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Survey Paper

Tracking for mobile devices: A systematic mapping study

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ABSTRACT

Tracking is an important task that is used for several applications, such as navigation assistance and augmented reality. The improvement and popularization of mobile devices in recent years allowed these applications to be executed on such devices. Thus, several tracking techniques proposed lately take into consideration the benefits and limitations of handheld devices. Therefore, the goal of this work is to perform a systematic mapping in order to provide trends and classification regarding the recent publications in the area of tracking for mobile devices. This study collected 2276 papers from three scientific databases using an open-source crawler, from which 360 were selected to be classified according to four properties: tracking type, degree of freedom, tracking platform and research type. The analysis of these data resulted in a map of the research field, which was presented under three perspectives: the distribution and trends over time of each classification property and the relationship between them. Besides the visual map, the full list of classified papers is available through an open-source web-based catalog. The results showed that the number of publications is increasing every year, which shows a growing interest in this field. Moreover, most works use the device's sensors for tracking in location-based applications and almost all of them calculate a 2D or 2D + θ pose. There are also several papers about vision-based techniques to compute the device's pose and in the majority of them a full 6D pose is computed. Beyond that, there is a clear preference for systems that calculate the pose locally on the device and only a few use a remote server to assist in this task. Moreover, more than 92% of all papers propose a new technique or use existing ones to create a solution.

1. Introduction

There are several applications that require tracking, which is the computation of an object placement relative to a real world element or location over a time period. For instance, some augmented reality software use the camera pose related to a marker to display a virtual content registered with the pattern [1]. Another example is a GPS navigation device that calculates its location relative to the road in order to show the driver directions to a destination [2]. However, this is a challenging task. Moreover, determining this placement can demand a lot of computational power and memory depending on the approach and the required information.

Mobile devices, such as phones and tablets, are becoming increasingly popular. Research shows that approximately a third of the world's population owns a handheld device [3,4]. Moreover, these devices are constantly improving regarding processing power and memory space available [5], which makes them powerful enough to perform complex tasks, such as tracking. This scenario favors the creation of numerous types of applications since such devices create several opportunities that are only possible when the user can be mobile.

During the past years, researchers have proposed different techniques to perform tracking on mobile devices. As the research area matures and the number of related papers increases, it becomes important to summarize the current state-of-the-art and provide an overview of the trends in this specialized field. In order to address this issue, this paper presents a systematic mapping of the literature in this area. The main goal of this mapping is to analyze, classify and map existing papers about tracking for mobile devices, providing a primary study and an inclusive overview of this topic.

Systematic mapping is a method to review, classify, and structure papers related to a specific research field [6]. It is frequently used in medical research and lately has been applied to software engineering. Unlike systematic reviews, the goal of this research method is not to perform a deep analysis of works in order to identify the best practices of a field, which usually includes a quality evaluation. The aim of a systematic mapping is to provide an overview of a wide range of papers. This broader analysis enables to observe more papers, which allows more general conclusions [6]. Nevertheless, both methods use a well-defined methodology, which reduces bias [7]. Moreover, systematic mapping papers have an educational value to provide

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valuable information for students and young researchers, being a useful first step for Ph.D. candidates [8].

To the best of the authors' knowledge, there is currently no study that synthesizes or systematically analyzes, classifies and maps existing papers about tracking for mobile devices. However, some surveys were found about the field or one of its specific subareas. For instance, [9] evaluated wireless indoor localization techniques and [10] listed tracking algorithms for mobile phones that use only their sensors, as well as their applications. There are also surveys regarding mobile augmented reality, in which tracking is an important step. Examples are [11] that studied the overall acceptance and user experience of mobile augmented reality consumer applications, [12] that presented the technologies and methods to perform augmented reality on mobile devices and introduces some applications, and [13] that conducted a survey about augmented reality browsers and performed a quantitative and qualitative analysis regarding the usability aspects of these tools.

In this work, tracking for mobile devices means that an off-the-shelf cell phone or tablet extracts information from the environment and then processes it locally or remotely in order to compute the device's pose related to the world, which will be used by an application or a service on the device itself. Thus, this study collects and analyzes works published in scientific databases, categorizes them according to four classification criteria and provides a visual summary of this result, as well as discussions about it. As part of the methodology, a list of research questions is proposed, which guides the search strategy, the definition of inclusion and exclusion criteria for relevant studies and the classification schema of all the selected studies. Moreover, the final classification is presented as a catalog of papers on a web application in order to make the data from this work public. Additionally, this website allows collaborators to contribute with new studies.

The remainder of this work is organized as follows: Section 2 describes the methodology used in this study, including the research questions and the classification schema. Section 3 reports the results regarding paper selection. The systematic mapping is presented in Section 4. Section 5 discusses the main findings of this paper and its implication for future studies. Finally, the conclusion is stated in Section 6.

2. Methods

The systematic mapping was conducted based on the process proposed by [6] and illustrated in Fig. 1. The process steps performed in this study are described in the following subsections.

2.1. Research questions

The goal of this systematic mapping study is to provide an overview of the current research on the topic of tracking for mobile devices. The overall objective was defined in the following four research questions:

*RQ*1: How has the frequency of research on tracking for mobile devices changed recently?
*RQ*2: What are the most frequent approaches of tracking for mobile devices?
*RQ*3: In which platforms has tracking for mobile devices been executed?
*RQ*4: In which forums has research on tracking for mobile devices been published?

The first question aims to use the number of publications to investigate trends of the field in the past few years. The second and third questions explore the approaches and platforms researched in the field. The objective of the fourth question is to identify where tracking for mobile devices research can be found, which could be targets for the publication of future studies.

2.2. Scientific databases and search strategy

Three online academic search engines were used to find the relevant papers:

- ACM Digital Library;
- IEEE Xplore Digital Library;
- ScienceDirect.

In order to perform an automatic search on the selected libraries, the search string consisted of two parts. The former regards the tracking domain and the latter covers the device used. Thus, the search string was the following:

(“*tracking*” *OR* “*registration*” *OR* “*localization*”)
AND
(“*phone*” *OR* “*tablet*” *OR* “*handheld*” *OR* “*smartphone*”)

Tracking is the key term of the first segment and the other ones are its most used synonyms. Other terms were not used because a quick analysis showed that the majority of the papers found would not be selected for classification. An example is “positioning”, which appears mostly in studies in which the device's pose is used only by an external agent and not on the device itself, such as the phone's position that is used by the carrier to determine in which GSM antenna it will connect to. Moreover, the analysis revealed that the relevant papers were already found using the chosen terms.

