robots. The paper modeled a part of the vehicle as an inverted pendulum that requires self-stabilization throughout a trajectory planning task. This algorithm was tested on a rectangular path and showed good results with 45 mm deviation; however, the MPC model outperformed it by causing deviations less than 20 mm, which resulted in a smoother path trajectory.

In [25], [28], [29], [30], [36] convex optimisation techniques were used to design a robot path from one point to another. For example, [25] assumed an environment containing multiple mobile robots, in which each robot considers the other robots as a dynamic obstacle defined through a mixed integer problem while maintaining a target goal [81]. [29] utilized non-linear model predictive control (NMPC) to achieve path following and obstacle avoidance goals through solving a single optimisation problem. It proposed a new control algorithm that predicted an auxiliary path at each prediction step and this was done to maintain path feasibility whenever there was an obstacle in the reference trajectory. However, the paper did not discuss the effect of multiple planning iterations on operation time. In other words, the paper demonstrated the accuracy and performance of the proposed controller but neglected the feasibility of the solution for real time applications in terms of operating time.

[21] and [30] used neural networks to propose a sequence of control actions required for planned path trajectory. In particular, [21] proposed an approach which combined multiple control algorithms, called sectionalised motion control. The paper's approach combined model predictive control and neural dynamics-based tracking, along with energy-efficient tracking to provide energy efficient solutions that could compensate for limited battery capacity. The algorithm provided robustness, smoothness, and global stability; however, the parameters of the control law were not deeply discussed.

[30] applied delayed neural network (DNN) combined with real time method for model predictive control to solve a generated quadratic problem (QP). The paper formulated path trajectory as quadratic problem in order to plan a trajectory with minimum velocity and control signal, thus saving battery energy and increasing operation time [82]. However, finding the proper controller parameters was a hard task since these parameters were manually tuned and had a great effect on the system stability. Thus, the paper obtained these parameters using multiple iterations in trial and errors. On the one hand, the paper offered good insights about parameters tuning, such as: choosing small values for control horizon and choosing relative values for weighting matrices. On the other hand, though, a noticeable shortcoming was the computational time needed for the application of the algorithm itself, which was not considered.

To sum up, each of the trajectory planning algorithm reviewed here has its own advantages and disadvantages. For example, PID suffers from windup effect, which causes the robot to excessively vibrate at the final joint and this may cause a steady state error. LQR only deals with linear systems and its computational time increases significantly with high dimensional problems. Similarly,

Table 11
Technical limitations of trajectory planning and control algorithms.

Algorithm	Limitations
Proportional Integral Derivative (PID) [20], [22], [24], [26]	• Tuning process • Windup effect • Steady state error
Model Predictive Control (MPC) [20], [22], [23], [24]	• Computational Time
Linear Quadratic Regulator (LQR) [31]	• Deals only with linear systems • Computational time is $O(n^3)$ so it increases with high dimension problems
Neural Networks (NN) [21] and [30]	• High computational time • Requires training data

Table 12
Applications of trajectory planning and control algorithms as mentioned in [20–37].

Applications	No. of papers addressed this application
Autonomous navigation for mobile robots	11
Autonomous cars in urban streets	2
Autonomous cars in rough streets	1
Delivery robots	1
No application mentioned	1
Total	18

Neural Network's speed is affected by its high computational time. For a more general overview of the technical limitations of the algorithms reviewed in this study please refer to Table 11.

With respect to the kinematic models discussed, the papers we reviewed addressed different models, such as: differential drive, double steering, omni directional wheels, and bicycle models. For instance, [22] used a double steering model to enable the robot to successfully navigate through narrow corridors of warehouses (pretty much in the same way as industrial forklifts do). Other researchers, [23–26], used differential drive, which provides easier kinematic equations to make the robot rotate instantaneously around its center of mass. Other papers utilized the bicycle model to resolve the problem of the turning radius, which is the minimum available space required for a robot to make a semi-circular U-turn without skidding. Such model is mainly used in autonomous vehicles in urban environments. On these grounds, we can say that the adopted kinematic models depend mostly on the hardware used and on the level of complexity of the robot. In addition, the majority of the models reviewed appear to work better at low speed rather than at high speed. However, it is worth mentioning that most of the papers we reviewed used simplified kinematic models since warehouse robots need to fulfill the tasks safely rather than quickly.

Although, the main focus of this study is on automated guided vehicles in industrial warehouses, the trajectory planning and control algorithms we reviewed can be applied to other domains as well. One application is autonomous navigation for mobile robots (such as delivery robots). Another application is autonomous vehicles moving in urban roads or through rough terrains. Material handling and transporting is a third area of potential application for such algorithms. Table 12 shows a list of potential applications of these algorithms. For a fuller discussion of this point see also [20–37]. It is worth noting that MPC is utilized almost in all the above-mentioned applications. This indicates that this module is not an ad-hoc solution to a specific application/problem; but rather that it can be applied in different environments and set-ups because of its ability to provide adequate performance accuracy (see Fig. 13).

