IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 5, 2020, accepted February 26, 2020, date of publication March 4, 2020, date of current version March 18, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2978174

Event-Based Control: A Bibliometric Analysis of Twenty Years of Research

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This work was supported in part by the Spanish Ministry of Science, Innovation and Universities, under Project DPI2016-77677-P, Project DPI2017-84259-C2-2-R, and Project CICYT RTI2018-094665-B-I00, and in part by the Community of Madrid, under the research network CAM RoboCity2030 S2013/MIT-2748.

ABSTRACT The potential benefits of networked control systems are tremendous, as they can be easily upgraded by just including new components (i.e., sensors, actuators, or controllers), avoiding any further modifications to their structure. A critical approach to unleash such potential benefits is event-based control, where the system output turns to be sampled on demand, instead of being sampled constantly at rigid periods of time. This paper analyzes from a bibliometric point of view the literature published for the last twenty years on event-based control, identifying the most relevant articles, authors, institutions, and journals. Moreover, the principal topics, motivations, and problems faced by the researchers are discussed, identifying distinct challenges and opportunities for future research.

INDEX TERMS Bibliometric analysis, event-triggered control, self-triggered control, distributed systems, estimation, nonlinear systems.

I. INTRODUCTION

Most control applications are implemented in digital platforms, which need to exchange information between sensors, controllers, and actuators at discrete instants. Traditionally, these instants are set by a sampling period, which equally distributes them in time. If the sampling period is sufficiently fast, then the control strategy can be designed assuming a continuous exchange of information. However, the development of communication, control and computation technologies in the last decades has produced great interest in networked control systems (NCSs), which involve a communication network. NCSs provide multiple benefits: cost reduction of installation and maintenance, reliability improvement, flexibility increase, etc. As a consequence of this change of paradigm, controllers have to be designed by taking into account the network's implementation.

In this context, the interest in the idea of when the system's output should be sampled and when the control's action should be executed has considerably grown. *Event-based strategies* introduce a ‘‘feedback’’ in the sampling tasks: instead of a constant sampling period, the information transmission is carried out when the system ‘‘demands’’ it.

Before going into the paper, it is worth noting that there is a lack of uniform terminology for this concept. Following [1], in this paper *event-based control* denotes control strategies in which measurements rather than the time determines when to sample. We differentiate between the two main strategies: *event-triggered control* and *self-triggered control*. The first one is a reactive strategy: a triggering condition is monitored; and when it is violated, an event is generated, producing the transmission of information. Depending on the characteristics of the condition, different notations might be used, such as *send-on-delta control* or *deadband control*. The second one is a predictive strategy. Using the available information and a model or knowledge of the system's dynamics, the next transmission instant is precomputed during the current transmission. One of the most important applications of event-based control is to distributed and decentralized systems. In general, each node in a decentralized system

The associate editor coordinating the review of this manuscript and approving it for publication was Zheng H. Zhu.

makes the decisions based only on its own behavior, while each node in a distributed system takes into account the information of its neighbors, but it does not have access to global information. However, these definitions are not followed consistently in the literature, and usually the terms distributed and decentralized are equally used. Moreover, both ideas can be mixed, e.g., a distributed controller with decentralized event-triggering mechanisms. For that reason, in this paper we simply denote an approach as *distributed* when there is no global information available.

Since 1999, abundant research has been undertaken on event-based control. To understand the extensive literature on this topic, this paper analyzes 2,299 research articles, providing the answer to the following research questions:

- What articles are the most influential?
- What actors lead the research on event-based control (authors, institutions, and journals)?
- What control and estimation problems have proved to be more interesting from the point of view of event-based control? How has this interest evolved over time?
- What challenges does future research need to address?

The remainder of this paper is organized as follows: In Section 2, related books and overviews about event-based control are presented. The methodology followed to conduct our bibliometric analysis is sketched in Section 3. Then, the results are summarized and discussed in Section 4. Finally, the main conclusions are provided in Section 5.

II. RELATED WORK

Research on event-based control has grown considerably since the publication of Årzén's [2] and Åström *et al.*'s [3] seminal papers twenty years ago. As we will see in Section IV-F, this trend has accelerated recently: the number of articles published in the last two years is nearly the same as in the previous eighteen years.