Regarding the second segment, the authors chose to search for each device instead of using the terms “mobile” or “mobile device”. The reason is that these keywords returned too many papers and a quick analysis revealed that the vast majority of them use a broader concept of mobile device than the desired in this mapping. For instance, there are works that use mobile objects,

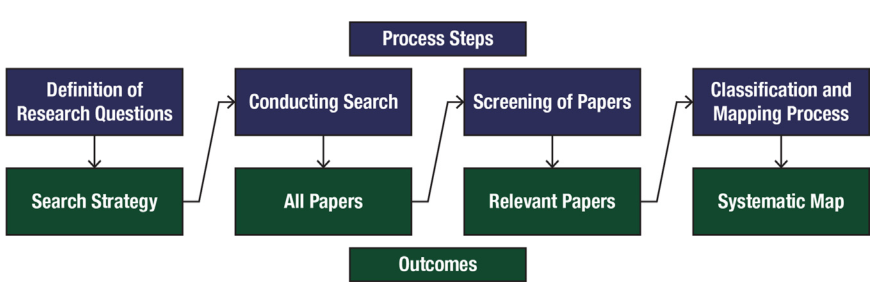

Fig. 1. Systematic mapping process. The research question guides the definition of the search strategy, which is used to collect the works. Some criteria are defined to select the relevant studies that are classified in order to provide the systematic mapping.

which are objects with sensors embedded that are tracked by computers. There are also several references to mobile device as a large object that is used for tracking-related activities, such as an airplane radar or a medical scanner, that was shrunk to become mobile. Therefore, using the mobile device types as search terms showed to be more effective.

An automatic search was performed in the above-mentioned databases using an open-source paper crawler software and applying the search in the title, abstract and keywords. The crawler was developed by the authors and aims to automate the process of retrieving papers. Hence, the crawler accesses the digital libraries, performs the search using the search strings, collects the papers, eliminates duplicate versions and creates a worksheet containing all the works with their title, year, source, primary affiliation, abstract and web address. The source code is available at http://www.cin.ufpe.br/~rar3/tracking_sm/paper-analysis.tar.gz.

2.3. Screening of papers

After collecting the papers, duplicate works were removed. Whenever a work had multiple publications, only the most complete version was selected and the other ones were removed as duplicates. Later, relevant papers were selected using the following inclusion and exclusion criteria.

- *Inclusion criteria*:
  - Papers about tracking techniques implemented on mobile devices.
  - Papers about mobile applications that use existing tracking techniques, even if they do not explain how tracking was implemented.
- *Exclusion criteria*:
  - Papers published before 2009.
  - Papers not written in English language.
  - Papers published on non-peer reviewed vehicles, such as books and magazines.
  - Papers not related to tracking techniques on mobile devices.
  - Papers about tracking techniques that were implemented only on desktop platform and that have no indication of how they can be developed for mobile devices.

2.4. Classification

Following, all included papers were classified according to four properties in order to answer the research questions. They are detailed next.

2.4.1. Tracking type

Each paper was classified regarding its tracking type. The classification was adapted from [14], which is shortly explained below and illustrated in Fig. 2:

- *Sensor-based tracking:* Techniques that calculate device's pose relative to real world using exclusively sensors. This approach can be divided in two categories: *single sensor*, which uses only one sensor for tracking, and *sensor fusion*, which uses different sensors to perform the same task.
- *Vision-based tracking:* Techniques that use images captured by the device camera to calculate pose relative to real world. This approach can also be divided into two categories: *marker-based* and *natural feature-based*. The former method calculates device's pose from artificial markers placed in the scene and the latter performs the same task using natural characteristics from the environment, such as points and edges. The natural feature-based approach was also split into two subcategories: *static model* and *dynamic model*. The first one uses prior knowledge of the scene that does not change during tracking to compute device's pose and in the second one the tracker can use an initial model if it is available or build it entirely from scratch and this environment information is updated during computation of the device's pose.
- *Hybrid tracking:* Techniques that combine sensor-based and vision-based methods to calculate device's pose.
- *Several:* Papers that present techniques from several categories, such as surveys.

2.4.2. Number of degrees of freedom

This property details the degree of freedom required to compute the information desired. This classification was based on [15]. One modification was the addition of the 3D degree of freedom, which was not mentioned in the original work. Thus, the complete degree of freedom classification used in this work is detailed in the following list:

- 0*D*: Techniques that detect a pattern and display an information about it without any relationship with its position and orientation.
- 2*D*: Techniques that provide information about the position, being indoor, outdoor or in the screen. It can also be called “2D Location”.
- 2*D* + θ: Techniques that extend the position information with orientation, providing the location with direction. It can also be named “2D Location + Orientation”.
- 3*D*: Techniques that compute the device's rotation in all three axis.

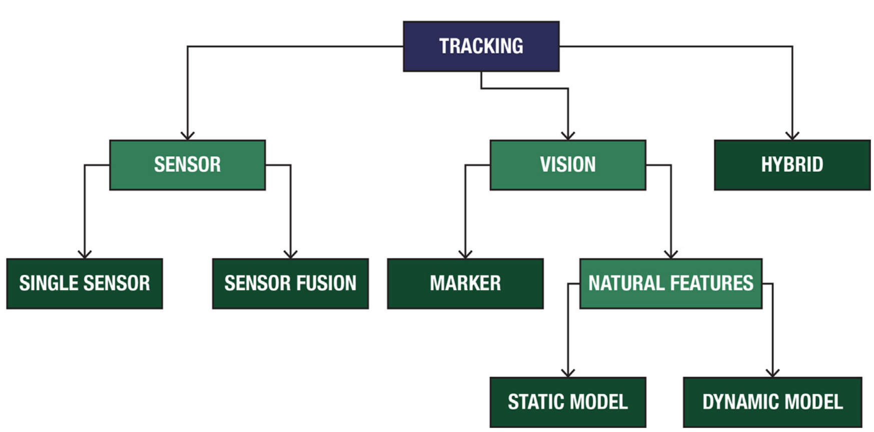

Fig. 2. Tracking type classification diagram.