4.2. AGVs and ethics

A lot of work has been carried out at the intersection between ethics, robotics, and artificial intelligence [83], [84]. Table 13 shows a mini clustering of the application domain for the works included in this SLR. Some of these works specifically target the relation between ethics and AGVs [58], [59]. All of them nevertheless clearly demonstrate a general consensus concerning the importance of taking ethical considerations into account when dealing with automation [85], [86]. Our findings are exemplary in this respect, as most of the works we found and reviewed in this SLR explicitly dealt with identifying problems, issues, and concerns surrounding the large scale implementation of automation in human societies [87].

These problems, issues, and concerns include:

- Inadvertently creating unethical robots in the attempt to make robots ethical [9], [10]. In [9], the authors realized that by embedding ethics in robotics we might end up creating competitive and/or aggressive robots. Two *Nao* humanoid robots (60 cm tall) were used to illustrate how behaviour could be controlled by simply rewriting codes. Specifically, it was shown that changing just a line of the code could change the robot's behaviour from altruistic to competitive. In [10], the authors reflected on the issue of agency, in which autonomous agents might end up making very bad decisions from an ethical standpoint and for these reasons a human kill-switch was proposed to limit the potentially catastrophic outcomes of robots' decisions on humans.

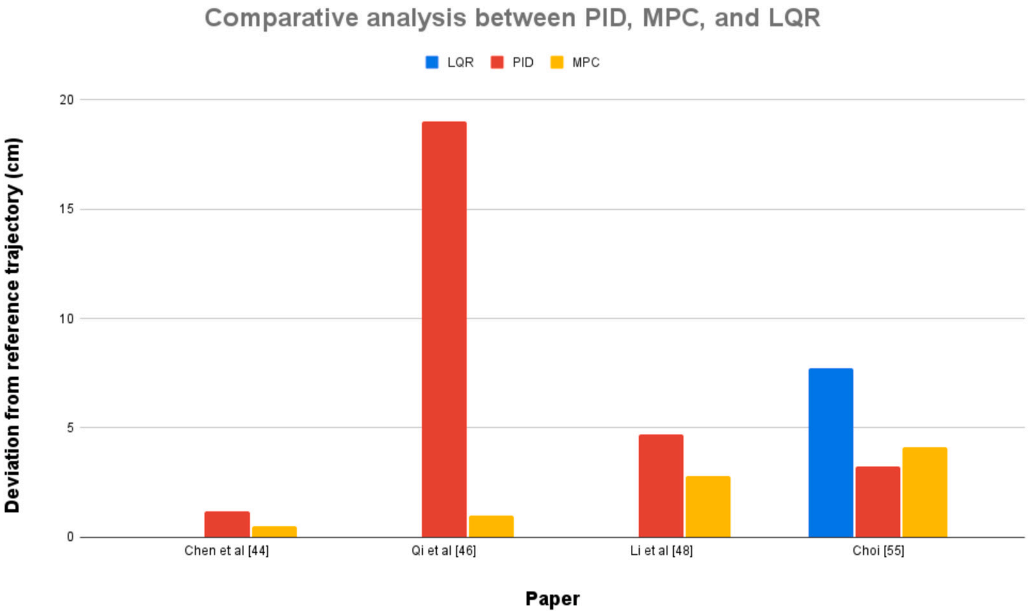

Fig. 13. Comparative Analysis between trajectory control algorithms in terms of deviation from reference trajectory, as recorded in some of the papers we reviewed.

Table 13
Primary focus of discussion in Ethics of Robotics.

Application	Papers
Generic	[61], [59], [65], [64], [10], [67]
Human - AI Teams (HATs)	[62], [63]
Humanoids	[9]
Automated Vehicles	[58], [60], [66]