To analyze the extensive literature that has been published, several surveys and literature reviews have been written addressing different aspects of the field. In 2007, Hespanha *et al.* [4] published an introduction to NCSs. Even when event-based control strategies are not considered in this paper, it states the main advantages and disadvantages of communication networks, and therefore, the main issues with which event-based control strategies are going to deal.

Later, in 2012, Heemels *et al.* [1] published the first introduction to event-triggered and self-triggered control. After this article, different surveys have been published, such as the one devoted to event-based control for NCSs [5], event-based estimation [6], event-based nonlinear control [7], periodic event-triggered control [8], event-based filtering [9], event-triggered consensus [10] or event-based communication [11].

Several books have also been published with the aim of compiling the knowledge about the field: in [12], the event-based paradigm is examined in control, communication, and signal processing; [13] describes different techniques of asynchronous control and focuses specifically on event-based control strategies; and, finally, event-based estimation is studied in [14].

This paper contributes by analyzing a much larger number of articles with an alternative approach: instead of a survey or a literature review on a more reduced number of papers on the topic, we present a longitudinal bibliometric analysis that provides a general overview of the whole literature published on event-based control, detecting also trending topics that foreseeably will be further developed in the near future.

III. MATERIALS AND METHODS

A. RESEARCH QUESTIONS

This paper targets the following research questions:

RQ1. What articles are the most influential? Rationale: A goal of this paper is to offer guidance on the vast literature available about event-based control. A fundamental aspect of this guidance is identifying the most prominent articles (see Section IV-A).

RQ2. What actors are leading the research on event-based control?

Rationale: In addition to the most relevant articles, our work looks for identifying the main contributors distinguishing: (i) the most cited authors and their collaboration networks, (ii) the principal journals, and (iii) the institutions/-countries that have contributed the most to the research area (see Section IV-A).

RQ3. What control and estimation problems have proved to be more interesting from the point of view of event-based control? How has this interest evolved over time?

Rationale: Control engineering is a vast and horizontal field with applications in many other areas. Recognizing which specific problems have been successfully solved using event-based control may reveal new areas of future utilization. Moreover, our work examines if the relation between theoretical and practical research is balanced, investigating to what extent articles go beyond academic concerns, and deal with actual industrial problems (see Sections IV-B to IV-D).

RQ4. What challenges does future research need to address?

Rationale: With the aim of detecting new challenges or research gaps that need future explorations, this paper puts particular emphasis on the literature published recently (see Section IV-F).

B. PAPERS' IDENTIFICATION

The first step we took for answering this work's research questions was obtaining a representative publication sample. As other authors have pointed out [15]–[17], finding the complete set of all relevant articles for a broad scope literature review is unrealistic. Accordingly, we pursued the more modest goal of getting a sound publication sample able to represent the population adequately. To do so, we followed the systematic procedure summarized in Figure 1.

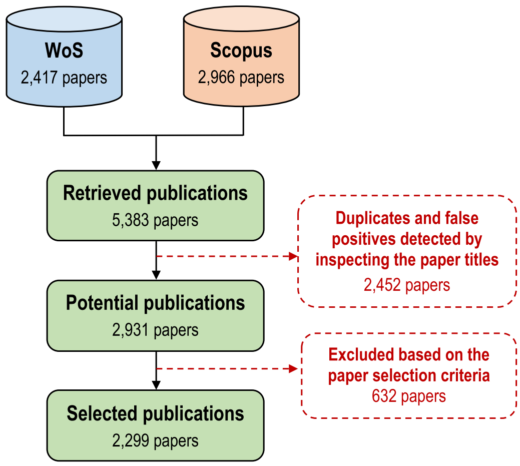

FIGURE 1. Schematic summary of the publication selection procedure. 5,383 candidate publications were gathered from WoS and Scopus. After discarding duplicates and papers out of scope, 2,299 publications were selected for analysis.

