A Comprehensive Study on Artificial Intelligence Algorithms to Implement Safety Using Communication Technologies

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Abstract The recent development of artificial intelligence has increased the interest of researchers and practitioners towards applying its techniques into multiple domains like automotive, health care and air space to achieve automation. Combined to these applications, the attempt to use artificial intelligence techniques into carrying out safety issues is momentarily at a progressive state. As the artificial intelligence problems are getting even more complex, large processing power is demanded for safety-critical systems to fulfill real-time requirements. These challenges can be solved through edge or cloud computing, which makes the communication an integral part of the solution. This study aims at providing a comprehensive picture of the state of the art artificial intelligence based safety solutions that uses different communication technologies in diverse application domains. To achieve this, a systematic mapping study is conducted and 565 relevant papers are shortlisted through a multi-stage selection process, which are then analyzed according to a systematically defined classification framework. The results of the study are based on these main objectives: to clarify current research gaps in the field, to identify the possibility of increased usage of cellular communication in multiple domains, to identify the mostly used artificial intelligence algorithms and to summarize the emerging future research trends on the topic. The results demonstrate that automotive domain is the one applying artificial intelligence and communica-

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The advances in the *Artificial Intelligence (AI)* field enabled different software systems to achieve higher levels of automation. This evolution moves towards a less dependence on human intervention for an intelligent system to make decisions [4]. This also brings the possibility to have systems that interacts with humans in different manners. However, autonomy and interaction mechanisms must be designed in a way to ensure safety of the whole ecosystem. Consequently, *safety* becomes a key component of AI-based autonomous systems [16]. Some examples of these systems include in which autonomous agents are involved that can operate in a heterogeneous environment, intermixed with humans, and perform a broad spectrum of tasks (for example general purpose robots [25], autonomous vehicles [7], Internet-of-Things (IoT) in industry 4.0 [52], and drones [49]). These smart autonomous agents are equipped with sensors and AI to operate in an automated or semi-automated fashion.

The smart autonomous agents are part of a big and complex smart *Cyber Physical System (CPS)* in which they cooperate with each other and humans in a safe, autonomous, and reliable and trustworthy manner [23]. These agents are used in a vast set of application domains ranging from automotive industry [7], robotics [22], air space using unmanned aerial vehicles (UAV) [18], agriculture [29], healthcare [54], smart manufacturing [52], telecommunication [50], Internet-of-Things (IoT) [27], and more. AI algorithms usually require efficient hardware processing capabilities to train and execute, which is not always possible to do on the agent or device which usually have limited resources. Additionally, for safety-critical systems there are mostly real-time requirements to execute the algorithms. As an example, the processing of large amount of sensor data generated by autonomous vehicle must be made in real-time to avoid any accident. Thus, there is a need for AI-based safe operations and, at the same time, for powerful processing hardware.

All these challenges make the *communication* to remote agents and remote processing infrastructures (e.g. edge or cloud computing) an integral part of the whole system. Based on the system’s demands, the communication needs could be very different. Two main types of communication technologies that play a significant role in such systems are *cellular* [49] and *non-cellular communications* [42]. These technologies must fulfil system requirements, otherwise,
communication can introduce safety risks by not making the system able to respond in a precise and timely manner.

Notably, a strong correlation between AI, safety and communication technologies exist and the progresses made in one field have a direct impact on the others [43]. Traditionally, these fields were treated separately, but more recently a plenty of work covers the integration of AI using communication technologies to implement safety in different application domains. This is reflected in the publications made in recent years, which supports the convergence of these areas [44].

**Paper Contributions:** The main goal of this study is to identify, classify, analyze and to identify gaps in the state-of-the-art research publications that utilizes AI algorithm(s) using communication to achieve safety in diverse domains. The study exclusively focuses on software aspects. To target this goal, a structured map of the available research literature is constructed by conducting a well-established methodology from Software Engineering research community called systematic mapping [59]. Using the systematic mapping process, we searched and selected relevant studies, defined a classification framework, applied the classification on the shortlisted studies in relation to various AI algorithms and communication technologies used in different domains to implement safety, and analysed and discussed the obtained results.

The main contributions of this study are:

- A systematic review of current methods or techniques of AI and communication technologies applied in different domains to implement safety and to identify gaps in it;
- An investigation on the potential possibility of replacement of non-cellular communication technologies by the cellular ones to implement AI-based safety;
- A discussion of the current challenges and emerging future research trends on the topic, from both industry and academia perspectives, and to identify the interest of the industry on the topic;
- Investigate the maturity of the performed research and the research approaches in general by considering the research type;
- Observe trends in the community’s research focus by considering the research contribution for finding the increased focus on developing new methods, models or tools;

To the best of our knowledge, this paper presents the first systematic investigation into the state of the art on safety using AI and communication technologies in different domains.

**Paper outline:** The paper is organized as follows: Section 2 presents an overview of related studies that covers AI for safety or communication; Section 3 describes each step of the process of the systematic mapping used in the current study; Section 4 presents the classification schemes developed in this study; Section 5 analyses the mapping results and provides the plots generated in the mapping process; Section 6 describes the threats to the validity of this work; and finally Section 7 concludes this systematic mapping.
2 Related Works

There are many efforts in the literature to provide a comprehensive study that cover AI to implement safety. Neural networks (NNs) and more specifically, deep learning (DL) is a technique that is widely adopted in a variety of safety related problems. More recently, Huang et al. [23] presents the growing interest to train safe DL models for critical applications (e.g. autonomous vehicles and autonomous surgery). The work of Huang explores a variety of strategies to ensure model safety, such as interpretability, verification and testing. Tran et al. [48] presents an overview of verification methods to ensure the correctness of AI in safety systems. Fayyad et al. [17] presents a study on the use of deep learning based algorithms for perception, localization, and mapping used in autonomous vehicle systems in short-range or local vehicle environments.

Reinforcement learning (RL) is an AI technique that is getting more popular in safety applications. For instance, in [20] is made an overview of studies that employ a particular RL method that incorporates safety, named safe RL, which basically investigates techniques to ensure safe exploration. The combination of computer vision and safety also brought the interest of researchers to elaborate survey works as in [3]. Clustering is also another AI algorithm that is getting attention, specially inside vehicular communication problems [12]. There are also works that make analysis of safety in a more general context of AI. To exemplify, [32] presents a comprehensive study of AI ethics and safety, and compiles papers related to this field. While [16] reunites studies that discusses the safety of Artificial General Intelligence (AGI) algorithms. It covers studies that bring ideas of how AGI can be designed in a safe manner.

Additionally, there are literature review studies that analyse safety in different application domains. [22] discusses different solutions proposed by the scientific community to guarantee safety when interacting with robots. Similarly, [7] presents strategies to avoid accidents in intelligent transportation systems (ITS) when dealing with unforeseen situations. AI in healthcare is a topic that is covered in the review article of [54], which brings the usage of different AI methods and data infrastructure for medicine related problems. [15] examines the perceived benefits and risks of AI medical devices with clinical decision support features from consumers’ perspectives using an online survey based data from 307 individuals, and reveals that technological, ethical (trust factors), and regulatory concerns significantly contribute to the perceived risks of using AI applications in healthcare. Agriculture is yet another area that has large application of AI, specially in problems related to automation as raised in the review study of [29]. This work also highlights the use of communication technologies in the agricultural automation, specially in those solutions that involve Internet of Things (IoT).

Besides not having survey works covering safety in communication domain, there are plenty of studies that explore AI in communication domain. [37] covers different AI solutions employed together with vehicle-to-everything (V2X) communication to leverage traffic safety and efficiency. While in [4] AI is targeted for robot communication to enable complex decisions in a efficient way. In
the cognitive radio field, which deals with dynamic reconfiguration of telecommunication networks, there are surveys studies that discusses the application of different AI algorithms as in [9] and [1]. Self-organizing network (SON) is a topic related to automation of telecommunication tasks that have derived literature review studies investigating the usage of different AI techniques [31]. The recent advent of 5G also brings survey that involves the employment of AI [36]. [44] study the use of convolutional neural networks (CNN) and their variants for object detection, localization, and classification in modern 5G enabled ITS. Moreover, there are also studies that narrows down to specific machine learning techniques, mainly deep learning [14] and reinforcement learning [34].

Another perspective explored by the studies is the relationship between the communication technologies and the different application domains. For example, there are survey studies that investigate different communication architectures and strategies used in the health care domain as presented in [27] and [2]. There are also studies that make a wider analysis of a particular communication technology in different domains. In [49], the impact of 5G communication is addressed in intelligent transportation, drones and healthcare. With the rise of Industry 4.0, the communication in manufacturing field also has been investigated in [52] and [55]. Other studies cover communication needs for specific machines, such as automated grounded vehicles (UAV) [18] and drones [43].