- Responsibility and privacy, the question of responsibility is closely tied to that of agency, and represents a well known problem for researchers in the field [58], [59], [61]. When the public is asked questions concerning the adoption of autonomous agents (or robots), one of the first issues that comes up is who is going to be held responsible in the face of a bad decision. Think about specific contexts such as autonomous driving vehicles [88], [89], [90], AI medicine [91], [92], and/or criminal justice [93], [94], [95]. This is investigated at length in -for instance- [58] and in [9]. Another important issue as mentioned in [59], concerns privacy. Since humans and robots work in increasingly close proximity and towards the realisation of collaborative tasks, privacy has become a very serious concern for researchers worldwide. Think, for example, about drones [96], [97]. Robots too can seamlessly gather data about humans' behaviours or preferences without the human knowing it [61]. Interestingly, [59] places full responsibility in the hands of engineers and designers and argues that ethics should be inculcated into intelligent autonomous systems prior to their widespread implementation in society.
- Human-Robot interactions, [61], [62] As stated above, humans and robots are increasingly engaged in collaborations, which leads to the problem of defining roles and expectations. [61] provides 4 areas to consider in developing guiding principles for governing ethics in AI. These include human dignity, design, legal, and social considerations. Likewise, [62] offers a model for the creation of human - AI teams that function ethically. The paper argues that implementing ethical principles is difficult in practice. However, by providing a model were team members working with each other share ideas and principles, the team can achieve significant results.
- Policies for the regulation of AI research, [60], [63], [65], [67] There is a tendency to address ethical issues from a normative standpoint [60], which require providing general principles or guidelines for the regulation of human-robot collaborations. Such guidelines are often developed with the intent of teaching researchers and engineering students -who will eventually be tasked with the responsibility of building robots and intelligent autonomous systems- to think ethically. For example, case studies of autonomous driving are studied to figure out how students can think of implementing ethics into such systems. Although it is challenging to find mathematical equations that satisfy all the requirements for a particular ethical problem, thinking in this direction, gives a possibility of adopting ethics by modeling the problem using weights and biases, which may be beneficial in future policy making. [63] indicates that part of the problem of ethics legislation is that legislators and guideline creators don't always have exact knowledge of what happens in the field. That is, in practice, some guidelines break down. Their work highlighted several case studies affected by this limitation. This demands, the authors suggest, that legislators and guideline creators develop expertise in the field in which they want to draft legislation or -alternatively- work in close collaboration with developers and researchers who have the necessary experience in the field. Otherwise, the legislation that are made to safeguard

ethical concerns, ends up being useless in practice, unless it is complemented by insights gained through practice. [65] sees the problem of incorporating ethics into robots from a linguistic perspective. They argue that a good understanding of the language used in ethical thinking is important for embedding ethics into autonomous systems. We also see in this work that thinking is classified as *Heteromerous* (were thinking is emotional, automatic and uncontrolled) or *Autonomous* (were thinking revolves around the actual problem at hand). Here, a method for implementing ethics into autonomous systems is suggested and involves:

- building an ethical decision-making support system;
- integrating a decision – support tool into the autonomous system;
- implementing automatic judgements in trained autonomous systems.

[67] also describes the roles of governments and corporations in the task of ensuring that robots and autonomous systems function ethically.

In this section of our research, we found only 2 papers [9] & [58] that implemented some form of design and simulation to buttress their concerns about the ethics of robots. [9] suggests that manufacturers should strive to apply standards and guidelines, such as those in [98] and [99], for the development of ethical robots.

As a potential limitation of this work, [9] we can mention the fact that the paper recommends running simulations with an ethical robot at a frequency of about 1 Hz. However, robots typically operate at higher frequencies for sensing and motoring.

Nevertheless, we should note that most of the works we reviewed were sound in terms of questions raised and suggestions proffered. For instance, as stated above, [62], suggested a technique for modeling the creation of Human and AI teams and guiding their interactions.

From most of the papers relating to ethics of AGVs, [58], [10], [60], [61], [63], [67] we realize that the society has a lot of concerns about how robots function and how they may impact society; thus there is a need for regulation in the field.

We also found out that ethics and its implementation can be seen from several perspectives, the two primary ones that appeared were *deontology* and *consequentialism*. [60], [62]. When deploying *deontology* in AGVs, the focus is on the aspect that human life safety is the most important feature to preserve. Actions are evaluated on their merits/demerits not based on their results or consequences. Applied to an AGV, it could be a rule such as “the AGV should never pick an object when a human is not present”. It can be seen that in this case, the result of the action is not important, rather the focus is the action in itself. And this action has merits/demerits, which are in turn used to generate rules that guides an AGVs behavior. While *Consequentialism* only cares about the results of actions. Actions are considered, and the actions which have the likelihood of yielding the most favourable results for the greatest number of people are recommended. So, for example, when inculcating ethical behaviour into an AGV, the focus would be on choosing the action that would return the maximum utility for the greatest number of people. Hence, possible results of actions could need to be evaluated by some scale and the most favourable only could ultimately be considered.

Finally, as summarised by [67], governments and corporations are stepping up the ante to ensure there is a sound framework for governance and policy in the field of robotics and AI. The trend is mainly observed in developed countries, which might lead to biases in regulations and policies. However, this shouldn’t necessarily impede developing nations; quite the opposite- more significant efforts should be made towards the inclusion of ethical concerns on a global landscape and, therefore, researchers from developing countries should also take the baton to their own countries.

4.3. Impact of AGVs on the industry

There is a general consensus among the papers we reviewed that the use of AGVs is of considerable significance to the industry. Several authors- using both simulations and hardware implementations- factually demonstrated the extents of this impact [48–53, 55,56]. The perspectives through which these impacts are considered include but are not limited to:

- working hours;
- production rate;
- socioeconomic view;
- as well as flexibility in integration with other devices.