The following string query was designed to get the publication sample from bibliographic databases, looking for an equilibrium between identifying the maximum amount of articles related to the topic and minimizing the number of false positives.

```
1 (
2   ( event-based OR event-trigger* OR event-driven
3     OR send-on-delta OR self-trigger* )
4   W/10 (
5     control* OR sampl* OR transmission* OR communication*
6     OR consensus OR feedback OR estimation OR measure*
7     OR strateg* OR stabiliz* OR synchronization
8   )
9 ) OR ( "lebesgue sampling" ) OR ( "lyapunov sampling" )
```

We restricted our search to the databases that nowadays render the highest quality for longitudinal bibliometric analyses [18]–[20]: Web of Science (WoS) by Clarivate Analytics, and Scopus by Elsevier. The query combines different terms using the Boolean connector `OR`, and the proximity operator `W` (i.e., `word1 W/10 word2` means that `word1` and `word2` can be placed at a maximum distance of ten words). It also includes the asterisk symbol (`*`), which represents any group of characters, including no character.

The query has three main parts: first, in lines 2-3, the two sampling approaches are included. In the self-triggered control approach, the notation has stayed the same since the seminal paper [21]. However, in the event-triggered control approach, different names have been equally used, such as *event-based* [2], *event-trigger** [22], and *event-driven* [23]. We include the term *send-on-delta* as well, since it is a strategy of event-triggered control that usually appears without reference to *event-triggered* [24].

Second, in lines 5 and 7, we consider the different problems, frameworks and situations intrinsically related to the approaches. Hence, *control**, *feedback*, *stabiliz** usually refer to control problems; *consensus* and *synchronization* are related to distributed and/or multi-agent systems; *sampl**, *transmission**, *communication**, *measure** are oriented to papers which emphasize the sampling approach; *estimation* is logically dedicated to estimation problems; and *strateg** tries to cover papers that do not specify more information in their title. Naturally, many papers include more than one of these terms.

Finally, line 9 is incorporated to consider some publications specifically focused on Lebesgue and Lyapunov sampling. They are separately included because the terms *Lebesgue sampling* and *Lyapunov sampling* always appear in that form [25], while terms like *Lyapunov control* can refer to a wide range of topics out of scope. For the same reason, we do not consider terms like *feedback scheduling*, even when some papers are related to event-triggered control, such as [26].

5,383 candidate articles were retrieved from the databases, which were subsequently filtered according to a precisely defined protocol. Papers were selected whenever they satisfied some of the following paper **I**nclusion criteria:

I1 Publications focused on event-based control.
I2 Publications that contribute to ask at least one of these paper's RQs.

and none of the following **E**xclusion criteria.

Non-peer
E1 reviewed publications.
E2 Articles not written in English.
E3 Publications not accessible in full-text.
E4 Papers presenting summaries of conferences/editorials, or published in the form of abstract or poster.

Each paper's filtering was conducted by two of the article's authors selected at random. In the case of disagreement, a third author arbitrated the final decision. The process ended up with a sample of 2,999 articles that fulfilled the inclusion/exclusion criteria above.

C. PAPERS' CLASSIFICATION

To analyze the discipline development over time and to detect future research trends, the publication sample was classified. Several aspects were considered to set the categories of interest for the classification, including (i) the thematic areas discussed in the surveys summarized in Section II, (ii) some dedicated conferences to this thematic (e.g., the IFAC Workshop on Distributed Estimation and Control in Networked Systems, and the International Conference on Event-Based Control, Communication, and Signal Processing), and (iii) the paper authors' knowledge and expertise. As a result, the following categories were adopted:

- *Timing:* In the literature, there are two main approaches to decide when the system is sampled, monitored or when new control actions are computed: event-triggering and self-triggering. The last strategy avoids the waste of resources in monitoring the state or other variables of the system by making a prediction, based on the current measurement, of when a new action will be required. For event-triggered control, we distinguish the nature of the time sets depending on if they have a continuous or discrete nature. In the latter case (discrete event-triggered control), it is relevant to analyze if the model for the system is also discrete or not. When discrete models are considered, most of the existing strategies for continuous time can be extended easily. Another interesting approach is when the model of the plant is continuous, but a kind of "sampled-data" strategy is taken, yielding to what is known as *periodic event-based control*. Thus, three categories have been considering regarding the timing: *self-triggered control*, *continuous event-triggered control*, and *discrete event-triggered control*, which merges the aspects mentioned above.