The current study takes a different perspective from the previous works by providing analysis of studies that make use of AI and communication technology to provide safety in diverse domains. As shown in this section, these three key terms (AI, communication and safety) have been used separated or combined, but their simultaneous usage is neglected and is not covered so far to the best of our knowledge. As AI is getting more and more used in different fields, the safety of its application have a proportional importance. Likewise, communication and AI is even more related as both depends on each other either to provide an efficient communication or ensure the real-time execution through cloud computing.

3 Study Method

The systematic mapping (SM) method is employed in this study to understand how the field of AI-based safety enabled by communication technology is evolving. Essentially, SM performs an overview of research works to answer key research questions of this field. The SM analysis is also supported by visual maps that bring temporal and quantitative perspectives of different aspects of the study field. The SM process can be performed in different manners, like systematic literature review [30], or systematic mapping study [38]. This study follows the guidelines from Peterson et. al. for conducting systematic mapping studies, first presented in 2008 [38] and then improved in 2015 [39] and divide the overall process into three main classical phases for systematic mapping.
studies: planning, conducting, and documenting, and then further divide each phase into multiple steps as depicted in Figure 1.

![Fig. 1: Overview of the research method process and its main activities. Diagram adapted from [10].](image)

**Planning:** The first phase in the study process and it aims at (i) demonstrating the need for performing a mapping study on the use of AI algorithms using communication in diverse domains to implement safety; (ii) defining the main research questions (see Section 3.1); and (iii) defining the search string and selecting the scientific online digital libraries to perform the systematic mapping study (see Section 3.2).

**Conducting:** This phase consists of the following steps:

(i) **Study retrieval:** The final search string is applied to the short-listed well-known academic search databases (see Section 3.3). The output of this activity is a comprehensive list of all candidate studies resulting from the search in the digital libraries.

(ii) **Study selection:** Duplicates are removed from the candidate entries. Then entries are filtered first using the inclusion and exclusion criteria, and second using the Title-Abstract-Keywrods (T-A-K) criteria (see Section 3.4) to obtain the final list of relevant studies to be considered in later steps of the study.

(iii) **Classification scheme definition:** The next step in the systematic mapping study is to establish how the relevant studies are going to be classified. The classification scheme are designed to collect data for addressing the research questions [51] as formulated in the planning phase. The process of defining the classification scheme is described in Section 3.5 and the obtained classifications are explained in Section 4.

(iv) **Data extraction:** Each selected relevant study is analysed and then information are extracted. For this purpose, a data extraction form is generated.
and filled with the extracted information in order to be analyzed during the next step. More details are presented in Section 3.6.

(v) **Data analysis:** Comprises the last step of conducting phase. A detailed and comprehensive analysis of the extracted information (performed in the previous step) is made in the form of different maps (i.e. plotting charts such as bubble charts, pie charts and graphs) and an analysis is made, with the aim to address each research question of the study. The details about this activity are in Section 3.7.

**Documenting:** The last phase in the study process aims at (i) generating a detailed analysis of the extracted information in the previous phase and thorough explanations of the obtained results as presented in Section 5; (ii) the analysis of possible threats to validity see Section 6.

### 3.1 Definition of Research Questions

The main goal of this systematic mapping study is to observe and analyze the use of AI algorithms implementing safety using communication technologies in different application domains. As part of analyzing, we aim to investigate research gaps by highlighting topics where research results are lacking, and identify the potential for cellular communication adoption for industrial use. This goal is refined into the set of the following research questions (RQs):

**RQ1a:** What types of AI algorithms are used to implement safety?

**RQ1b:** What kind of communication technologies are mostly used to implement safety?

**RQ1c:** Which are the main application domains where these AI algorithms find applicability in order to provide safety?

- **Objective:** This three-part question aims to obtain from the current state-of-the-art the types of AI algorithms, communication technologies and the domains where they are applied to implement safety.

**RQ2a:** What are the current research gaps in the use of AI to implement safety using communication technologies?

**RQ2b:** Which application domains bring the opportunity to use cellular communication to implement AI-based safety?

- **Objective:** The aim of this two-fold research question is to (i) identify the gaps in the current research area on the use of AI algorithms and communication technologies in different application domains; and to (ii) investigate in different domains which of the non-cellular communication technologies can potentially be replaced by the cellular ones to implement AI-based safety.

**RQ3a:** What is the publication trend with respect of time in terms of cellular and non-cellular communications technologies?
RQ3b: What is the publication trend with respect of time in terms of AI-based safety?
- **Objective**: This two-part question aims to illustrate the current state of the topic and establishes a better understanding regarding the future trends.

RQ4: What type of research contributions are mainly presented in the studies?
- **Objective**: This research question aims to reflect new methods, tools or techniques, that might be further developed by researchers in this area.

RQ5: Which are the main research types being employed in the studies?
- **Objective**: This research question aims to understand the importance of the research approach and what it represents.

RQ6: What is the distribution of publications in terms of academic and industrial affiliation?
- **Objective**: The goal is to know at what extent the industry is interested on the topic.

Research questions determine the main objectives of the systematic mapping study, and thus this step delineates how the remaining steps of the study process will be performed, specially the search process, the data extraction process, and the data analysis process.

### 3.2 Search String and Source Selection

This section aims at the identification of the search string and the selection of database sources to apply the search in order to achieve a good coverage of existing research on the topic and have a manageable number of studies to be analysed as required to perform systematic review [30] and systematic mapping study [39]. The search string is a logical expression formed by a combination of keywords that is used to query the research databases. A relevant search string should return research works that address the study’s RQs. The proper selection of the research database sources is also primordial for a good coverage, and for this, database sources related to both engineering and computer science were selected. The following sections detail the search string formulation and the database source selection:

#### 3.2.1 Search string

In this work, the Population, Intervention, Comparison and Outcomes (PICO) method proposed by Kitchenham and Charters [30] is used to define the search string. PICO is based on the following set of criteria:

- **Population**: The category, application area or a specific role that covers this systematic mapping study.
Table 1: Composition of search string.

- **Intervention**: Methodology, tool or technology that is applied in the study field.
- **Comparison**: Methodology, tool or technology that is used to compare in the study field.
- **Outcome**: The expected consequences (i.e. outcomes) of this study.

For this systematic mapping study, PICO was defined as follows:

- **Population**: AI-based safety algorithms.
- **Intervention**: Communication technologies.
- **Comparison**: No empirical comparison is made, therefore not applicable.
- **Outcome**: A classification of the primary studies, which indicates the role of AI algorithms to implement safety using communication technologies.

Analysing the **Population** and **Intervention** categories, relevant keywords are identified: “AI algorithm”, “safety” and “communication technology”. From that, the following sets are derived, which groups synonyms and similar terms of the keywords:

- **Set 1**: Terms related to “safety” field.
- **Set 2**: Terms related to **Intervention** are searched for.
- **Set 3**: Terms related to the classification of AI algorithms are searched for.

Based on PICO and research questions, the following search string shown in Table 1 was composed. In this search string composition, logical operators (AND and OR), keywords, synonyms of the main keywords and terms related to the respective field, where the classification process will be based on, were taken into consideration to be used. It has to be noted that, the use of the search string may not be precisely the same for every digital library depending on their query syntax.

The final search string that is used to retrieve the studies is derived by the combination of **Population** and **Intervention** search strings obtained during the PICO process. The resulting string, presented in the Table 2, is formed by the association of three logical expressions separated by **AND** operator. Each expression represents “safety”, “AI” and “communication” fields.
safety AND ( "artificial intelligen*" OR "Machine learning" OR "regression analysis" OR "supervis* learning" OR "unsupervis* learning" OR "clustering algorithm" OR “fuzzy logic” OR “image process*” OR “deep learning” OR “computer vision” OR “neural network” OR “augmented reality” OR “virtual reality” OR “speech recognition” OR “image recognition” OR ontology OR “state machine” OR “cognitive architecture” OR “language processing” ) AND ( communicat* OR cellular OR 2G OR 3G OR 4G OR 5G OR LTE OR GSM )

Table 2: The search string is formed by three logical expressions combined by **AND** operator.

### 3.2.2 Source selection

In order to find the existing relevant occurrences for this topic, four scientific online digital libraries were chosen: *IEEE Xplore Digital Library*¹, *ACM Digital Library*², *Scopus*³, and *Web of Science*⁴. According to P. Brereton et al. [11], these libraries are known to be valuable in the field of software engineering when performing literature reviews or systematic mapping studies. Additionally, these libraries exhibit a high accessibility and support the export of search results to computationally manageable formats.