As discussed by [48], [49], [51], AGVs can allow for a significant increase in working hours. [49], compared the performance of traditional AGVs and cassette-based systems (such as the Improved Port Ship Interface) in diverse conditions, including that of moving shipping containers from a QC (Quay Crane) to a container stack. The results of this study showed that for single cassettes, the service time is the same, but with three or more cassettes, IPSIs perform slightly better than traditional AGVs. However employing four cassettes, with an extra IPSI AGV seems to have little effect on ship service time. The QC utilization rate was also measured and used to compare the effects of deploying more AGVs. In general, when more AGVs are deployed the utilization rate increases. For multiple-cassettes-IPSI AGVs, the rate of utilization approaches one, when three or more units are used. However, for traditional AGVs the utilization rate can be close to one for just one AGV. Fig. 14 shows the comparative analysis done by [49] on the service time of traditional AGVs (T-AGV) and IPSI, while Fig. 15 further compares the operating cost of different AGV types.

[51], [52], show that AGVs consistently boost production rates. In particular, [51], compares the effect of various AGVs dispatching algorithms on the rate of production. It showed that in a Flexible Management System (FMS) machine, the average output rate of each of the generated dispatching rules are the same. It also showed that situations of shop locking due to traffic in the shop floor can be reduced by using the number of machines that provide the maximum output rate and that further increasing the number of

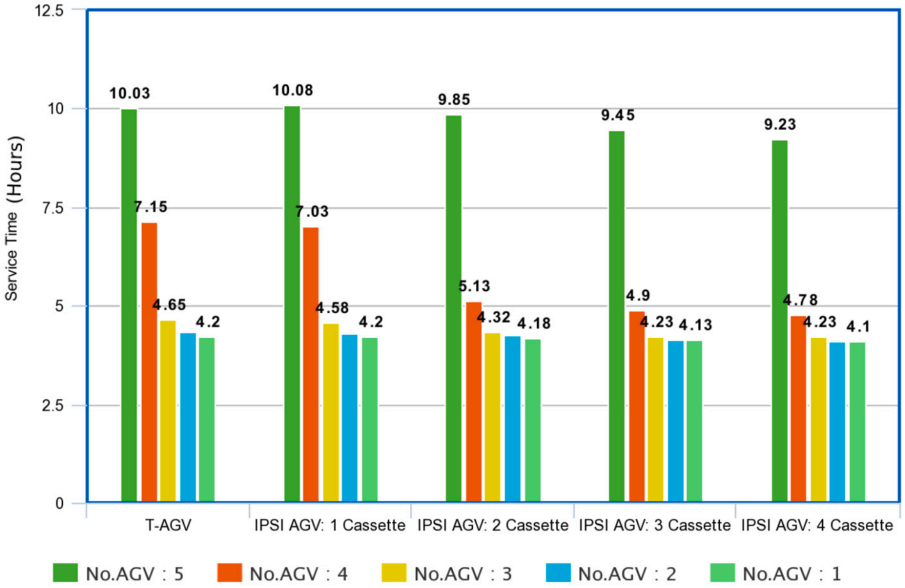

Fig. 14. Comparative Analysis of Average ship service times [49].

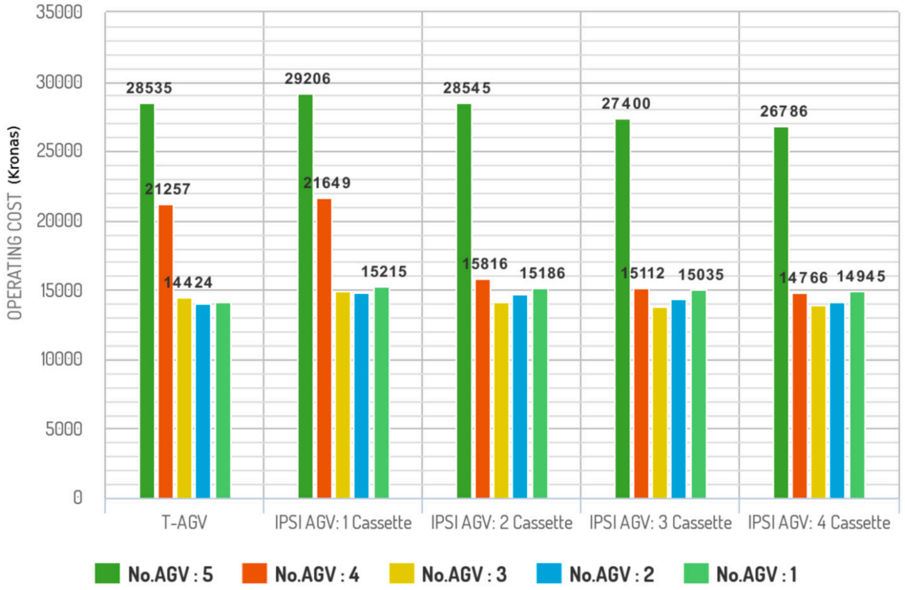

Fig. 15. Comparative Analysis of AGV Operating Costs [49].