- *Objective:* We mainly focus on two topics here: estimation and control. The *estimation* category may cover papers on state estimation, signal processing, filtering or fault detection; whereas the *control* category includes those works where a controller for the system is designed, independently of the objective (stabilization, tracking, consensus, synchronization, to cite a few). Moreover, those architectures that consider an observer to include the estimation in the control algorithm are classified into the topic of control rather than estimation. An issue that falls out of these two is the design of network architectures or protocols for event-triggered control systems, and hence, this has been considered as a different category.
- *Design method:* For those papers that come under the control topic, the design method employed for the controller has been examined. More specifically, it is distinguished between *state feedback*, *output feedback*, *model predictive* or *model-based controllers*, *PID*, and *other design methods*, which may include nonlinear methods or intelligent control techniques, for example. It is important to remark that state and output feedback approaches may consider dynamical controllers, where PID control is included. However, a separated category is considered for PID because of its importance in the industry [27].
- *Architecture:* While the first papers on event-triggered control focused on single plants and centralized approaches, the proliferation of networked control systems, especially over wireless communication, has made that decentralized/distributed implementations are more convenient. Thus, this aspect has been used in the analysis. Moreover, the recent interest and considerable amount of papers on the topic of multi-agent systems (mainly based on decentralized/distributed approaches) has motivated to treat this issue separately.
- *System dynamics:* Many processes and systems cannot be modeled adequately through linear systems. Consequently, the classification distinguishes when the system dynamics are linear and nonlinear.
- *Experimental results:* Given the importance that published research includes some empirical validation, implemented over real systems, that tests its robustness and effectiveness, our classification identifies whether such validation is reported or not.

It is worth noting that we performed the categorization manually: each paper was classified by two of us, participating a third author in case of disagreement. Bibliometric studies often use automatic procedures to classify the papers [28], [29]; for instance, applying clustering algorithms to extract patterns from the articles' keywords. However, we found those approaches superficial for the kind of classification that our work pursues, since it requires a deep understanding the papers. For example, some articles do not explicitly mention if they deal with discrete or continuous models, or if any experimental validation has been performed. That information needs to be determined by a human expert after reading the paper.

D. IDENTIFYING THE MOST PROMINENT PAPERS

One of this paper's goals is identifying the most influential papers on event-based control. For that, we have adopted the *h-index* approach by Martínez *et al.* [30] to characterize the area's *citation classics* [31].

The h-index was developed by Hirsch [32] to measure with a single indicator both the productivity and impact of a scholar. A researcher has index h if she has published h papers that have been cited at least h times. Analogously, a research area has index h if h papers have been published in the area that have been cited at least h times. As a result, the top h papers of a research area constitute its citation classics.

An article may sometimes appear in both databases WoS and Scopus with different citation counts. For those cases, we have considered the maximum count, as recommended in other bibliometric analyses [28], [33].

IV. RESULTS AND DISCUSSION

A. OVERALL HISTORICAL REVIEW

The basic idea of event-based control is to take into account the process state to decide when to execute the control and sampling tasks. Although this idea appears in the *adaptive sampling* popularized in the 60s and 70s [34], [35], it was the increasing interest on wired and wireless networked control systems, together with the potential advantages of applying event-based techniques over them, in terms of energy, computational and bandwidth savings, what caught the attraction of researchers at the beginning of this century.

To facilitate the comprehension regarding how the event-based control literature has grown over time, Figure 2 depicts the number of papers published per year since the publication of the Årzén's [2] and Åström *et al.*'s [3] works. It is worth noting that some other papers explored different aperiodic control strategies before and after them, such as the aforementioned adaptive sampling, non-uniform sampling [36], controlled communication [37] or intermittent control [38], and even the term "event-based" was used before in the context of discrete event specified systems [39]. Nevertheless, [2] and [3] are the first articles that show the

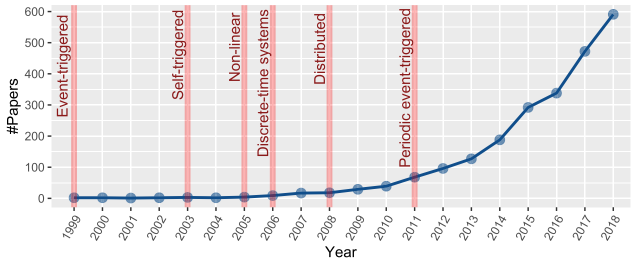

FIGURE 2. **Number of published papers over time.**

potential benefits of the event-based control, especially for NCSs, and for these reasons, they are the starting point of our analysis.