### 3.3 Study Retrieval

This is the first step in the conducting phase, in which the finalized search string is used to query the studies from the short-listed libraries with some small necessary adaptations in its syntax. Table 3 describes the adaptations made in the search string for each online digital library. The query resulted in a total amount of 8760 potentially candidate studies, mostly from the Scopus and IEEE databases. Table 4 presents the respective number of studies for each database.

### 3.4 Study Selection

This step is used to determine the relevant studies matching the goal of the systematic mapping study. The automatic search results from digital library

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¹ IEEE Xplore Digital Library [Online]. Available: [https://ieeexplore.ieee.org/](https://ieeexplore.ieee.org/)

² ACM Digital Library [Online]. Available: [https://dl.acm.org/](https://dl.acm.org/)

³ Scopus [Online]. Available: [https://www.scopus.com/](https://www.scopus.com/)

⁴ Web of Science [Online]. Available: [https://www.webofknowledge.com/](https://www.webofknowledge.com/)
### Digital Library | Description
---|---
IEEE Xplore Digital Library | The search string is applied on text box of “Command Search” found in the “Advanced Search”.
ACM Digital Library | The search string is performed in the “Advanced Search”. Since the number of occurrences was very large, the search was divided into three parts and applied within Title, Abstract and Author Keywords. In “View Query Syntax” → “Edit Search” the parts are connected with operator AND by default; it is changed to OR.
Scopus | In “Advanced Search” of Document Search, the search string is applied as three sub-strings.
Web of Science | In the text box of “Advanced Search” the string is applied. The string “TS=’” is added in the beginning of the string, where TS=Topic.

Table 3: Query process of each digital library.

| Digital Library                  | Search Results |
|----------------------------------|----------------|
| ACM Digital Library              | 413            |
| Web of Science                   | 1361           |
| Scopus                           | 2885           |
| IEEE Xplore Digital Library     | 4101           |
| **Total**                        | **8760**       |

Table 4: Amount of studies retrieved from each database and the total number of potentially candidate studies.

might have inconsistencies, due to presence of ambiguities and lack of details in the retrieved studies. Therefore, relevant studies must be extracted by following a selection process. The first step is the removal of duplicates as same studies can be retrieved from different sources. To identify these duplicates and remove them, the EndNote tool was applied. This step removed 2219 studies and leaving 8760 studies after this step.

The selection process continues with the criteria definition and selection of relevant studies. Details are provided below.

3.4.1 Criteria for Study Selection

The study selection criteria step is used to determine the relevant studies that match the goal of the systematic mapping study according to a set of well-defined inclusion (IC) and exclusion criteria (EC). To classify a study
as relevant, it should satisfy all inclusion criteria at once, and none of the exclusion ones. The applied inclusion and exclusion criteria are presented in the [Table 5](#).

| ID | Criteria |
|----|----------|
| IC 1 | Studies implementing safety. |
| IC 2 | Studies presenting AI algorithms in different application domains. |
| IC 3 | Studies proposing the use of any type of communication technology. |
| EC 1 | Studies that are duplicate of other studies. |
| EC 2 | Studies that are considered secondary studies to other ones. |
| EC 3 | Studies that are not peer-reviewed, short papers (4 pages and less). |
| EC 4 | Studies that are not written in English language. |
| EC 5 | Studies that are not available in full-text. |

Table 5: Inclusion (IC) and exclusion (EC) criteria.

3.4.2 Evaluation of Study Relevance

These inclusion and exclusion criteria were firstly applied on the Title-Abstract-Keywords (T-A-K) tactic of each study to determine its relevance to the RQs. The relevant studies were classified according to the following terminology:

- A study is marked as relevant (R) if it meets all the inclusion criteria and none of the exclusion criteria.
- A study is marked as not-relevant (NR) if it does not fulfil one of the inclusion criteria or meets at least one of the exclusion criteria.
- A study is marked as not-clear (NC) if there are uncertainties from T-A-K analysis.

If a study is labeled as NC, which could be due to the lack of information in T-A-K fields, the full-text (title, abstract, keywords, all sections and appendices, if any) skimming is conducted to decide about its inclusion in our set of relevant studies. From a total of 105 NC studies, 25 studies were evaluated as R after full-text skimming, bringing the mapping study to 601 relevant R studies. To better visualize the selection process, Figure 2 illustrates the detailed workflow of the whole process with the amount of studies obtained in each phase.

One of the sub-steps of the selection process described in the guidelines is to perform snowballing sampling. According to [28], snowballing is a method of identifying additional relevant studies after obtaining the primary ones. Considering the slightly large number of papers obtained from the criteria described above, it was decided not to adopt snowballing in this systematic mapping study.
3.5 Classification Schemes Definition

This step in the systematic mapping study establishes how the relevant studies are being classified to address the research questions presented in the previous section. For that, we first need to define a classification scheme, and for this purpose **six main facets** are added (which are associated with research questions).

The first two of the main facets are *type of research contribution* and *research type* which are adopted unaltered from categorization presented in [38] and [50]. The two used methods to develop more facets for our classification are *initial categorization* and *keywording*. The initial categorization is based on the discussions with experts from their respective fields and have an initial set of facets based on acquired knowledge from the experts. Few regular meetings were held in order to refine the categories further. The last four facets, *AI algorithm*, *cellular communication technology*, *non-cellular communication technology* and *application domain* were chosen after an initial categorization.

After that, a systematic *keywording* method proposed in [38] is applied in order to refine the categories further. The keywording method is applied as follows:

- **Reading**: The abstracts and keywords of the selected relevant studies are read again. The intention is to look for a particular set of keywords representing the application domains, cellular and non-cellular communication types, and AI algorithms used to implement safety. Regarding *application domain*, the keywording was mostly applied in the keywords of the studies rather than in the abstract.
- **Clustering**: Obtained keywords are grouped into clusters to have a set of representative clusters of keywords, which are used during the study classification.
Table 6: Data extraction form.

| Data item            | Value                          | RQ                  |
|----------------------|--------------------------------|---------------------|
| General              |                                |                     |
| Study ID             | Number                         |                     |
| Title                | Name of the study              |                     |
| Abstract             | Abstract of the study          |                     |
| Keywords             | Set of keywords                |                     |
| Author               | Set of authors                 |                     |
| Author affiliation   | Type of affiliation            | RQ6                 |
| Pages                | Number                         |                     |
| Reference type       | Type of reference              |                     |
| Year of publication  | Calendar year                  | RQ3a, RQ3b          |
| Database             | Name of the database           |                     |
| Specific             |                                |                     |
| AI algorithm         | Type of AI algorithm           | RQ1a, RQ2a, RQ2b    |
| Communication technology | Type of comm. tech.         | RQ1b, RQ2a, RQ2b, RQ3a |
| Application domains  | Type of application domain     | RQ1c                |
| Research contribution| Type of contribution           | RQ4                 |
| Research type        | Type of research               | RQ5                 |

Table 7: Validation results from the total studies. 170 (3.54\%) studies were randomly reviewed from 6541 studies.

Both an initial categorization and keywording methods resulted in a set of classes (clusters) for each of the targeted facet. The obtained classes for each facet are described in Section 4.

3.6 Data extraction

To extract the data from the selected relevant studies and to store it, a well-structured data extraction form is generated. This form is based on the classification scheme and the research questions. The data extraction form is shown in Table 6. It contains the data items and their respective values and the RQs which they are derived from.

For this step of the systematic mapping study process, Microsoft Excel spreadsheet was used to organize and store the extracted information from each relevant study for subsequent analysis. During this step, we found that some studies could be classified into more than one category according to the classification schema defined in the previous step. These studies were thus classified into all relevant categories.

In order to validate our data extraction process, 170 studies from 6541 studies (601 R + 5940 NR) of the initial classification have been randomly se-
lected. One author checked whether the results were consistent, independently who performed the initial extracted data. We calculate the overall agreement over the 170 studies as 80% (36 studies out of 170 studies were found as non-Relevant which were marked as Relevant by the other author). This means, if a randomly selected subject is rated by a randomly selected rater and then the process is repeated, there is 80% chance to get the same rating decision the second time.

The output of this step was a filled data-extraction form consisting of all relevant studies that were categorized and validated in identified classes (see Table 7 for the total numbers).

3.7 Data analysis

Data analysis is the last step of the systematic mapping study process. In this step, the map of the field is produced from the classified studies. Through the maps a comprehensive analysis of the studies is performed to finally answer the research questions presented in Section 3.1. Different methods to produce the map can be used, such as bubble charts, pie charts and line graphs. Produced maps and the derived analysis are presented in Section 5. The spreadsheet of the classified relevant studies can be found at https://bit.ly/39cBNAy.

4 Classification Scheme

This section presents the classification schemes developed in this study to address the research questions.