- *6D*: Techniques that calculate the device's pose with rotation and translation. Systems that also compute scale were considered 6D as well.
- *Several:* Papers that present techniques from several categories.

2.4.3. Tracking platform

Two tracking platforms were considered to classify papers regarding this property, as detailed below:

- *Local tracking:* Techniques that compute all the required information at the mobile device.
- *Distributed tracking:* Techniques in which part or all the information is calculated on a server and the result is transmitted to the device and used to display the content.
- *Several:* Papers that present techniques from several categories.

2.4.4. Research type

The research type feature concerns the research approach used in the papers. This classification was adapted from [16] and is summarized in the list below:

- *Evaluation research:* Papers that present implementation and extensive evaluation of existing techniques in order to determine their benefits and drawbacks.
- *Opinion papers:* Publications in which the author expresses a personal opinion whether a certain topic is good or bad without relying on related work.
- *Philosophical papers:* Papers that present new ways of looking at existing things, such as structuring the field in form of a new taxonomy.
- *Proposal of solution:* Works that propose solutions for problems, which can be based on novel or existing techniques.
- *Survey papers:* Papers that summarize and organize a research field based on other publications.
- *Technique research:* Publications in which the authors propose and implement a novel technique.

2.5. Threats to validity

It is important to consider threats to validity in order to judge the systematic mapping strengths and limitations. The main issues are related to incomplete sets of relevant papers and researcher bias with regard to inclusion/exclusion criteria and classification.

Limitations with search string, scientific databases and search strategy can result in an incomplete set of relevant papers. As a way to mitigate that risk, three strategies were used. In order to validate the search string, the terms were discussed with three other experienced researchers in the field of tracking. The scientific databases that publish works from the most important conferences and journals in the area were selected. As for the search strategy, a different approach was used to maximize the number of papers found. Instead of using the complete search string, twelve different searches were performed using a combination of every term in both parts of the search string. Using this strategy, it was possible to retrieve almost 34 times more papers than when the complete string was employed.

The analysis to include/exclude and classify a paper was conducted by one of the authors. Since this may lead to a researcher bias, 15% of the papers were randomly selected before the subjective part of the screening phase to compose a set of control papers, and one of the other authors analyzed them. The authors compared their results using Cohen's Kappa coefficient, which measures the agreement between the two classifications taking into account how much agreement would be expected to be present by chance [17]. The coefficient lies between -1.0 and 1.0 in which 1.0 denotes perfect agreement, 0.0 indicates that any agreement is due to chance and negative values present agreement less than chance. Cohen's Kappa was used to measure the reliability regarding inclusion and exclusion of papers and the classification of the included papers in common according to the classification schema. There is no consensus on what are good levels of agreement. Nevertheless, a common scale [18] indicates that there is no agreement for negative values, poor agreement between 0.00 and 0.20, fair agreement between 0.21 and 0.40, moderate agreement between 0.41 and 0.60, good agreement between 0.61 and 0.80 and very good agreement for values higher than 0.80. Firstly, the classification ratio was below acceptance. The main reason for that was the fact that the first classification schema was leading to dubious interpretations. For instance, natural feature tracking was divided into model-based and model-less approaches, in which it was not clear if information used could be considered a model or not. The authors refined the classification schema to the one previously presented, which uses a more straightforward classification and reclassified all papers. Thus, the included/excluded papers Cohen's Kappa coefficient was 0.8062 ± 0.0495 and the classification Cohen's Kappa was 0.8345 ± 0.0303.

3. Results

The search was made between 29 and 30 October 2015 and resulted in 2276 papers found. As can be seen in Fig. 3, 593 papers were removed for being duplicated and 1231 papers were available for the subjective steps of screening. Only 360 papers remained for trends analysis and classification.

The annual trend of papers is shown in Fig. 4. It is possible to see that the number of works is growing since 2009, which indicates an increasing interest in tracking for mobile devices in recent years.

The 360 papers were published in 212 forums. As seen in Table 1, almost thirty percent of all works came from the top 15 venues. ISMAR is the flagship event in the field with 27 studies. Preferable targets for such works are conferences and symposiums in which 162 papers were published. They were followed by 41 journals works and 9 workshop studies.

Each paper was classified according to the scheme presented in Section 2. The full list of works can be accessed through an open source web application [19]. Using this system, it is possible to filter the papers according to the year and forum in which the works were published as well as the classification criteria. Moreover, collaborators can send new entries of studies about tracking for mobile devices, which will be revised by the authors and then added to the online data set. The web application can be accessed at http://www.cin.ufpe.br/~rar3/tracking_sm.

4. Mapping

From the classification of the studies it is possible to establish a mapping that aims to provide an overview of tracking for mobile devices and can help to identify potential research gaps. This map gives the distribution of works for each classification criteria, their annual trends and the relation between them.

4.1. Classification distribution

It is possible to see in Fig. 5 that most of the works, such as [20], rely on a combination of the devices' sensors to calculate pose and that marker-based tracking, which is used for example in [21], is the least used method for the same task. Moreover, it can be noted

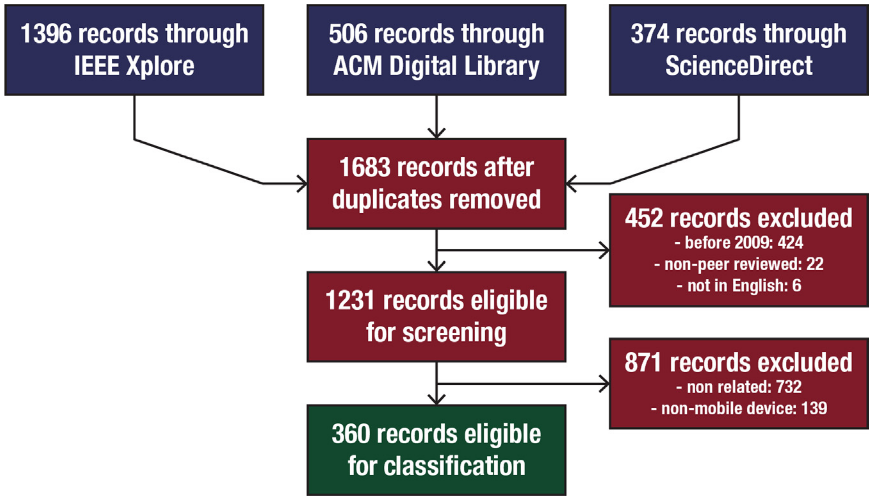

Fig. 3. Selection process shows the number of papers included and excluded and the reasons for exclusions.