AGVs beyond this optimal value leads to an increase in collision rates. [53], [54], explores the socioeconomic impact of the adoption of AGVs, [53] shows a socioeconomic analysis of the use of AGVs by considering configurations such as:

- replacing the forklifts on AGV with improved method for pickup a delivery;
- replacing two operators per shift with AGVs.

The results were studied in terms of:

- buffer Size - the first AGV setup decreased the space needed, but still required more than was available. The second setup freed up that space, which may now be employed to improve vehicle maneuverability;
- distance traveled by the operator - the second arrangement is preferable on this measure since it eliminates the need for the operator to travel vast distances every shift;
- total traveled distance- this is the sum of the distances traveled by the AGV or forklift and the distance traversed by the operators. The number of trips made by the AGV will grow during the first setup, consequently decreasing the number of bags waiting on

Table 14
Socioeconomic Pros and Cons of AGV use according to [54].

Advantages of AGVs	Disadvantages of AGVs
Reduces the necessity human labor, lowering labor expenses.	Large upfront costs – AGVs must be considered a long-term commitment. Initially, manual labor and the use of human-operated machines may be less expensive for a small business. It normally takes awhile for the cost-cutting benefits to become apparent.
Increase in Safety Standards	Costs associated with equipment maintenance. Maintenance, whether scheduled or unscheduled, can hinder output.
Efficiency and consistency Optimisation.	Inadequate for non-repetitive production lines.
Ease of Expansion and upgrade	Inflexibility of Operations: Because of its fixed structure, an AGV can only do one duty at a time.It cannot switch duties at will, like a person can.

the buffer. In the second setup, no extra trips were made; the only thing that varies is the amount of bags transferred in each journey. The ratio of bags moved in every trip will increase as well production wastes;
- output units lost.

[54] showed that work, injury, and mishap expenses have been reduced. Manpower, servicing, and resource expenditures were also reduced. According to [54], Automated intelligent vehicles will reduce distance walked per task by personnel that distribute products by pushing carts in manufacturing plants globally. The following socioeconomic pros and cons of AGV usage are summarized in Table 14 and further analysed in [54]

[55], analyses the impact of AGVs from the perspective of different actors in the industry such as:

- workers and work unions;
- shareholders and managers.

[55], shows that workers and unions are more concerned about preserving current jobs as well as health and technical issues related to safety. Shareholders and managers however care more about financial issues and profits. The only criteria on which all players agreed were greater productivity and efficiency, as well as the establishment of flexible production systems. Thus, the use of AGVs seems to be advantageous only when these concerns are addressed. [56], demonstrated that easiness and flexibility in operations are offered by AGVs. Since the network flow of AGVs can be reprogrammed for production changes, the use of AGVs for warehousing applications facilitates a more flexible manufacturing system [55].

Tasks can be scheduled, and real-time feedback can be received from AGVs, and this can be used to improve accuracy [56]. In addition, because AGVs and many other IoT-enabled wetware have easy connectivity (typically wireless), the need for a centralized control system is reduced [56].

4.4. Performance assessment metrics

The most used metric in the papers we reviewed is *Trajectory Deviation*, which is used in 24% of our papers. More specifically in: [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], which used Model Predictive Control. This is understandable. As we explained in section 3.3, this metric specifies how much the planned trajectory of the robot arm or path varies from the actual path followed by the robot. It actually makes sense for it to be the most used metric in research involving AGVs. Autonomous systems are required to perform their tasks by maintaining their assigned trajectory. This means that for any AGV a deviation from the actual trajectory represents an error, and the extent of this error is tracked by the *Trajectory Deviation*.

The second most used metrics deployed in the study we reviewed is *Accuracy*. Accuracy tells the likelihood of a measurement or prediction being close to the accepted value. This metric was used by 16% of the papers we reviewed.

Other metrics that had fair usage were the *AGV Utilization* (in hours) and the *Production Rate*. These two metrics are discussed in the results section. Used together with the first two metrics we discussed above, they provide a good measure of how well an AGVs are currently performing in the industry.

A few researches such as [20], [22], [26], [27], [28], [31] also used custom quality metrics. As a result, numerous papers were clustered into this group, which we labeled -as noted above- as “Others”. We note that each of the metrics contained in this group was applied to at most 1 paper and was tailored to cater for the requirements of the particular research.

5. Critical review of our research questions

The purpose of this SLR, as the reader may recall, was to determine if AGVs with serial manipulators are reliable solutions for material transportation and handling in the industry. This work was needed to provide businesses and companies with an objective and critical analysis of the effects of adopting this solution. Our research question (RQ) and sub-questions (SRQ 1-3), as presented in section 2.1, explored the challenges faced by these solutions in terms of trajectory planning, safety during collaboration, as well as ethics. Below, we offer a brief critical analysis of each of them, starting with our RQ.