4.1 Artificial intelligence algorithm classification

Classes were obtained from an initial categorization and keywording (see Appendix B). For each data item of this facet a short description is presented as follows:

- **Clustering** - An unsupervised learning method that groups similar data without having the target features in the training data [53]. Outputs might be less accurate compared to supervised methods due to the absence of expert knowledge input during the training. Examples of methods are K-means, DBSCAN and MeanShift.

- **Cognitive Architecture** - Aims to use the research of cognitive psychology in order to create artificial computational system processes reasoning like humans [33]. Although complex behaviors can be modeled, the development of such architectures might require some effort. Soar, COGNET and CLARION are examples of cognitive architectures.
− **Computer Vision** - It is a class of problem that relates to the process of automating the visual perception by including tasks from low-level vision as noise removal or edge sharpening to high-level vision by segmenting the images or interpreting the scene [6]. This class includes primary studies in the field of image processing, virtual reality, or augmented reality, but did not specify the specific AI algorithm. Although computer vision can be implemented using different AI methods, neural networks (which includes deep learning) are popularly used.

− **Fuzzy logic system** - Solves a problem through a set of If-Then rules that takes into account the uncertainties in the inputs and outputs by imitating human decision-making [13]. As these rules are written in natural language, this method provides explainability of the decisions. However, it demands a manual process to model the rules and the models might have lower accuracy as compared to other AI algorithms.

− **Natural Language Processing (NLP)** - It is a class of problems that studies mechanisms to make the computer program understand the human language. Most of the NLP solutions rely on deep learning or rule-based systems [45]. This category include studies that mention the usage of NLP solution, but did not make clear about the specific AI algorithm used.

− **Neural Network (NN)** - Refers to a set of algorithms designed to simulate the connection between the neurons [40]. This method has large popularity given the ability to solve complex problems in different fields. As a drawback, it demands NN architectures with thousands or millions of neurons, which makes necessary large dataset to train the model and lead to high inference times. Examples of NN include multilayer perceptron (MLP), Long short-term memory (LSTM) and Deep Learning (DL).

− **Ontology** - Refers to a formal and structural way of representing concepts, relations or attributes in a domain [19]. This requires a domain expert knowledge to design the ontology and the usage of a specific language.

− **Optimization** - Class of an iterative procedures that aims at achieving ideally the optimal solution of a problem beginning from a guessed solution [41].

− **Regression Analysis** - Studies the relationship between a dependent and independent variable to models a function that makes predictions. The model is obtained by iteratively adjusting the function parameters to map a given set of input and outputs [8]. Usually it is applied to problems that are linearly separable.

− **Reinforcement Learning (RL)** - Class of methods that determines optimal actions that maximizes the reward of an agent that is continuously exploring the state space and taking observations [46]. It is widely applied in problems that involves automating the decision taken by an intelligent agent. Q-learning and its DNN variant, DQN, are examples of RL methods.

− **Finite State Machine (FSM)** - Represents a computational model that performs predefined actions depending on a series of events [21]. It requires knowledge from the domain expert to model the states and the transitions between them. Commonly, it is used in tasks that involves simple
decisions. Hierarchical FSM and fuzzy state machine are examples of FSM algorithms.

- **Non-specified** - Relates to primary studies that mention the use of AI or ML, but do not elaborate into a particular technique.
- **Other** - Relates to primary studies that use a AI technique that is not part of the above-mentioned ones. This includes random forests and gradient boosting.

4.2 Communication technology classification

Based on the initial categorization for communication and the process of keywording, the following classes were extracted (see Appendix B):

- **Cellular**
- **Non-cellular**
- **Not-mentioned**

To address the first and second research questions (RQ1, RQ2), cellular and non-cellular communication technologies are further divided into subcategories. This is necessary to investigate which of the communication technologies are mostly used to implement safety in different application domains and which of the non-cellular communication technologies can be potentially replaced with the cellular ones [37].

4.2.1 Cellular communication technology classification

- **2G** - Second generation of cellular communication technology that incorporated digital speech and medium-rate data transfer. GSM, GPRS and EDGE are also other terms used for 2G.
- **3G** - The third generation brought higher speed data transfer and improved quality in the services compared to 2G. WCDMA is also referred to 3G technology.
- **4G** - A higher data transfer rate leveraged new use-cases such as IoT and industry automation. LTE is another term usually associated to 4G technology.
- **5G** - Low latency communication with high data rate made possible to expand the use-cases to diverse domains.

4.2.2 Non-Cellular communication technology classification

- **WiFi** - Includes communication technologies based on IEEE 802.11 standard, such as vehicular ad hoc networks (VANET) and dedicated short range communication (DSRC).
Radio-frequency identification (RFID): A short distance communication technology that uses electromagnetic field to transfer data. This class also includesNear Field Communication (NFC), which is a technology derived from RFID.

Bluetooth: Communication technology intended for low energy consumption, short range communication and low data transfer rate.

Satellite: Long range communication technology, however sensitive to noises and dependent on line of sight.

Zigbee: Radio-based communication that has lower cost and energy consumption compared to WiFi and Bluetooth. Although it can achieve similar coverage as these technologies, it supports a much lower bandwidth.

Non-cellular (not-specified): Comprises studies that do not specify the employed non-cellular technology in the T-A-K fields.

4.3 Application domain classification

From keywording, the following classification scheme was derived for the domains where safety is provided by applying AI:

- Air space: Includes unmanned aerial vehicles (UAV) and airport management systems.
- Automotive: Encompasses intelligent transportation systems, with predominance of advanced driver-assistance systems (ADAS), autonomous vehicles and truck platooning.
- Construction: Monitoring of building infrastructure and monitoring of construction workers.
- Education: Includes personal training and academic learning applications.
- Factory: Mainly covers warehouses, chemical industries and nuclear plants.
- Health care: Referees to automation of patient care, remote surgeries and monitoring of elderly people.
- Marine: Underwater applications, unmanned surface vehicles (USVs) and vessels.
- Mining: Covers monitoring of mining workers and autonomous underground machinery.
- Robotics: Comprises utilization of robots for process automation.
- Surveillance: Environment monitoring for security and dangerous areas.
- Telecommunication: Applications in the communication domain, such as enhancements in the reliability and traffic capacity.
- Other: Specifies studies that do not fit in the aforementioned application domains.

4.4 Research contribution classification

By defining a classification framework for types of research contribution, new methods, techniques or tools can be developed in the future by the researchers
to implement safety. In order to categorize this facet, the classification scheme presented and defined by Petersen et al. in [38] is used. This scheme is highly adopted by researchers when conducting a systematic mapping study [5]. This facet was formed with the following data items:

- **Model** - Refers to studies that present information and abstractions to be used in AI-based safety.
- **Method** - Refers to general concepts and detailed working procedures that address specific concerns about implementing AI-based safety.
- **Metric** - Refers to specific measurements and metrics to assess certain properties of AI-based safety.
- **Tool** - Refers to any kind of tool or prototype that can be employed in the current models.
- **Open Item** - Refers to the remaining studies that do not belong to any of the above mentioned categories.

### 4.5 Research types classification

To categorize the research types, the classification scheme proposed by Wieringa et al. in [50] was applied, which includes the following data items:

- **Validation Research** - Investigates the novel techniques, that are yet to be implemented in the practice. Examples of investigations include experiments, prototyping and simulations.
- **Evaluation Research** - Evaluates an implemented solution in practice considering the benefits and drawbacks of this solution. It includes case studies, field experiments and related studies.
- **Solution Proposal** - Refers to a novel solution for a problem or a significant extension to an existing one.
- **Conceptual Proposal** - Gives a new approach at looking topics by structuring them in conceptual frameworks or taxonomy.
- **Experience Paper** - Reflects the experience of an author explaining at what extent something is performed in practice.
- **Opinion Paper** - Refers to studies that mostly express the opinion of the authors on certain methods.

### 5 Results of the field map and discussion

This section presents the analysis made on the relevant studies, which is organized as follows:

- Each subsection covers one or a set of research questions from Section 3.1.
- Outcomes of the research questions are presented in chart format.
- An analysis supported by a chart is provided to answer the research question.
5.1 Results of Research Question 1(a-c)

The first research question is a three-part question. It aims at making an analysis towards AI algorithms, communication technologies and application domains.

**RQ1a. What types of AI algorithm are used to implement safety?**

The AI algorithms used to implement the safety was summarized in a bar chart presented in Figure 3. From this chart, we analyze that neural networks was the largest adopted method, with 132 studies (23.36%). Alongside, computer vision and clustering corresponds to 18.05% and 9.56% of studies, respectively. Cognitive architecture was the least used algorithms with only 3 mentions. However, most of the studies (25.31%) did not specify the employed AI method. A detailed classification of the studies in terms of AI algorithm can be checked in Table 10 of Appendix B.