It can be observed that, after an inception period where first theoretical frameworks were proposed (e.g., [22], [23], [40], [41]), the research literature has increased dramatically up to nowadays. The red bars in Figure 2 highlight the following milestones:

- *Seminal papers on event-triggered control*: Årzén. "A simple event-based PID controller", 1999 [2], and Åström and Bernhardsson. "Comparison of periodic and event based sampling for first order stochastic systems", 1999 [3]. The first article [2] can be considered the paper that introduces first the concept of event-based control in the context of saving resources in a digital control loop. The authors present an event-based implementation of a PID controller over a two-tank system with a substantial reduction in the number of measurements. However, the potential benefits of its usage in networked environments and distributed systems is already commented in the introduction, and the problems that face event-based control such as the lack of stability theory, proper design methods, and the impact of noise over the number of samples are also identified. The second paper [3] compares analytically (in terms of closed loop variance and sampling rate) the performance of event-based and periodic sampling for a first order stochastic system with impulse controller, showing the improvements that event-based sampling can achieve. However, the results are limited to the aforementioned class of system and the authors comment on the difficulty of extending the results to a general case.
- *Self-triggered*: Velasco *et al.* "The self triggered task model for real-time control systems", 2003 [21]. This paper introduces the idea of self-triggering as a way of optimizing control performance and computing resources jointly. The authors propose a method that estimates the next sampling instant based on the current state (using a nonlinear function) and the utilization factor of the processor. The main issues of the work are the analysis and the design of the control law that can support this sampling policy and the vulnerability to disturbances, since the controller is not aware of what happens in the inter-sampling times. Later, in 2008, two papers formalized the idea of self-triggered control, where analytical expressions of how to compute the sampling instants are provided [42], [43].
- *Non-linear*: McCann *et al.* "A new multisensor network for collision avoidance and jackknife prevention of articulated vehicles using Lebesgue sampling", 2005 [44]. The paper proposes Lebesgue sampling (also known as send on delta sampling) for a sensor network of accelerometers and gyroscopes in charge of monitoring the state of a truck for safety reasons. The work shows that such sampling method increases the speed of response, for instance, in case of a rapid braking or a lane change are required to avoid a collision, and there exists an experimental validation. However, though a nonlinear model for the truck is considered, there is no supporting theory to derive the stability bounds or to design the Lebesgue sampler. From an analytical point of view, the first paper that deals with event-triggered control for nonlinear systems is [22], which is the most cited article in the field, since addresses for the first time several aspects that are crucial in the theory of event-based control such as existence of lower bounds for the interexecution times.
- *Discrete-time systems*: Bao *et al.* "Encoder-decoder design for event-triggered feedback control over band limited channel", 2006 [45]. This paper introduces the use of a discrete-time model for the system, since the objective is to minimize a design criterion, e.g., a quadratic cost over a finite horizon. Thus, the use of such discrete models is common in networked control systems where there exists an optimization function, for instance, in model predictive controllers [46], or when there are any kind of iterative processes, such as receding controllers or estimation across the network [47].
- *Distributed*: Mazo *et al.* "On event-triggered and self-triggered control over sensor/actuator networks", 2008 [48], and Wang *et al.* "Event-triggered broadcasting across distributed networked control systems", 2008 [49]. The first paper presents an event-triggered strategy in which each node uses its local information to determine when to make a transmission and a self-triggered strategy in which the actuator node determines for how long the sensing nodes should sleep before collecting and transmitting fresh measurements. The fact that each node handles only local information involves a change of paradigm in the event-based control. However, the proposed algorithm requires to reconstruct the state and the control signal of the overall system by means of an algorithm called *Tree Wave*, which introduces delays in the system. This issue was addressed in subsequent work [50]. The second paper presents a distributed event-triggered communication strategy for linear interconnected systems and proofs of the exclusion of Zeno behavior are given. The results are extended to a more general setup in [51].
- *Periodic event-triggered*: Heemels *et al.* "Periodic event-triggered control based on state feedback",