5.1. Analysis of RQ: can industrial corporations depend on AGVs with mounted manipulators as a reliable and robust solution for efficient warehouses automation?

This question allows us to analyse AGVs in three key domains: Efficiency, Reliability and Robustness.

[48], [49], [51], [52] show that AGVs with mounted manipulators are indeed an efficient and reliable solution for efficient warehouses automation, as they provide increased work hours, production rate, as well as reduced personnel costs, and reduction in work mishaps. We must also note that efficient navigation algorithms eliminate the error caused by environmental changes [54]. The robustness of the solution can be considered in, at least, two ways, in terms of:

- scalability and;
- ability to extend the solution to solve other related issues.

As shown by [53] low-cost AGVs increased speed and adaptability, as well as greater precision and performance. This could allow small businesses to increase the number of unit they can incorporate in their operations. In [55] it is shown that since the network flow of AGVs can be reprogrammed for production changes the use of AGVs for warehousing applications facilitates a more flexible manufacturing system. Also, because AGVs and many other IoT-enabled equipment communicate effortlessly, the need for a centralized control system is reduced [56].

5.2. Analysis of SRQ1: in tasks which require human-robot intervention, does collision handling (detection, localization, classification, and reaction) ensure human safety while al- lowing workers to achieve high productivity?

This subresearch question attempted to figure out the effect of collision handling in ensuring human safety in production lines. As illustrated in section 4.1.1, Neural Network algorithms have proven to be reliable approaches in collision handling due to their significant accuracy.

In [41], transfer learning was applied to enhance the performance of neural networks that localize the point of collision between the robot and its human ecosystem. This was pursued with 2 approaches in mind. The first approach predicted the collision point on the internal robot's axis while the second approach localized the point through choosing one of 20 points on the robot's surface. The paper's results showed that performance was improved by more than 36% for classification and regression tasks in comparison to previous studies.

In [45], the authors proposed an approach for achieving a safe human-robot interaction in a dynamically changing environment. Based on the type of intervention, the current state, and the target trajectory, the robot should choose the best appropriate reaction. The paper presented an algorithm for collision identification and reactions based on Neural Network and finite state machine, and it was found that neural networks demonstrated the reliability of the proposed approach in contact estimation and localization.

In [46], a new approach was designed to allow robots to learn from demonstrations. Given a video of a human executing a task as an input, the robot had to learn the temporal structure of the activity shown in the video and transfer the model in form of commands for execution. To do so, the paper introduced a Convolutional Neural Network (CNN) for object detection, which was used to estimate the shape and location of human hand in the training videos displayed. This allowed the robot to eventually predict the future movements of the human hand as well as the objects' spatial locations. This approach showed the possibility of introducing a way for safe and more precise human-robot collaborations, since it could predict the future movements of human hand, which can be useful to classify accidental collisions.

5.3. Analysis of SRQ2: does AGVs achieve optimal trajectory planning with model predictive control (MPC)

This question was about the control methods used for automated guided vehicles (AGVs) and whether model predictive control (MPC) could be considered as the optimal controller for them. In the literature, there are multiple control algorithms applied to AGVs. We found that the most used ones are:

- PID [20], [22], [24];
- Neural Network [21], [30];
- Convex optimisation [25], [28], [29], [30], [36];
- Model Predictive Control [23], [26], [27], [28].

As stated in section 4.1.2, each one of the above mentioned control algorithms has their own drawbacks, ranging from high deviations to impractically large computational time. However, we should also note the benefits of adopting MPC, as it provides design flexibility and proper performance even in complex environment, as shown by [20], [23], [37]. MPC is also used for both path planning and tracking [22] and can be successfully deployed to avoid both dynamic and static obstacles [24], which are usually abundantly present in warehouses. In addition, MPC can be integrated with other techniques (such as energy efficient tracking and neural dynamics based tracking [22], state classification model (SCM) and state transition (ST) [34], computer vision algorithms [26], [35], and various other optimisation techniques [37]). Another advantage of MPC, that is mentioned in the literature we reviewed, consists in its ability to be applied in different mobile robots structures and situations. For examples, MPC was applied -quite successfully- to both single steering [31] and double steering robots [22]. It also offered apt performance in multiple robots' cooperation [25], high speed applications [28], and at handling limit constraints [34].

It is worth noting that we identified three papers that illustrated the critical yet delicate process of tuning MPC parameters, a relatively new trend in the literature. The first paper [20] found that the tuning of these parameters can be done through simulation if the simulation truly reflects the nature of the real environment. The second paper [21] explained the important role of tuning these parameters and how they can affect the overall controller performance; yet, it did not give concrete steps for developing such a procedure. The third paper [30] demonstrated that tuning can be attained using multiple iterations and also provided good practical insights on how to pursue them (e.g., choosing small values for control horizon or choosing relative values for weighting matrices).