**Discussion:** The larger use of NN, computer vision and clustering as compared to the other AI techniques is obvious from the results. It is mainly due to their use in the field of automotive domains as discussed in RQ1c.

Overall, a slight predominance of the non-cellular communication can be seen. This reveals that so-far the cellular technology is not the first option to be used together with the AI-based safety problems. However, when analysed the AI-algorithms individually, in some cases there are a larger adoption of cellular communication especially in reinforcement learning, NLP, state machine, optimization and cognitive architectures. This demonstrates that cellular communication has large opportunities to be used as will be discussed in RQ2.

![Fig. 3: Distribution of studies according to AI method.](image-url)
**RQ1b. What kind of communication technologies are mostly used to implement safety?**

This research question depicts the analysis of the publications with respect to the communication technologies. In [subsection 4.2](#) a classification scheme focusing on communication technologies was discussed, which includes 2G, 3G, 4G, 5G, cellular (not-specified), non-cellular, satellite and not-mentioned. The pie chart in [Figure 4](#) presents the outcomes for each category addressing the number of relevant primary studies and their respective percentages. From the results, it can be inferred that the dominant technology with 207 studies (36.64%) is the non-cellular communication. From that, WiFi is the most employed non-cellular technology, with 88 studies (15.58%).

On the other hand, cellular communication is has slightly lower mentions, resulting in a total of 164 (29.03%) publications. In this category, 5G is the most used communication with 8.85%. Behind that, 2G and 4G technologies appear with 3.01% and 2.3%, respectively. 3G is the least addressed communication with 1.24% of the studies. There are also 194 papers (34.33%) that do not specify the communication technology used.

![Distribution of studies for communication technologies.](#)

**Fig. 4:** Distribution of studies for communication technologies.

**Discussion:** We believe there could be three reasons for a lower usage of cellular technologies as compared to the non-cellular ones: First, the usage of non-cellular technologies is easy for research purposes, specially in academic sector due to its non-propriety nature; second, cellular technology’s focus was initially limited to provide connectivity to only cellphones. Another reason might be the higher bandwidth and lower latency of the WiFi compared to most of the cellular technologies (i.e. 2G – 4G). Last but not the least, due
to the propriety nature of cellular technologies, most of the research done in industry is published as patents or standards, which are not part of this study.

Among the cellular technologies, 5G is the most used one, although it is the newest among all the network generations. We think the reason is that 5G supports the connectivity of industry verticals through its network slicing concept [24], especially for automotive domain [26], which was missing in its predecessor network generations. And this enables a big number of new use cases which are extended to a diversity of domains, resulting in its larger adoption as compared to the previous generations of mobile communication technologies.

The communication technology classification of each relevant study can be found in Table 9 of Appendix B.

**RQ1c.** *Which are the main application domains where these AI algorithms find applicability in order to provide safety?*

Figure 5 depicts a bar chart presenting the number of publications and the percentage of the pool of the relevant studies addressing the application domains in which the AI algorithms are applied. From the chart, an unequal distribution of the publications can be seen. The majority of the publications focus on the *Automotive* domain, mostly within the field of Intelligent Transportation Systems (ITS) with 52.21% of studies (295 publications). The second most discussed domain is *Surveillance*, which is mostly dominated with the use of cellular technology. *Health care* and *telecommunication* comes after, with 7.79% (44 publications) and 7.43% (42 publications). In both domains, cellular communication has a larger presence. The application domains with the least recognition are *Education* and *Agriculture* with 0.42% (1 publication) and 0.85% (2 publications), respectively.

![Fig. 5: Distribution of studies for application domains.](image-url)
Discussion: We believe that the reason for Automotive being the most used domain is due to the inherent mobile nature of the autonomous vehicles and its need for a reliable cellular communication to connect to the other infrastructures (e.g. an intelligent traffic light) and to access services residing in the edge or cloud. Although cellular communication promotes higher mobility, non-cellular technology is predominant in this scenario.

The analysis of the communication aspect indicates that most of the non-cellular technology is used in the automotive domain. This reveals a gap and a potential opportunity to increase cellular technology usage in the automotive related problems as will be discussed in more detail in subsection 5.2.

The reason for the least used Agriculture and Education domains does not mean that AI and communication are ignored, but that safety is not currently a key required aspect in these domains. The complete classification of the studies according to the domain is presented in Table 11 of Appendix B.

5.2 Results of Research Question 2(a–b)

This section presents the results of the RQ2, which is divided into two research questions. The RQ2 covers the relationship between AI-based safety and two classification schemes: communication technology and application domain.

RQ2a. What are the current research gaps in the use of AI to implement safety using communication technologies?

This research question investigates the existing gaps and the future opportunities in the AI-based safety using communication technologies. The bubble chart on Figure 6 presents the amount of publications for each pair of AI algorithm and communication technology. The bubble size is proportional to the number of publications. There are no bubbles for the pairs that have no publications.

The chart shows that the gaps mostly belong to Cognitive Architecture, Optimization, Regression Analysis, and State Machine have the lowest amount of publications (less than 10). A possible explanation is that these AI algorithms have low applicability on problems that combine safety and communication.

Examining the largest bubbles (excluding the not-specified and not-mentioned ones), for the non-cellular communication, the pair “Clustering” – “Wi-Fi” has 19 publications, while for the cellular communication, the pair “NN” – “5G” has 13 publications. Neural networks also have a relatively large adoption in the non-cellular communication, which has 16 studies using WiFi.

Discussion: This suggests that neural networks are widely used to implement safety using either WiFi or 5G. Still in neural networks, it is also noticed that the bubbles are spread over different communication technologies, which indicates high popularity of this AI algorithm. A similar scenario is present in Computer Vision, which has a considerable presence on both WiFi (10 studies)
and 5G (7 studies), and the bubbles are distributed on other communication technologies.

Reinforcement learning, has lower numbers compared to the aforementioned methods, but as it is getting increasingly popular, there might be some opportunity to invest on this algorithm to implement safety using communication. It can also be noticed that besides cognitive architectures and NLP being popular in other areas, they are not commonly chosen in the safety field. From the communication perspective, it is observed that 5G and Wi-Fi are the common choice for most of the AI algorithms. Therefore, there is a large gap in the usage of other communication technologies, such as 4G and ZigBee together with the AI algorithms.

**RQ2b. What is potential for using cellular communication to implement safety using AI in the most popular application domains?**

This research question addresses the possibility of using cellular communication to implement AI-based safety in application domains that do not have large presence of this communication technology, but have brought lot of attention of non-cellular communication. Figure 7 presents a similar chart as used in RQ2a, but with pie charts placed in each bubble. Each pie chart

![Bubble chart](image)

**Fig. 6: Bubble chart presenting the amount of publications according to the AI algorithm and the communication technology used to implement safety.**
Fig. 7: Bubble pie chart illustrating the relationship between communication technologies, AI algorithms and number of relevant publications.

presents the amount of publications that correlates to a certain AI algorithm and application domain, and the distribution of communication technology.

In this chart, the top five largest bubbles are predominant in the automotive domain. This includes the intersections with “NN” (53), “Clustering” (46), “Computer Vision” (42), “RL” (27) and “Fuzzy Logic” (22). The corresponding pie charts from this list show a bigger portion of non-cellular communication than cellular one in all cases. This indicates that cellular communication has some opportunity to embrace automotive problems as already discussed in RQ1c (Section 5.1). The subsequent largest bubbles are located in “Surveillance” domain, where “NN” and “Computer Vision” have 16 and 17 studies, respectively.

Discussion: The analysis of the pie charts show a large portion of cellular communication in “NN” and an opposite situation in “Computer Vision”. This shows an opportunity to address safety using computer vision in surveillance combined with cellular technology. There are few large bubbles in “Health Care” domain. In this, the pair with “NN” (10 studies) shows a pie chart that has non-cellular communication as the main option. Therefore, an opportunity exists to use cellular communication together with health care and neural networks. It is also noticed that some domains have a low usage or even absence
of cellular communication as observed in “Marine”, “Mining” and “Robotics” domains. In case of marine and mining, the coverage of cellular networks is still limited in these areas. Similarly, as robotic applications are usually targeted to indoor spaces, cellular communication becomes a natural choice.

In summary, we can interpret that in many domains, there is a potential to replace non-cellular communication by cellular one. In particular, the advent of 5G could promote this transition as higher coverage, capacity, speed and lower latency are expected.

5.3 Results of Research Question 3(a–b)

This section presents results for RQ3, which addresses the publication trends in point of view of communication technology and AI algorithms to implement safety.