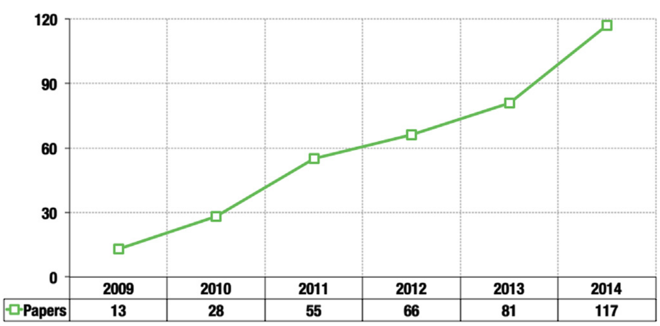

Fig. 4. Publications over time. Annual trend of papers included.

that vision-based methods like [22] are present in almost a third of the papers.

Table 2 lists the sensors used on each paper on which the tracking type is hybrid or based on sensors as well as the number of studies that uses them. Several works fuse different sensors and Table 2 also lists the 12 most common combinations.

Regarding the degree of freedom found in the works, several of them calculate a 6D pose [23], as shown in Fig. 6. However, in 58.6% of the studies a 2D position is computed. In some papers a 2D position on the screen is found [24], but the majority discover this 2D position on the environment [25]. In the latter case, there are more works that also discover the orientation θ [26], and the least common papers are the ones aiming 0D systems [27].

In the majority of the works all the processing needed to calculate a pose is done at the device [28]. Only 15.6% use a remote server to assist in this task [29] or completely perform pose calculation [30], as illustrated in Fig. 7.

Table 3 lists relevant studies for each classification, those with more citations per year.

As for research type, approximately two-third of the papers propose a new technique to perform tracking [53] and 28.6% use an existing technique to develop a mobile solution that requires tracking [54], as can be seen in Fig. 8.

4.2. Classification trends

The annual trend per tracking type shows that the number of papers about sensor-based systems is increasing. Moreover, the number of works that use a single sensor in 2014 is 9 times higher than in 2009 and 19.5 times larger for sensor fusion techniques, as can be seen in Fig. 9. From Fig. 9 (top) it is also possible to conclude that the other tracking types have an overall growing tendency. From 2009 to 2014 hybrid solutions went from 0 to 15 studies and natural feature solutions went from 3 works to 13 with static model studies and 3 to 11 with dynamic model papers. The growth of marker studies occurred in the last two years.

Regarding the annual trend per degree of freedom, it is possible to see in Fig. 10 an increasing number of publications about 2D, 2D + θ and 6D trackers. Respectively, they went from 4 to 50, 1 to 24 and 7 to 31 between 2009 and 2014. The image also shows that the community did not demonstrate the same interest in systems with 0D and 3D approaches, even though there were more 0D works in 2014 than in the previous years combined.

Most of the works use a local approach to calculate the device's pose and this fact is reflected in the annual trends per tracking platform, as shown in Fig. 11.

4.3. Classification relationship

The relationship between the classifications can provide a powerful and quick overview of tendencies on tracking for mobile devices. A bubble chart was used because it offers a more visual result than tables. Fig. 12 presents a bubble plot in two dimensions in which the leftmost represents the tracking type by tracking platform and the rightmost displays the tracking type by degree of freedom. It should be noted in the first dimension that the ratio of publications between local systems and the total of works is approximately the same for every tracking type.

The same balance cannot be seen in the second dimension, in which the majority of the sensor works are location-based solutions, such as [55] that computes a 2D pose and [56] for 2D + θ papers. Only three publications present a system that computes a 6D pose using only a combination of the device's sensors. One example is [57], in which the authors append a pico projector to a mobile device in order to make projective drawings on the wall. The approximated position is computed in a calibration step using the sensors, in which the user has to move the device according to a projected guide. All 94 2D works that use sensors to compute the pose are location-based systems, as well as both marker papers, such as [58], six of the hybrid works, like [59], and two of the static model studies, such as [60]. All the other 24 works compute a 2D position at the screen, as in [61].

Single sensor and sensor fusion systems are the only two tracking types in which a 6D pose is not the most common information required. For all other tracking types at least 58% of the papers are about a system that calculates a full rotation and

Table 1
List of the most popular publication forums.

Forum	Acronym	Type of forum	Number of papers	Percentage of the total
International Symposium on Mixed and Augmented Reality	ISMAR	Symposium	27	7.50
International Conference on Indoor Positioning and Indoor Navigation	IPIN	Conference	14	3.89
Conference on Multimedia and Expo	ICME	Conference	7	1.94
International Conference on Mobile Computing and Networking	MobiCom	Conference	6	1.67
Conference on Embedded Networked Sensor Systems	SenSys	Conference	5	1.39
IEEE Virtual Reality Conference	IEEE-VR	Conference	5	1.39
International Conference on Computer Vision	ICCV	Conference	5	1.39
Symposium on 3D User Interfaces	3DUI	Symposium	5	1.39
Conference on Computer Vision and Pattern Recognition	CVPR	Conference	4	1.11
Conference on Computer Communications	INFOCOM	Conference	4	1.11
Transactions on Visualization and Computer Graphics	TVCG	Journal	4	1.11
International Conference on Mobile Systems, Applications and Services	MobiSys	Conference	4	1.11
International Conference on Multimedia	MM	Conference	4	1.11
Sensors Applications Symposium	SAS	Symposium	4	1.11
Workshop on Applications of Computer Vision	WACV	Workshop	4	1.11
Other 197 Forums	–	–	258	71.67

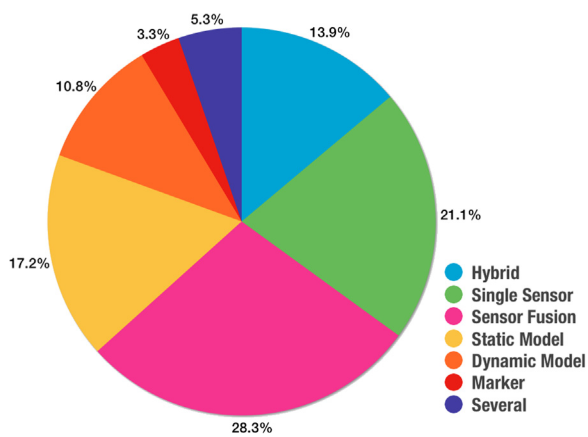

Fig. 5. Tracking type distribution over the database.