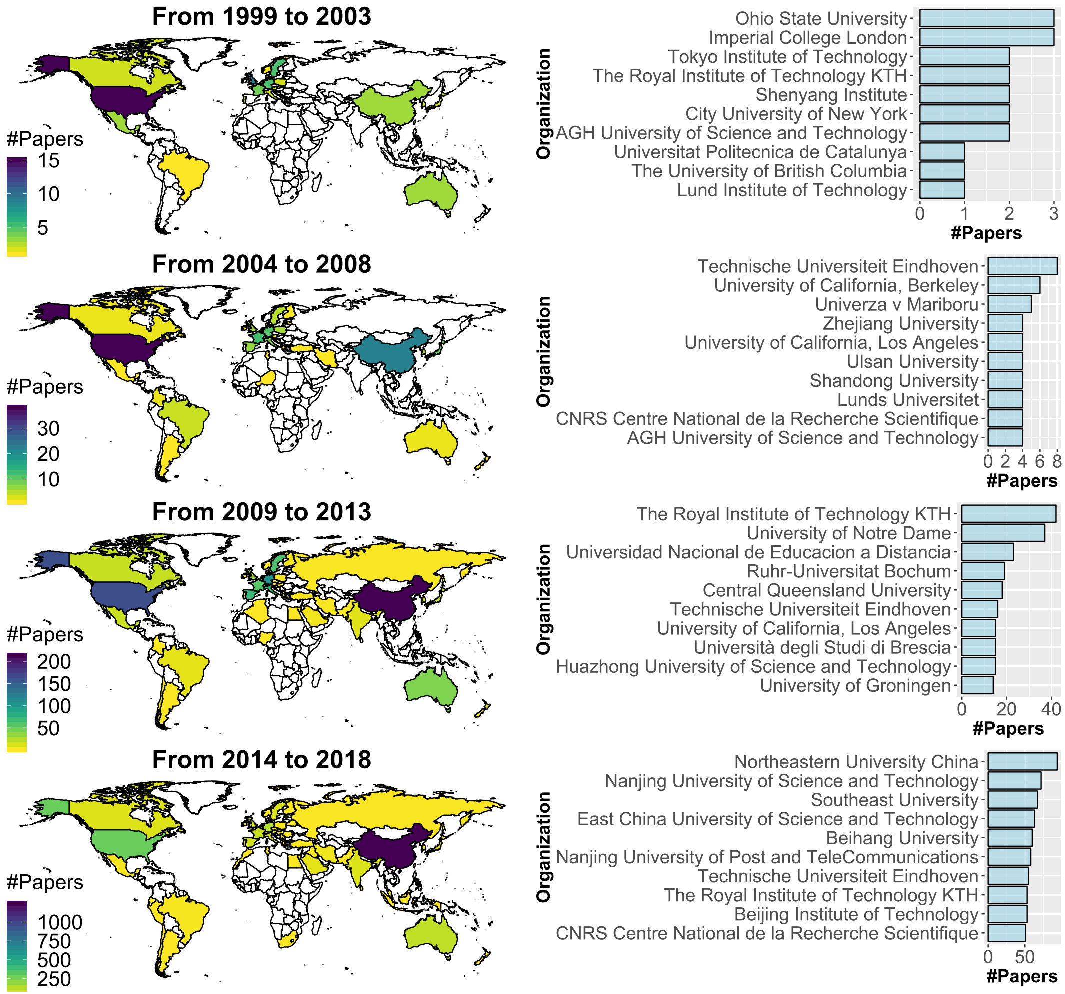

FIGURE 3. **Most prolific countries and research centers over time.**

2011 [52]. This paper addresses for the first time the problem of the practical implementation of continuous event-triggering (continuous monitoring of signals is required) but without ignoring that the system dynamics is still continuous. Then, the triggering mechanism is only checked at discrete instants of time specified by a period, and the event times are only a subset of those, hence, avoiding by design the occurrence of Zeno behavior. This paper started a new research line in which the rate at which the event condition is checked becomes part of the design of the event-triggering policy. A different approach that yields to a similar design was also published in 2011 [53], where the theory of time-delay systems is applied. This will be commented in detail in the next section.