Summing up, we can confidently assert that MPC increases the efficiency of AGVs in warehouses and is superior to other control algorithms in terms of accuracy and computational time. Since it gained very high research interest in the past ten years, MPC is also becoming more flexible and it bears the promise of being integrated with other controllers for even better performance.

5.4. Analysis of SRQ3: are there any potential societal benefits from incorporating ethical considerations in the usage of AGVs?

From the studies we reviewed it emerged that society may well benefit from incorporating ethical legislation in the usage of autonomous systems. The entire debate going on concerning autonomous systems and ethics revolves around how the society will be affected, positively or negatively.

As stated by [58] and [64] significant swathes of society are very skeptical about the widespread application of autonomous systems in human settings, as they point out potential safety issues in the increased societal adoption of unsupervised machines. A crucial point that emerged concerned the relation between autonomous agent and trust; this trust naturally depending on whether the systems could ever be able to function within our moral set of values and ethical principles.

As we discussed in [61], social robots can be even more invasive than most mainstream internet apps. The worst thing is that people are hardly aware of this intrusion or of the silent manner in which these robots might gather data. Thus, this gullibility could be exploited to produce regulations for autonomous systems that could greatly benefit society, by demanding such systems to pursue social and moral good.

An additional danger presented and discussed by [9] concern the development of unethical robots; clearly legislation in how ethics is implemented in autonomous systems should ensure that we don't end up creating dangerous (e.g., aggressive) robots, which may utilize their ethical knowledge in a detrimental way.

Incorporation of ethical legislation into transnational guidelines for the development of Autonomous Systems is also of paramount importance, as it will ensure that ethical concerns are fished out and properly addressed internationally, rather than being swept under the carpet.

5.5. Synoptic summary

In this subsection, we offer schematic summarises of the research questions proposed in this SLR. Such summarises are based on the major findings we obtained. Generally speaking, in this research, we tried to offer a concise critical analysis for companies, warehouses, and businesses that would like to adopt AGVs with mounted serial manipulators as a technological solution in their environment. We also tried to offer some insights and preliminary reflections about various other aspects of AGVs with mounted serial manipulators, such as: a. the possibility of successful human-robot interaction; b. issues surrounding trajectory planning and control; c. the potential socioeconomic impacts concerning the adoption of AGVs as well as d. its potential ethical repercussions. A short summary of the main point discussed in this work follows below, in bullet points.

- Industrial corporations can profitably use AGVs with mounted manipulators because such systems provide an efficient and robust solution to warehouses handling and transportation problems.
- Model predictive control increases the efficiency of AGVs in warehouses and is superior to other control available algorithms in terms of accuracy and computational time.
- Society can benefit from incorporating ethical considerations in automation systems and by applying sound frameworks for governance and policy making in the field of robotics and AI.
- Such frameworks may gradually eliminate people's concerns about robots (e.g., trust) and therefore result in more confidence towards the adoption in society of robotic solutions.

6. Limitations, threats to validity, and review assessment

In this section, we list some of the shortcoming that may affect the objectivity and academic soundness of our research. By doing so, we offer a critical and objective overview of the weaknesses characterising our work. We note that pointing out these limitations may pave the way for future progresses and improvements in the field.

6.1. Limitations

We start by reviewing factors that may hamper or restrict the breath and scope of our research. Such factors include:

1. **Limited number of databases** can be seen as a potential limitation of any SLR. As stated before in section 2.2.2, we used five main databases for our research (Google scholar, Springer Link, IEEE Xplore, ACM Digital Library, Elsevier). These databases are

the most widely used in our discipline. In addition, one of them - Google Scholar- aggregates data from all databases available. We believe our selection of databases ensured soundness and variety to our searches. Therefore we don't think that this is a significant limitation for this study.
2. **Grey literature is not used**. Although grey literature is increasingly used in research studies and even in SLRs, we did not use it in our own, and preferred sticking with high quality peer reviewed publications, as shown in section 2.4.
3. **All papers reviewed were written in English**. This requirement may affect the diversity of our literature log [68]. Although we value diversity in our research, as shown in (Fig. 6), this constrains is beyond our hands since most of the papers in this subject are written in English and top tier journals only accept submissions in English.
4. **Impact of automation on employment rates is not covered.** This is a more serious concern, since it points to a limitation in the scope in our work. We focused only on human robot interactions; hence, we tried to answer the question of whether robots are safe for humans in the workspace. Although possible economic impacts are mentioned in section 4.3, the effect on employment rate is not discussed extensively, since it does not fall within the scope of this research.
5. **Comparison with other types of mobile robots is not mentioned.** Even though comparative analysis of control algorithms of AGVs has been discussed thoroughly, no comparison was made between AGVs and other robots used in warehouses automation such as mobile industrial robots (MIR). We believe that this issue can not be seen as a critical limitation to our report since AGVs are nowadays the most widely used robots in warehouses worldwide. This is due to their fixed infra-structure, which makes them a less costly solution if compared to MIRs.