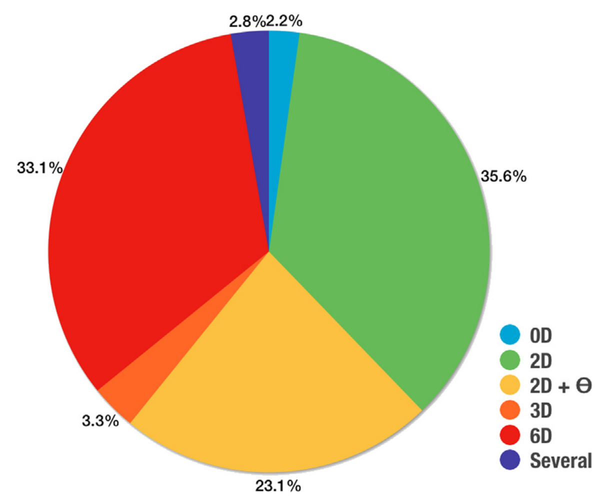

Fig. 6. Degrees of freedom distribution over the database.

Table 2
List of sensors and their most used combinations.

Sensor	Number of papers
Accelerometer	103
GPS	84
Wi-Fi	81
Magnetometer	68
Gyroscope	57
Cellular Network (GSM, CDMA)	28
Acoustic	13
Bluetooth	8
Barometer	4
Depth	4
Illuminance	2
Thermal	1
Combination of sensors	**Number of papers**
Wi-Fi	35
GPS	30
Accelerometer and Gyroscope	16
Accelerometer, Gyroscope and Magnetometer	14
Accelerometer	11
GPS and Wi-Fi	8
Accelerometer and Magnetometer	7
Accelerometer, GPS and Magnetometer	7
Cellular Network and GPS	6
Cellular Network	6
Accelerometer, Gyroscope, Magnetometer and Wi-Fi	6
Accelerometer and GPS	6
Other 42 combinations	76

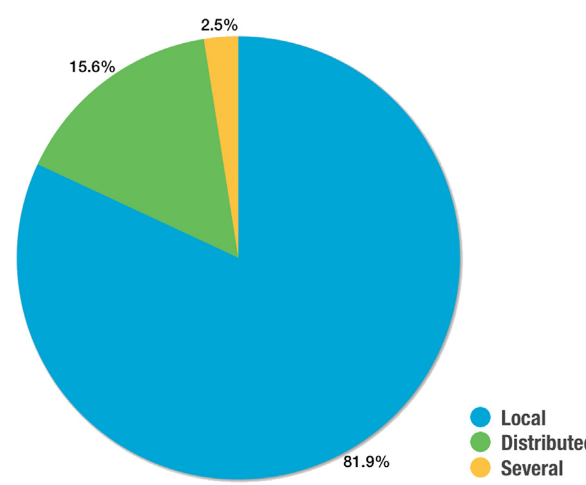

Fig. 7. Tracking platform distribution over the database.

translation pose, as exemplified in [62–65]. Additionally, the dynamic model technique is the only tracking type that has at least one paper for every degree of freedom.

The bubble chart in Fig. 13 presents the same dimensions of Fig. 12. The difference is that it combines the vision-based and sensor-based techniques. Additionally, it also combines both

Table 3
Relevant papers for each classification.

Tracking type	Relevant studies
Hybrid	Kurz et al. [31] and Ventura et al. [29]
Single sensor	Shin et al. [32] and Gozick et al. [33]
Sensor fusion	Chon et al. [34] and Zhang et al. [35]
Static model	Wagner et al. [22] and Hu et al. [36]
Dynamic model	Klein et al. [37] and Wagner et al. [38]
Marker	Oui et al. [21] and Gherghina et al. [39]
Degree of freedom	**Relevant studies**
0D	Rai et al. [40] and Lunbo et al. [41]
2D	Shin et al. [32] and Lv [42]
2D + θ	Schall et al. [43] and Shin et al. [44]
3D	Mingyang et al. [45] and Elloumi et al. [46]
6D	Takacs et al. [47] and Tanskanen et al. [48]
Tracking platform	**Relevant studies**
Local	Arth et al. [49] and Schöps et al. [50]
Distributed	Chen et al. [51] and Ventura et al. [52]

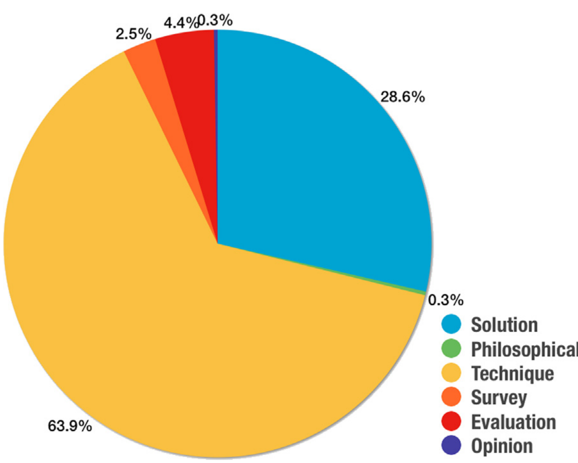

Fig. 8. Research type distribution over the database.

location-based solutions. These combinations make more evident that most of the vision-based techniques calculate a 6D pose and that the majority of the sensor-based approaches are location-based services. Regarding the first dimension, it is possible to see that the ratio between the number of local and distributed solutions for each tracking type stays almost the same.

The relationship of degree of freedom by tracking platform is shown in Fig. 14. The chart shows that for every degree of freedom category more than 80% of the publications are local. Moreover, all works that compute a 0D detection are local, such as [66].