Table 1 lists the all-times most influential papers on event-based control. Note that excluding [2], [3], [21], [25], [40], the rest of the papers have been published in the last decade, once the theory on event-based control was established. This fact can also be noticed when looking at Figure 3, where the number of publications per institution is depicted over time. Note that from 2004-2008 to 2009-2013 the average of publications for the most prolific institutions was multiplied by 5, approximately. Regarding the geographic localization, Figure 3 illustrates how the leading institutions have moved in the last five years from Europe and North-America to China, since 7 out of 10 of the most prolific institutions were Chinese in 2014-2018.

Figure 4 shows the most prominent journals on event-based control. Most of them belong to the category "Automation & Control Systems" of the Journal Citation Reports (JCR). However, there exists a group that belongs to the area of computer science (information systems or artificial intelligence), in which the number of publications on the topic of event-based control has increased in the last years, when other strategies, such as neural networks or fuzzy logic, for example, have been applied to solve the problem of event-based control of (mainly) nonlinear systems. A third and reduced group of journals belongs to other engineering categories such as mechanical or multidisciplinary engineering, with a strong mathematical component.

TABLE 1. Citation classics (the *h*-index is 79).

Article	Year	#Citations
Tabuada [22]: Event-triggered real-time scheduling of stabilizing control tasks	2007	1484
Dimarogonas et al. [54]: Distributed event-triggered control for multi-agent systems	2012	698
Wang et al. [51]: Event-triggering in distributed networked control systems	2011	654
Åström et al. [25]: Comparison of Riemann and Lebesgue sampling for first order stochastic systems	2002	618
Lunze et al. [55]: A state-feedback approach to event-based control	2010	579
Seyboth et al. [56]: Event-based broadcasting for multi-agent average consensus	2013	514
Yue et al. [57]: A delay system method for designing event-triggered controllers of networked control systems	2013	512
Heemels et al. [1]: An introduction to event-triggered and self-triggered control	2012	500
Anta et al. [58]: To sample or not to sample: Self-triggered control for nonlinear systems	2010	478
Åström et al. [3]: Comparison of periodic and event based sampling for first-order stochastic systems	1999	468
Årzén [2]: A simple event-based PID controller	1999	451
Heemels et al. [23]: Analysis of event-driven controllers for linear systems	2008	444
Wang et al. [41]: Self-triggered feedback control systems with finite-gain $\mathcal{L}_2$ stability	2009	443
Donkers et al. [59]: Output-based event-triggered control with guaranteed $\mathcal{L}_\infty$- gain and improved and decentralized event-triggering	2012	420
Heemels et al. [60]: Periodic event-triggered control for linear systems	2013	391
Mazo et al. [50]: Decentralized event-triggered control over wireless sensor/actuator networks	2011	359
Fan et al. [61]: Distributed event-triggered control of multi-agent systems with combinational measurements	2013	342
Garcia et al. [62]: Model-based event-triggered control for systems with quantization and time-varying network delays	2013	279
Guo et al. [63]: A distributed event-triggered transmission strategy for sampled-data consensus of multi-agent systems	2014	271
Velasco et al. [21]: The self triggered task model for real-time control systems	2003	268
Heemels et al. [64]: Model-based periodic event-triggered control for linear systems	2013	264
Miskowicz [40]: Send-on-delta concept: An event-based data reporting strategy	2006	256
Peng et al. [65]: Event-triggered communication and H_∞ control co-design for networked control systems	2013	253
Zhu et al. [66]: Event-based consensus of multi-agent systems with general linear models	2014	245
Mazo et al. [67]: An ISS self-triggered implementation of linear controllers	2010	235
Zhang et al. [68]: Observer-based output feedback event-triggered control for consensus of multi-agent systems	2014	210
Dimarogonas et al. [69]: Event-triggered control for multi-agent systems	2009	203
Hu et al. [70]: Event-triggered control design of linear networked systems with quantizations	2012	193
Peng et al. [71]: To transmit or not to transmit: A discrete event-triggered communication scheme for networked Takagi-Sugeno fuzzy systems	2013	191
Eqtami et al. [46]: Event-triggered control for discrete-time systems	2010	181
Wu et al. [47]: Event-based sensor data scheduling: Trade-off between communication rate and estimation quality	2013	181
Li et al. [72]: Event-triggering sampling based leader-following consensus in second-order multi-agent systems	2015	179
Mazo et al. [48]: On event-triggered and self-triggered control over sensor/actuator networks	2008	171
Zhang et al. [73]: Event-based H_∞ filtering for sampled-data systems	2015	171
Henningsson et al. [74]: Sporadic event-based control of first-order linear stochastic systems	2008	166
Zhang et al. [75]: Event-triggered dynamic output feedback control for networked control systems	2014	160
Peng et al. [76]: A novel event-triggered transmission scheme and $\mathcal{L}_2$ control co-design for sampled-data control systems	2013	147