**RQ3a. What is the publication trend with respect of time in terms of cellular and non-cellular communications?**

This research question targets the publication trends of the communication technologies with respect to time. The total number of relevant publications of communication technology was plotted against the publication year. The outcome is displayed in the bar chart of Figure 8. Each stacked bar represents the amount of publication in a certain year and the contribution made by a particular communication technology in that year. The three curves represent the fitted line of cellular (red line), non-cellular (blue line) and total (black line) publications over the years. From these lines, a trend in the increase of publications in both cellular and non-cellular technologies is observed. Likewise, the “Total” curve follows the same tendency. By visually comparing the cellular and non-cellular trend curves, it is noticed that there are slightly more studies on the non-cellular communication. The amount of publication by year for each communication technology is presented in the Table 8.

From the Figure 8 (and Table 8), it can be observed that the first mention of particular communication technology, a cellular one, was far back in 1991. Between 1991 and 2008 the number of publications is mostly rare and not significant. In 2008 however, a total number of 10 studies were registered. In this year the first publication mentioning the use of cellular technology (3G) in AI to implement safety was registered. After a couple of years that followed a boost. In 2013 a big step had been taken, when the number of publications became more than twice larger than the one in 2008, resulting in 22 publications. After that year, the trend only moves upwards, reaching its peak in 2017 with 40 relevant studies. The first year where each category had at least 1 publication was in 2016. Further we observe an increased use of 5G from 2016 on-wards for safety implementations.

**Discussion:** In 2020 the amount of publications increased almost four times compared to the previous year, recording 200 publications. From this,
5G had a substantial contribution, with 23 studies, probably due to the rollout of this technology. At the end of the timeline, in 2021 is shown a drop in the amount of the total studies as not all publications were accounted. However, this number is already larger than the total amount found in 2019.

**RQ3b. What is the publication trend with respect of time in terms of AI algorithms?**

The essence of this research question is to analyse the publication trend in terms of AI algorithms to implement safety. Figure 9 shows the amount of publications related to AI algorithm to implement safety that were published in each year and are represented by the bubble size. The biggest bubble belongs to the pair “NN – 2020” (65 studies), reasoning that the popularity of neural networks is getting high even in recent years.

**Discussion:** While considering the whole timeline, it is verified that computer vision has the largest bubbles spread along the years. Meanwhile, fuzzy logic has the lowest bubbles spread over the timeline. A considerable change is present from 2019 to 2020 in reinforcement learning (from 3 to 22), which suggests that recently this method is getting more attention. Overall, a rapid increase is observed in 2020, almost all algorithms presented an increase in its usage, and is ongoing in 2021 also. A drop in the amount of the total studies in 2021 is because not all publications were accounted in this study. However, as mentioned previously, this number is already much larger than the total amount found in 2019.
5.4 Results of Research Questing 4-6

This section groups research questions related to research contributions, research types and author’s affiliation.

**RQ4. What type of research contributions are mainly presented in the studies?**

Figure 10 displays a pie chart, where every slice represents the number of publications according to the research contribution category defined in classification scheme (details in Section 4). The contribution categories are Methods, Metrics, Models, Tools and Open Items. The chart shows that the researchers are mostly focused on presenting Methods as a research contribution, comprising 65.31%, which corresponds to 369 publications. Models and Tools come after with 26.37% and 6.02% respectively. The least amount of studies, with only 6 publications (1.06%) discuss Metrics. There were 7 studies (1.24%) that was not possible to determine the contribution class.

**Discussion:** From the outcomes, it can be said that the spotlight from the research community is towards giving solutions in form of methods or approaches, and lacking especially metrics for providing safety using AI and
communication technology. One reason for this lack could be that the metrics to measure safety are usually provided in safety standards only, which could

Fig. 9: Bubble chart presenting the relationship between AI algorithm, year of publication and number of relevant studies.

Fig. 10: Distribution of studies regarding the types of research contribution.
only be implied or followed by the software implementing AI algorithms using communication.

**RQ5. Which are the main research types being employed in the studies?**

Figure 11 depicts a pie chart with the number of publications and their percentage grouped by research type classification. In Section 4.5 the research type classification was acknowledged as Validation Research, Evaluation Research, Solution Proposal, Conceptual Proposal, Experience Paper, and Opinion Paper. The chart shows that the vast majority of the publications embrace the Solution Proposal, which composes 89.20% of the total number of relevant studies (504 studies). Few studies fall in the remaining research types: Evaluation Research – 3.19%, Conceptual Proposal – 2.83%, Validation Research – 2.65%, Opinion Paper – 1.95% and Experience Paper – 0.18%.

**Discussion:** From these outcomes we could conclude that a large number of solutions are yet to be evaluated and validated by the industry. One reason for this could be the novelty of the topic and its recent boost.

![Fig. 11: Distribution of studies regarding the research types.](image)

**RQ6. What is the distribution of publications in terms of academic and industrial affiliation?**

In order to have a better understanding of publication origin, whether they come from academia or the industry, the affiliations of the authors were taken into account. The categorization was created based on the one in [5]. It contains three data items: academia, industry and both, as follows:

- **Academia** - The study is written only by academic authors.
- **Industry** - The study is written only by industrial authors.
- **Both** - The study is conducted as a consequence of a collaboration between academic and industrial authors.
In Figure 12 a pie chart depicts the distribution of the publications addressing the affiliation of the authors. The chart shows that majority of the studies, 75.04% (424 publications), correspond to Academic publications. The remaining is distributed into 6.55% (37 publications) from Industry and 18.41% (104 publications) of the studies are derived from Both. The lack of industrial publications was confirmed by the low number of industrial authors participating in the research area.

**Discussion:** The main reason for this low number of industrial publications is that usually the industrial research is not published in the form of research papers. Even if it does, most of industrial publications consist in a format of patents or white papers that might reveal less information and consequently not being considered by this study (as stated in the exclusion criteria). That is why, we think that this low number of papers is not a realistic indicator, considering the fact that AI techniques are already adopted in many application domains. However, there is a tentative to increase the joint studies, bringing the academia and industry to work together as we can see in the chart.

![Figure 12: Distribution of studies regarding the affiliation of the authors.](image)

### 6 Threats to validity

When conducting a systematic mapping study, there are usually some issues that might jeopardize the validity of the work. In this subsection, the method to mitigate the threats of validity is described, which follows the the guidelines of Wohlin et al. in [51].

#### 6.1 Construct validity

Construct validity in systematic mapping studies stresses the validity of the extracted data concerning the research questions. For this systematic mapping study, the guidelines in [39] were followed. The selection of the primary studies represents the research questions in a confident way. Starting with the search
string, it is well-formulated using the PICO method. Then, the most common
digital libraries in software engineering were chosen to perform the automatic
search, which gives more depth to the study as mentioned in Section 3.2. The
publications collected by performing the search were reviewed with respect to
their titles and abstracts. If a publication could not be judged for relevance
based on its title and abstract, full-text skimming was performed to decide
about its relevance in the research area.

Furthermore, the studies were screened under rigorous inclusion and exclusion
criteria. To be noted is that not using “snowballing sampling” might
reduce the credibility of the study, but the big number of primary studies
covers the desired scope. Considering all the above-mentioned, it is believed
that no relevant studies were left out of the research. Moreover, the selection
team members classified a certain number of common studies (170 out of 4808
studies have been randomly selected) to check the overall agreement, achieving
0.80 which shows almost perfect agreement.

6.2 Internal validity

Internal validity represents those threats that seek to establish a causal re-
lationship, where some conditions may influence the study. To mitigate this
threat, a predefined protocol with an exact data extraction form was used.
Regarding the data analysis, since descriptive statistics would be employed,
the threats are minimal.

Another threat is related to the classification schema for mapping. To mit-
gate, we partially based our classification of the primary studies on initial
categorization, which is based on the discussions with experts from their re-
spective fields and refined the categories further using few iterative meetings.
Further, we systematically applied the keywording method to define the clas-
sification schemes. We believe that this process of classification would have
refined our mapping to mitigate this threat.

6.3 External validity

Threats to external validity define the extent of the generalizability of the
outcomes of systematic mapping study. In this research, the most drastic
threat related to external validity is not covering the whole scope of AI using
communication technologies to provide safety. This threat is mitigated by a
well-established search string and the automatic search. Having a good set of
inclusion and exclusion criteria helped as well in the external validity of the
study. However, since the T-A-K skimming was performed, due to abstracts
with incomplete information, some relevant studies might have been wrongly
excluded. However, as it is known that abstracts do not always reveal the true
content of papers, there is a risk that we might have excluded a paper with
poor abstract but valid content.
To further minimize the external threat, only the publications written in English (widely used language in qualitative scientific studies) were chosen and additionally only the peer-reviewed studies were accepted.