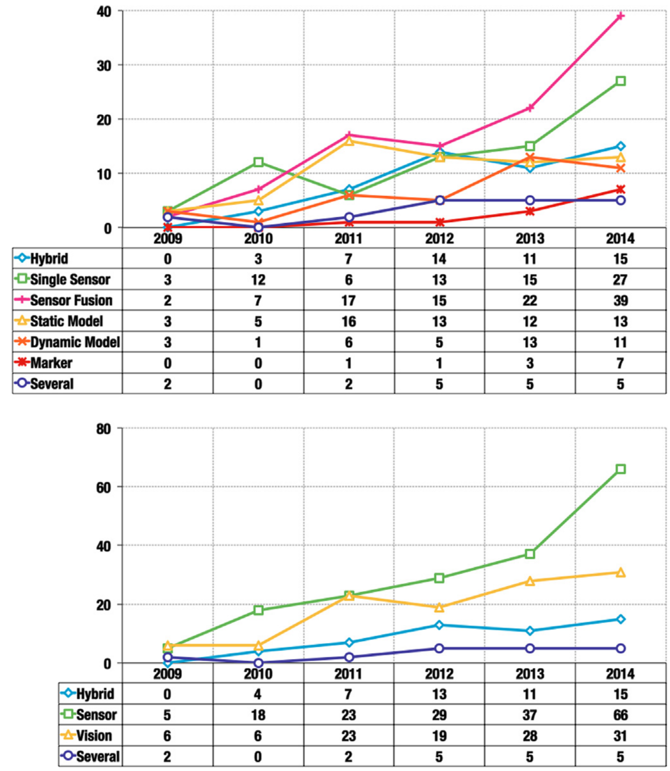

Fig. 9. Annual trend per tracking type. Trends of all tracking types (top) and yearly evolution of tracking types combining all vision-based techniques (bottom).

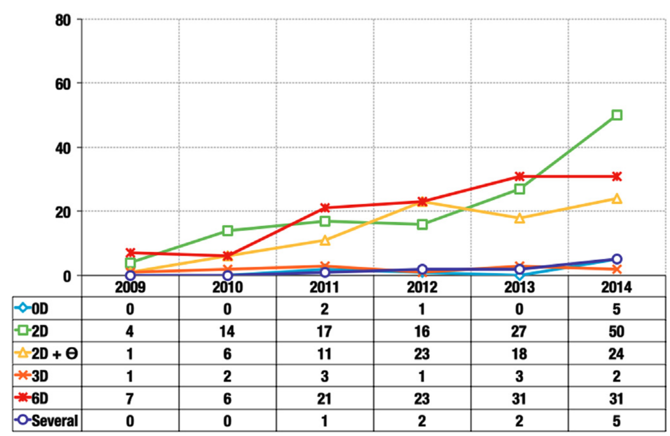

Fig. 10. Annual trend per degree of freedom.

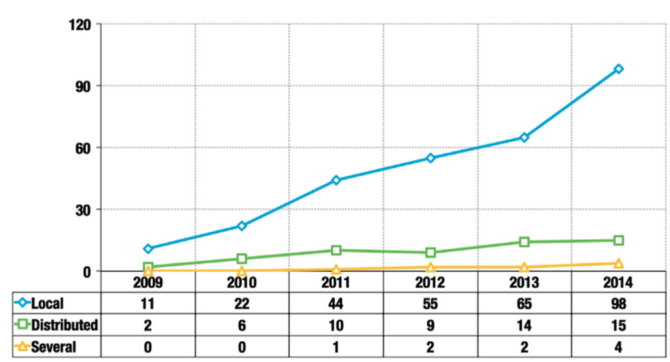

Fig. 11. Annual trend per tracking platform.

5. Discussion

Fig. 4 shows that the number of papers about tracking on mobile devices is increasing over the years. This is due to the improvement [5] and popularization [3,4] of such devices in recent years.

It is possible to see in Fig. 9 (top) that there was an increase of more than three times in the number of publications for all tracking types between 2009 and 2014. There is also a growth in the amount of vision-based works, as shown in Fig. 9 (bottom). These data indicate that this type of tracking becomes possible with the improvement of the computational power of devices, especially for natural feature tracking.

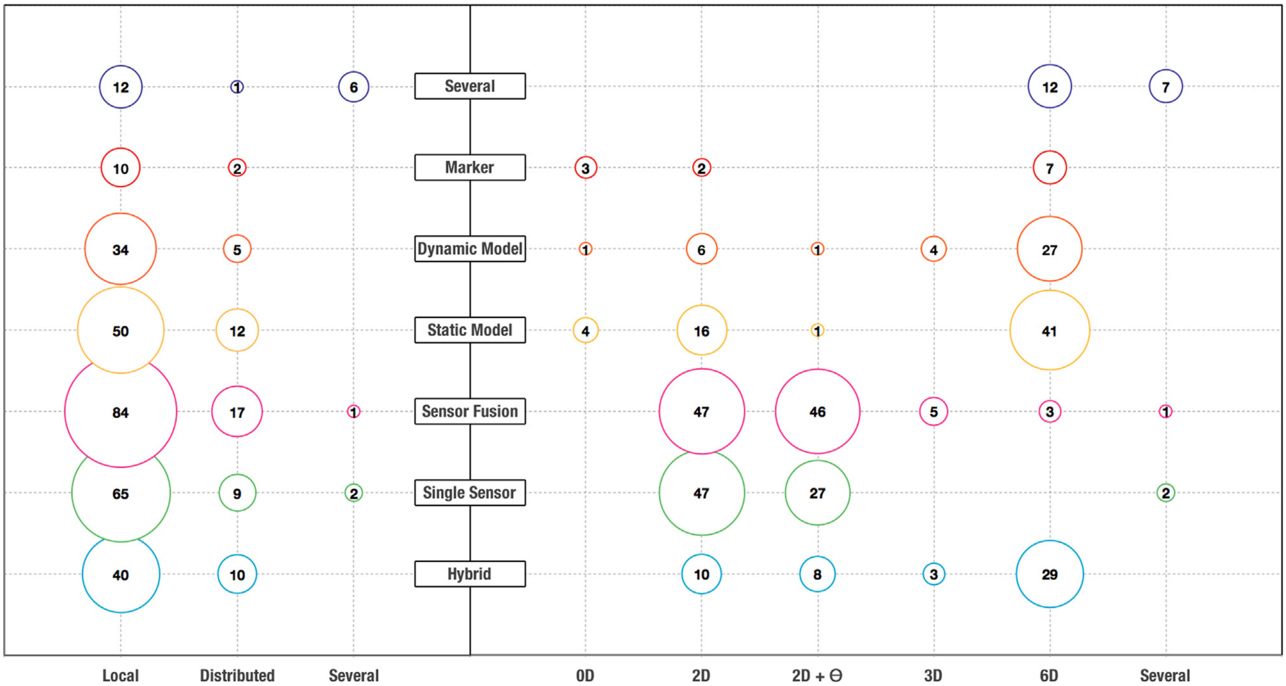

Fig. 12. Two dimensional bubble chart: left side presents the tracking type by tracking platform and the right side presents the tracking type by degree of freedom.