6.2. Threats to validity

Next, we identify the main factors that could affect the validity of our research. According to [69], there are seven different types of biases (publication, time lag, multiple (duplicate) publication, location, citation, language, and outcome reporting) that may affect anyone's work. However, only one of those biases is applicable to our study, we believe:

- **Language bias**, which occurs when the research is biased toward publications written in a certain language. This bias can be attributed to our research. However, as noted above, 6.1 English is the language of science and most -if not - all research papers are affected by it. Hence, in the economy of things, we believe it can be overlooked.

6.3. Review assessment

In this last subsection, we carefully assess, following the best norms of our discipline [70]- the consistency, overall soundness, and reliability of our work by asking four basic questions, as follows:

- **Are the inclusion/exclusion criteria objective and reasonable?** The answer to these questions lies in the protocol section 2.3, in which we clearly listed all the inclusion and exclusion criteria used in our research. This step was fundamental to get our final reading log and to ensure that our results are focused, on point, and credible.
- **Is the literature search likely to have covered all relevant studies?** As stated previously, we comprehensively reviewed most of the literature available to us from 2007. We already provided a justification for choosing 2007 as the starting point of our SLR above.
- **Did the reviewers assess the quality/validity of the included studies?** We did perform a quality assessment in section 2.4 to ensure the quality of our sources was up to standard. 86% of our papers are classified as good or excellent according to the five testing questions we developed.
- **Were the basic data/studies adequately described?** We created a detailed reading log in which we gathered all relevant information about each of the papers we reviewed, including the main findings, possible shortcoming, and possible developments. This delicate procedure made sure that the date we collected was carefully scrutinized by all group members. We must also note that all the researchers involved in this study cross-check their own work several times and were actively involved in the process that lead to the procurement and subsequent assessment of the data gathered. This was done to increase reliability and minimise the possibility of biases and mistakes.

7. Conclusion

The goal of this study was to assess and evaluate the role of automated guided vehicles (AGVs) with mounted serial manipulator in the industrial automation field. More specifically, our study focused on answering the proposed research question and sub-questions as listed in section 2.1.

After reviewing 50 papers, our results showed that industrial corporations can effectively and reliably use AGVs with mounted manipulators as a solution for systems automation due to their precision and high speed. Moreover, the findings of our SLR highlighted that there are multiple algorithms can be implemented to answer our research questions. For example, Neural Networks have shown effectiveness in collision handling tasks for safer collaboration tasks. We also showed that model predictive control is an efficient approach for vehicles optimal trajectory planning in terms of accuracy and computational time. Finally, we concluded that society could benefit from incorporating ethical legislation in automation systems and called for the implementation of a more comprehensive framework for governance and policy-making in the field of robotics and AI.

We understand that this topic is very complex and multifaceted; however, we hope that this systematic literature review (the first of its kind in the field) will widen researchers' horizons on this topic, while providing original grounds for more detailed explorations into the field of industrial automation.

For this reason, in the future, we plan to conduct a series of empirical studies, in which we will attempt to combine algorithms for trajectory control (such as MPC, LQR, and PID) with algorithms for human-robot interaction (such as Neural Networks and Computer Vision). Nevertheless, since all the papers reviewed in this SLR used different set-ups as well as various types of equipment, we will try to focus on a very specific type of hardware (mobile manipulator). This process will allows us to further test and validate the algorithms reviewed in this study, while providing the conceptual palette needed to replicate, verify, and ultimately corroborate the results presented in our work.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Declaration of competing interest

The authors have no conflict of interest to declare.

Data availability

Data will be made available on request.

Appendix A

Table 15: PRISMA 2020 Checklist
Template taken from: [77]

Table 15
PRISMA 2020 Checklist.

Section and Topic	Item	Location where item is reported
TITLE		
Title	1	1
ABSTRACT		
Abstract	2	1
INTRODUCTION		
Rational	3	1
Objectives	4	2.1
METHODS		
Eligibility Criteria	5	2.3
Information Process	6	2.2.2
Search Strategy	7	2.2
Selection Process	8	2.4
Data Collection process	9	2.3
Data items	10	3.2
Study risk of bias assessment	11	6.3
Effect measure	12	-
Synthesis methods	13	2.4
Reporting bias assessment	14	6.2
Certainty assessment	15	6.3
RESULTS		
Study selection	16	2.3
study characteristics	17	3.2, 3.3
Risk of bias in studies	18	6.1
Results of individual studies	19	5
Results of syntheses	20	5
Reporting biases	21	6.2
Certainty of evidence	22	6.3
DISCUSSION		
Discussion	23	4
OTHER INFORMATION		
Registration and protocol	24	2
Support	25	-
Competing interest	26	-
Availability of data, code and other materials	27	Appendix A

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