6.4 Conclusion validity

Conclusion validity demonstrates that the study can be repeated in the future and yet have the same results. The relationship between the extracted and synthesized data and the outcomes of the study may influence the repetitiveness.

In order to mitigate this threat, all the steps leading to data analysis including search string, automatic search, selection criteria, are well-documented. They can be used by researchers to replicate the study. Furthermore, the data extraction form is well-documented, decreasing the biases of that process. The same reasoning is followed with the classification scheme as well, where the framework is well-defined and has the respective references.

7 Conclusions and future directions

The main goal of this paper is first, to grasp an overview of the current state-of-the-art research publications that utilizes AI to implement safety using different communication technologies, second, to investigate gaps in it, and third, to identify emerging future research trends on the topic. To achieve this, a systematic mapping analysis is conducted. From an initial total of 8760 studies obtained after an automatic search, a number of 565 relevant studies were identified using structured selection process, covering three main aspects: AI algorithm, specific communication technology and safety as a property. By classification of these 565 studies, we have identified different application domains using AI and communications to implement safety aspects, the current challenges and emerging future research trends on the topic from both industry and academia.

The study results indicate the start of an increased use of the cellular communication, specially 5G, to implement AI-based safety in multiple domains and an increasing interest of the industry on the topic. The outcomes of the study also suggests that regarding AI algorithms, the attention of researchers is focused more towards applying neural networks and computer vision techniques, even though a high percentage of studies do not specify the technique, threatening the validation of the previous statement. Meanwhile, the use of techniques like optimization or cognitive architecture are less preferred. Despite reinforcement learning not being the mostly adopted algorithm, it is one of the algorithm that showed the highest increase in 2020. Concerning the other categories, non-cellular is clearly dominant in communication, however we observe a rapidly increasing recent interest in one of the latest cellular networks i.e. 5G specially from 2020. The topic is generally gaining the attention of the
researchers in the past years and the trend seems to remain increasing. The analysis further reveals that currently automotive outnumbers all the other application domains (52.21%) followed by surveillance and health care (8.5% and 7.79%, respectively). Moreover, it can be concluded that the majority of studies contribute with methods and solution proposals.

Concerning the future work, the results of this systematic mapping study benefit the researchers and the industry at the same time. Researchers can use this work, to further deepen their knowledge considering new challenges in this topic. The various classifications provided in this work may serve researchers as initial categorizations or a base foundation with the will to further extend them in conducting other systematic mapping studies or systematic literature reviews.

The study pinpoints current gaps in research that may represent opportunities for further research on different AI algorithms using communication in multiple domains. These gap areas lack the research which can be explored further. Few such research areas could be in the fields of robotics, mining, factory which are currently behind but can leverage on the results from the automotive area by applying and testing AI algorithms to autonomous agents like robots in smart factories, logistics etc. Further, different industries can not only benefit from this gap analysis in their respective areas, but can also start research in new required AI fields. Such as Autonomous vehicles are currently doing a lot of research on Computer vision, neural networks, clustering. One future direction could be to explore new areas like trustworthy AI aspects, health industry and surveillance also need this heavily.

Further, the study presents currently increasing research trend, such as one increasing trend is about the autonomous vehicle domain and the effect of the 5G on the studies. With the roll-out of 5G in 2020, an increased research trend is to use it in different domains. One future direction could be to research on the use 5G instead of WiFi technologies for safety.

The lack of evaluation researches indicates that the industry is either not putting the research into practice or not publishing research in the form of research papers. Therefore, an heightened interest in evaluating the proposed solutions like case studies or field experiments is expected. In the near future, more efforts could be put into providing new tools and defining metrics, as it, for now, the research area is missing it.

8 Declarations

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Conflicts of interest/Competing interests

The authors declare that they have no conflict of interest.

Availability of data and material

Not applicable.

8.1 Code availability

Not applicable.

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Appendix A  Primary studies

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Appendix B  Classification of primary studies
| 2G | S001, S046, S056, S075, S094, S124, S143, S228, S236, S332, S360, S366, S377, S379, S396, S444, S514 |
| 3G | S208, S209, S300, S359, S375, S432, S510 |
| 4G | S009, S154, S158, S185, S437, S465, S481, S485, S486, S487, S511, S516, S532 |
| 5G | S012, S022, S040, S060, S081, S099, S104, S111, S150, S186, S254, S257, S259, S261, S269, S275, S276, S277, S278, S281, S301, S302, S304, S316, S335, S339, S350, S383, S388, S400, S406, S438, S448, S452, S453, S472, S474, S483, S486, S494, S500, S519, S526, S538, S544, S547, S553, S554, S563, S565 |
| Cellular (not-specified) | S18, S21, S27, S29, S33, S42, S48, S50, S59, S71, S74, S76, S77, S86, S90, S91, S97, S101, S105, S117, S119, S147, S157, S166, S170, S171, S179, S201, S202, S204, S211, S223, S235, S237, S247, S256, S258, S268, S272, S273, S274, S285, S296, S303, S317, S319, S328, S344, S354, S372, S374, S391, S395, S409, S416, S418, S428, S431, S440, S448, S452, S453, S472, S474, S483, S486, S487, S511, S516, S532 |
| Bluetooth | S030, S043, S115 |
| RFID | S087, S103, S242, S266, S283, S334, S558 |
| Satellite | S034, S066, S199, S217, S234, S246, S264, S293, S337, S429, S496, S503, S539 |
| WiFi | S007, S011, S013, S023, S024, S025, S035, S044, S045, S051, S058, S063, S064, S068, S070, S073, S088, S089, S092, S096, S098, S100, S110, S112, S116, S121, S122, S125, S126, S128, S132, S135, S138, S144, S152, S174, S177, S182, S192, S218, S221, S224, S243, S244, S249, S260, S290, S305, S307, S309, S411, S413, S415, S425, S429, S438, S445, S464, S466, S467, S469, S470, S482, S501, S504, S506, S513, S524, S546, S548, S550, S552 |
| Zigbee | S384, S460, S492, S525 |
| Non-Cellular (not-specified) | S003, S014, S016, S017, S019, S020, S028, S057, S061, S065, S069, S072, S078, S085, S093, S095, S106, S107, S113, S118, S127, S129, S130, S131, S137, S140, S151, S172, S175, S176, S178, S181, S188, S191, S193, S194, S196, S197, S203, S212, S216, S222, S226, S230, S232, S239, S250, S251, S253, S262, S263, S267, S282, S288, S289, S299, S308, S314, S318, S321, S322, S331, S432, S436, S439, S532, S539, S562, S565, S567, S568, S581, S585, S586, S598, S401, S411, S417, S423, S435, S439, S463, S477, S479, S495, S498, S531, S542, S549, S556 |
| Non-Cellular communication technologies classification. | S002, S004, S005, S006, S008, S010, S015, S026, S031, S032, S036, S037, S038, S039, S041, S047, S049, S052, S053, S054, S055, S062, S067, S079, S080, S082, S083, S084, S102, S108, S109, S114, S120, S123, S133, S134, S136, S139, S142, S145, S146, S148, S149, S153, S155, S156, S159, S160, S161, S162, S163, S164, S165, S167, S168, S169, S173, S180, S183, S184, S187, S189, S190, S195, S196, S200, S205, S206, S207, S210, S213, S214, S215, S219, S220, S225, S227, S229, S231, S233, S238, S240, S241, S245, S252, S255, S270, S271, S279, S280, S284, S286, S287, S291, S292, S294, S295, S297, S298, S306, S310, S312, S320, S323, S324, S326, S327, S330, S333, S336, S343, S347, S348, S351, S353, S355, S356, S357, S358, S363, S370, S373, S376, S378, S387, S390, S393, S397, S399, S403, S404, S405, S410, S414, S416, S419, S422, S424, S425, S426, S430, S433, S434, S436, S443, S445, S446, S449, S450, S455, S457, S462, S468, S471, S473, S478, S484, S489, S490, S491, S497, S499, S502, S505, S507, S508, S509, S512, S515, S518, S520, S521, S523, S528, S529, S530, S533, S534, S535, S536, S537, S540, S541, S543, S551, S555, S557, S559, S561, S562, S564 |
| Not-Mentioned | (c) Studies that do not explicitly mention the communication technology used. |
| Table 9: Primary studies regarding the communication technologies classification. |
|                            | S009, S011, S025, S045, S057, S059, S071, S073, S078, S088, S089, S100, S116, S127, S133, S135, S137, S152, S161, S164, S169, S172, S185, S188, S189, S193, S224, S244, S258, S262, S310, S325, S335, S340, S348, S371, S383, S386, S401, S411, S427, S442, S463, S469, S480, S485, S486, S487, S498, S513, S516, S517, S529, S537 |
|---------------------------|---------------------------------------------------------------------------------|
| Clustering                | S02, S388, S499                                                                   |
| Cognitive Architecture    | S001, S014, S017, S019, S030, S033, S039, S043, S056, S066, S072, S074, S077, S080, S083, S087, S090, S102, S107, S110, S111, S112, S115, S121, S159, S160, S181, S187, S192, S211, S216, S221, S226, S231, S234, S236, S237, S239, S259, S261, S264, S267, S271, S280, S289, S291, S302, S311, S316, S317, S318, S320, S326, S328, S333, S335, S340, S348, S371, S383, S386, S401, S411, S427, S442, S463, S469, S480, S485, S486, S487, S498, S513, S516, S517, S529, S537 |
| Computer Vision           | S042, S388, S499                                                                   |
| Fuzzy Logic               | S010, S013, S022, S028, S037, S051, S083, S085, S086, S151, S176, S179, S194, S207, S215, S221, S288, S321, S330, S381, S382, S415, S438, S440, S456, S466, S489, S493, S527, S544, S553 |
| Natural Language Processing| S004, S173, S229, S270, S274, S333, S336, S360, S366, S372, S413, S416 |
| Neural Networks           | S002, S005, S020, S023, S024, S027, S029, S031, S032, S035, S040, S052, S054, S064, S067, S082, S084, S085, S093, S094, S095, S097, S103, S113, S117, S118, S119, S120, S126, S129, S130, S134, S143, S144, S147, S163, S166, S171, S174, S175, S183, S184, S198, S200, S205, S210, S212, S214, S217, S218, S219, S225, S227, S229, S233, S240, S241, S248, S250, S252, S257, S260, S266, S275, S276, S277, S286, S287, S290, S292, S293, S294, S297, S298, S301, S303, S306, S312, S314, S324, S327, S331, S332, S341, S342, S344, S352, S357, S364, S373, S374, S375, S384, S395, S414, S426, S432, S436, S439, S441, S447, S453, S457, S460, S465, S467, S473, S474, S475, S476, S481, S500, S501, S505, S506, S508, S511, S518, S519, S523, S524, S530, S538, S546, S547, S552, S555, S556, S557, S561, S564, S565 |
| Ontology                  | S061, S079, S138, S139, S140, S149, S155, S390, S430, S464, S471, S479, S534 |
| Optimization              | S021, S041, S062, S157, S238, S253, S392, S409 |
| Regression Analysis       | S099, S109, S136, S146, S178, S313, S319, S459 |
| Reinforcement Learning    | S026, S098, S101, S106, S108, S154, S182, S204, S247, S279, S282, S284, S295, S296, S305, S343, S351, S353, S367, S369, S390, S394, S399, S406, S412, S419, S422, S437, S502, S512, S521, S540, S541, S548, S550, S562 |
| State Machine             | S044, S081, S086, S158, S197, S209, S255, S531, S551 |
| Not-specified             | S003, S006, S007, S008, S012, S015, S016, S018, S034, S036, S038, S046, S047, S048, S049, S050, S053, S055, S058, S060, S070, S075, S076, S091, S092, S096, S104, S105, S114, S123, S124, S125, S131, S132, S141, S142, S145, S148, S150, S153, S156, S162, S168, S170, S177, S180, S186, S190, S191, S195, S196, S199, S201, S202, S203, S208, S213, S220, S222, S228, S232, S242, S243, S246, S249, S251, S254, S256, S263, S265, S268, S269, S272, S273, S278, S281, S283, S285, S299, S304, S307, S308, S309, S315, S329, S334, S337, S339, S345, S346, S349, S350, S354, S358, S359, S368, S377, S378, S385, S389, S393, S400, S402, S405, S407, S417, S418, S421, S424, S425, S428, S429, S431, S433, S434, S435, S445, S446, S448, S450, S452, S454, S455, S458, S470, S478, S492, S496, S507, S514, S520, S522, S526, S532, S535, S542, S549, S554, S558, S559, S563 |
| Other                     | S069, S122, S128, S165, S167, S206, S235, S323, S363, S380, S387, S490, S491 |