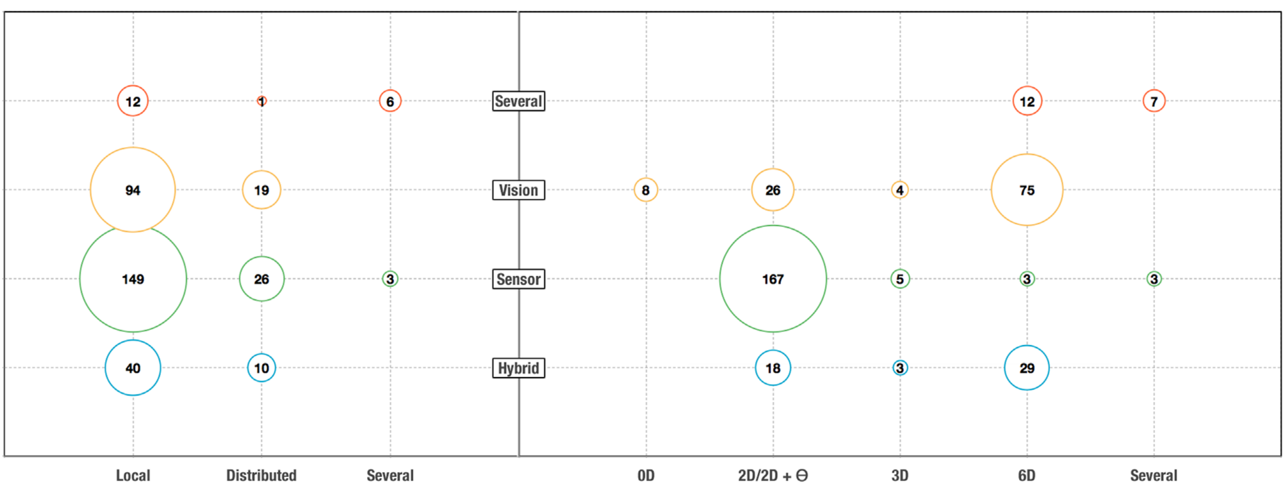

Fig. 13. Two dimensional bubble chart: left side presents the combined tracking type by tracking platform and the right side presents the combined tracking type by degree of freedom with location service systems combined.

Fig. 9 also shows that sensor fusion tracking had the biggest growth in the analyzed period. It is also possible to note in Fig. 5 that the majority of works use this type of tracking. Moreover, 49.4% of all studies do not rely on the camera to perform tracking. This is probably because it is the most suitable approach to compute a pose for location-based solutions, which use 2D and 2D + θ information, and this type of solution is one of the most common type of application for mobile devices. This relationship is emphasized in Figs. 12 and 13. Nevertheless, it should be observed that few works use sensors to compute a full 6D pose because of their technical limitation, such as noise and error accumulation.

The analysis revealed that 42.7% of all sensor papers use data from only one sensor to compute the device's pose. The other 57.3% perform tracking using a combination of different sensors. This fusion of sensors is important because it allows using the data from one sensor to overcome the weakness of another one. Moreover, all studies that use a single sensor are 2D or 2D + θ, as can be seen in Fig. 12. The 8 papers that use sensors to compute a 3D or 6D pose require a combination of them in order to perform tracking. As seen in Table 2, the three most common sensors are in some way related to providing the device's position. Wi-Fi is largely used to compute indoor position. Although noisy, GPS is a great way to determine outdoor localization. Accelerometer is very common because it can be used in combination with other sensors in both indoor and outdoor situations since it does not require any external infrastructure, such as access points.

Fig. 13 shows a clear trend that relates sensor techniques with location-based systems and vision-based approaches to solutions that require a 6D pose. Moreover, it is possible to see in Fig. 5 that static model tracking is the favorite among natural feature-based approaches. However, there is a significant amount of systems that use a dynamic model technique. One reason is that there are some works that use learning algorithms to calculate a pose, such as [67]. These techniques demand a huge processing power in the offline training phase that can be performed previously in a computer but does not use much processing for tracking, which

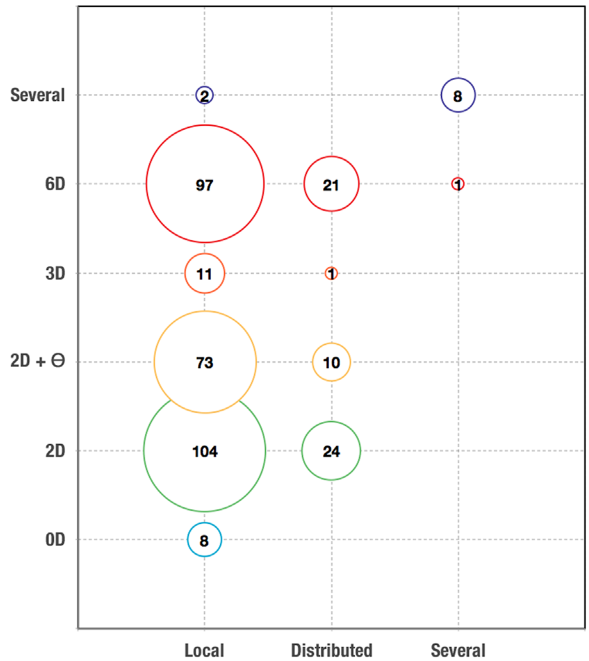

Fig. 14. One dimensional bubble chart of degree of freedom by tracking platform.

makes them more suitable for mobile devices. One advantage of these techniques is that the trained model is usually refined using the tracking results.

In fact, there was a huge increase in the number of publications of 2D and 2D + θ works, which had respectively a growth of 12.5 and 24 times between 2009 and 2014, as shown in Fig. 10. Papers with 6D systems grew almost 4.5 times in the same period, which is also a considerable value. All the other categories present a constantly low number of papers throughout the years. Moreover, Fig. 6 shows that 2D techniques are the most common ones. The main reason for this is that there is a high demand for location-based applications and the amount of publications reflect this. 6D systems are also very popular because it is the most traditional information required for tracking, especially for augmented reality systems. The fact that there are papers that calculate a 6D pose using every tracking type reflects the importance of computing the rotation and translation of the device relative to the real world, as observed in Fig. 12. Additionally, the majority of hybrid techniques calculate a full 6D pose. This approach is interesting because it combines the benefits of both vision and sensors to perform a more accurate and robust tracking. It is also possible to see in Fig. 6 that 0D and 3D approaches are the least common. This is due to the fact that there is a small number of applications that require a 0D or 3D pose.

Between 2009 and 2014 there was an increase of more than seven times in the number of publications of all tracking platforms, as observed in Fig. 11. Even with the devices' limitations, Fig. 7 shows that the majority of works execute all the steps to compute the pose at the device. One reason is the lack of a good communication infrastructure to transfer the data to a remote server. However, note in Fig. 11 that in the last two years distributed works are growing after a decline. This can be an indication that there is a recent improvement in the network infrastructure and researchers are exploring the use of a remote computer, which provides more resources than the mobile device, such as processing power, memory and storage space. Another reason is the possibility of using sensors that are not available in the device [68].

Fig. 12 indicates that there is no relationship between the tracking type and the execution platform since the proportion of local works per tracking type is almost the same as the distributed papers per tracking type. However, the same proportion is not seen when relating tracking platform with degree of freedom. It is possible to see in Fig. 14 that almost 80% of 2D papers are local while none 0D and only one 3D studies are distributed.

As seen in Fig. 8, the majority of the papers propose a new technique and there are also several works that use an existing technique to create a solution for an open problem. These two research types represent more than 92% of all studies classified. This is an indication that the demand for systems that use tracking is high. More than that, it is a clear suggestion that the field of tracking for mobile devices still has a lot of open problems to tackle.

5.1. Implications for future studies

This mapping study not only offers useful information for researchers who are interested in the existing works regarding tracking for mobile devices but also identifies gaps in this research topic.

Most of the works calculate the pose using devices' sensors or computer vision algorithms. However, there is a tendency to combine both approaches to provide a more robust tracking. One reason is the improvement and miniaturization of more complex sensors, such as depth cameras, which are already available on tablet devices [69] and have the potential to play an important role in new tracking techniques. In the near future, other sensors should also be embedded or integrated into mobile devices, like thermal sensors [70], stereo cameras [71] and radio frequency systems [72]. The use of these sensors in combination with the ones currently available and the camera will provide new tracking possibilities.

This mapping found a few studies focusing on the use of machine learning approaches to compute the pose. But this is a prominent research area because such algorithms learn what are the best features to be used for tracking [73]. Moreover, as mentioned before, learning techniques transfer most of the computational effort to an offline training phase while the tracking itself demands few processing resources, which makes them suitable for mobile devices. Machine learning is a mature area nevertheless, its use for tracking is recent. Thus, there are still several open problems in the area.

Recent improvements in communication networks enable the increasing number of works that use distributed approaches, as shown in this study. In the future, this infrastructure will probably be more reliable and faster [74], which creates new opportunities to perform tracking on remote servers, using the mobile device only to capture the input information and display the output results. Moreover, this connectivity is a basic requirement for creating sensitive environments using smart objects. These connected sensors can be used to share information with a mobile device in order to perform a more precise tracking. For instance, smart objects spread over an indoor place can be used to provide or improve the indoor localization of a person using a smartphone connected with them.

It is also important to be aware of the improvements of the hardware capabilities that will be available on mobile devices in a near future. New tracking techniques can be proposed or existing ones adapted taking into consideration the use of multiple cores of the device's processor and graphics processing unit (GPU). Beyond that, it is possible that several mobile devices will have chips dedicated exclusively to execute embedded computer vision algorithms, such as Qualcomm's Hexagon digital signal processor (DSP) [75]. These dedicated chips will allow tracking to be performed faster while consuming less energy.

It is possible to illustrate some technical problems that are still open in the field by using a challenging scenario, such as outdoor tracking on a mobile device in order to precisely annotate relevant information. Tracking an environment that is so large demands manipulation and storage of an immense amount of data. Since memory is a limited resource on mobile devices, one challenge is to develop a memory management system that is able to deal with such a big dataset. A similar approach was used to treat large scale mapping on desktop [76].

Another alternative to deal with large data would be to use a hybrid technique in which the device location is used in order to filter information with respect to what is seen on the screen [77]. Another possibility is to develop tracking systems capable of computing the device's pose both locally and distributed [29]. The challenge is to create an automatic evaluation procedure to determine which approach is more suitable depending on different characteristics, such as available network bandwidth or device's processing power.

Every city is a living organism. Thus, the environment can change because people will cross the camera field of view, illumination will vary during the day and the facades of buildings will be modified. One approach is to perform dynamic reconstruction and rely on a canonical map to track the environment, such as [78]. It can also be combined with different sensors and the challenge is how to combine different measurements in order to provide a unique tracking result.

6. Conclusion

This work presents a systematic mapping that summarizes existing works regarding tracking for mobile devices. In order to do so, 2276 unique papers were collected from three scientific databases using a crawler. After that, these works were screened using their abstracts. In total, 360 relevant records were identified in the 2009–2014 period and they were classified according to four properties: tracking type, degree of freedom, tracking platform and research type. Finally, this classification was analyzed and discussed.

The results obtained showed an increasing interest in tracking for mobile devices since the number of publications grew 9 times in the period. Sensor-based techniques are the most common approaches to perform tracking and the majority of the studies compute a 2D pose of the camera in relation the real world. Moreover, this study showed a clear trend that relates sensor techniques with location-based systems and vision-based approaches to solutions that require a 6D pose. There is also a preference for local-based tracking. Additionally, most of the studies propose a new tracking technique.

An open source web application is available containing the full list of classified papers, in which other researchers can access and filter the works according to their interest. Moreover, they can add new studies to the online data set. In the future, this web application will provide reports, rankings and charts, which can help new researchers by presenting an updated mapping of the field.

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