Table 10: Primary studies regarding the AI algorithm classification.
| Domain          | Pages |
|-----------------|-------|
| Agriculture     | S038, S122 |
| Air Space       | S004, S005, S010, S015, S020, S055, S070, S142, S173, S197, S217, S241, S246, S264, S303, S304, S306, S347, S357, S426, S431, S446, S449, S464, S495, S496, S503, S527, S537, S542, S560 |
| Automotive      | S001, S002, S003, S007, S008, S009, S011, S013, S014, S016, S021, S022, S024, S025, S026, S029, S030, S031, S032, S035, S036, S037, S041, S044, S045, S046, S047, S048, S051, S052, S053, S054, S057, S058, S059, S060, S061, S062, S063, S065, S067, S069, S071, S072, S073, S077, S078, S079, S080, S084, S085, S088, S089, S090, S091, S092, S093, S095, S096, S097, S098, S099, S100, S102, S104, S106, S108, S110, S111, S112, S115, S116, S121, S127, S128, S131, S135, S136, S138, S139, S140, S141, S144, S145, S146, S149, S151, S152, S154, S155, S160, S161, S162, S163, S168, S169, S180, S170, S172, S174, S175, S176, S178, S179, S182, S183, S184, S185, S186, S187, S188, S189, S190, S193, S194, S202, S207, S209, S211, S212, S215, S218, S219, S221, S222, S224, S226, S230, S232, S234, S235, S238, S239, S240, S244, S249, S251, S253, S258, S262, S263, S268, S269, S273, S279, S281, S283, S284, S285, S287, S288, S289, S290, S293, S295, S296, S298, S305, S307, S308, S309, S310, S311, S312, S313, S314, S315, S316, S317, S318, S321, S325, S326, S328, S330, S338, S339, S340, S341, S344, S346, S348, S349, S350, S351, S352, S353, S355, S358, S362, S363, S366, S367, S368, S369, S371, S373, S374, S375, S380, S381, S382, S383, S385, S388, S389, S391, S392, S393, S394, S396, S397, S399, S400, S401, S404, S405, S406, S408, S409, S411, S413, S417, S418, S420, S422, S423, S424, S427, S432, S433, S434, S435, S436, S437, S442, S445, S447, S448, S454, S456, S457, S458, S459, S462, S463, S468, S470, S471, S474, S476, S477, S478, S479, S480, S481, S483, S485, S486, S487, S490, S491, S493, S498, S500, S501, S502, S504, S507, S508, S512, S513, S514, S515, S516, S517, S520, S521, S522, S523, S532, S533, S534, S538, S540, S541, S543, S545, S548, S549, S550, S552, S553, S554, S555, S556, S557, S563 |
| Construction    | S083, S109, S113, S129, S192, S233, S415, S443 |
| Education       | S416 |
| Factory         | S006, S017, S019, S421, S482, S526, S551, S558 |
| Health Care     | S043, S040, S043, S049, S056, S079, S094, S103, S107, S124, S153, S159, S196, S201, S210, S225, S236, S255, S266, S271, S272, S274, S300, S318, S322, S323, S333, S334, S345, S360, S372, S376, S384, S430, S439, S444, S455, S473, S492, S499, S531, S535, S547, S562 |
| Marine          | S034, S082, S087, S096, S133, S181, S191, S199, S205, S213, S220, S229, S286, S337, S387, S403, S529, S539 |
| Mining          | S117, S118, S119, S120, S126, S132, S148, S297, S329, S331, S460, S511 |
| Robotics        | S157, S245, S270, S320, S324, S343, S361, S559, S561 |
| Surveillance    | S018, S028, S064, S130, S134, S180, S200, S214, S216, S223, S228, S231, S237, S248, S250, S260, S265, S267, S280, S291, S301, S336, S356, S370, S377, S379, S390, S395, S402, S407, S410, S419, S428, S441, S450, S451, S452, S461, S467, S497, S505, S506, S510, S518, S524, S525, S536, S546 |
| Telecommunication | S042, S074, S076, S081, S101, S105, S114, S125, S143, S147, S150, S158, S166, S171, S177, S204, S208, S227, S242, S243, S247, S252, S254, S256, S257, S259, S275, S277, S319, S335, S342, S354, S412, S429, S438, S440, S453, S465, S488, S519, S544, S565 |
| Other           | S012, S023, S027, S050, S066, S075, S086, S123, S137, S156, S164, S165, S167, S195, S198, S203, S206, S261, S270, S275, S282, S292, S294, S299, S302, S327, S332, S359, S364, S365, S378, S386, S398, S414, S425, S448, S466, S469, S472, S475, S484, S489, S494, S509, S528, S530, S564 |

Table 11: Primary studies regarding the domain classification.