TABLE 1. *(Continued.)* Citation classics (the *h*-index is 79).

Article	Year	#Citations
Hu et al. [77]: Consensus of linear multi-agent systems by distributed event-triggered strategy	2016	146
Postoyan et al. [78]: A framework for the event-triggered stabilization of nonlinear systems	2015	142
Girard [79]: Dynamic triggering mechanisms for event-triggered control	2015	139
Ge et al. [80]: Distributed event-triggered H_∞ filtering over sensor networks with communication delays	2015	136
Lemmon [81]: Event-triggered feedback in control; estimation; and optimization	2010	132
Zhu et al. [82]: Event-based leader-following consensus of multi-agent systems with input time delay	2015	128
Shi et al. [83]: Network-based event-triggered control for singular systems with quantizations	2016	118
Borgers et al. [84]: Event-separation properties of event-triggered control systems	2014	117
Yu et al. [85]: Event-triggered output feedback control for networked control systems using passivity: Achieving $\mathcal{L}_2$ stability in the presence of communication delays and signal quantization	2013	112
Zhang et al. [86]: An overview and deep investigation on sampled-data-based event-triggered control and filtering for networked systems	2017	112
Hu et al. [87]: Event-based H_∞ filtering for networked system with communication delay	2012	111
Li et al. [88]: Event-triggered robust model predictive control of continuous-time nonlinear systems	2014	108
Wang et al. [49]: Event-triggered broadcasting across distributed networked control systems	2008	104
Garcia et al. [89]: Decentralized event-triggered consensus with general linear dynamics	2014	103
Cervin et al. [90]: Scheduling of event-triggered controllers on a shared network	2008	102
Garcia et al. [91]: Decentralised event-triggered cooperative control with limited communication	2013	99
Zou et al. [92]: Event-triggered state estimation for complex networks with mixed time delays via sampled data information: The continuous-time case	2015	99
Ding et al. [93]: Event-triggered consensus control for discrete-time stochastic multi-agent systems: The input-to-state stability in probability	2015	99
Cheng et al. [94]: An asynchronous operation approach to event-triggered control for fuzzy Markovian jump systems with general switching policies	2018	96
Wang et al. [95]: On event design in event-triggered feedback systems	2011	95
Liu et al. [6]: A survey of event-based strategies on control and estimation	2014	95
Zhang et al. [96]: Network-based output tracking control for T-S fuzzy systems using an event-triggered communication scheme	2015	95
Li et al. [97]: Event-triggered H_∞ state estimation for discrete-time stochastic genetic regulatory networks with Markovian jumping parameters and time-varying delays	2016	95
Garcia et al. [98]: Model-based event-triggered control with time-varying network delays	2011	94
Donkers et al. [99]: Output-based event-triggered control with guaranteed $\mathcal{L}_\infty$- gain and improved event-triggering	2010	93
Lehmann et al. [100]: Event-based output-feedback control	2011	93
Zhang et al. [101]: Event-driven observer-based output feedback control for linear systems	2014	93
Yang et al. [102]: Decentralized event-triggered consensus for linear multi-agent systems under general directed graphs	2016	93
Han et al. [103]: Stochastic event-triggered sensor schedule for remote state estimation	2015	92
Pawlowski et al. [104]: Simulation of greenhouse climate monitoring and control with wireless sensor network and event-based control	2009	91
Trimpe et al. [105]: Event-based state estimation with variance-based triggering	2015	91
Anta et al. [42]: Self-triggered stabilization of homogeneous control systems	2008	90
Sijs et al. [106]: Event based state estimation with time synchronous updates	2012	90
Fan et al. [107]: Self-triggered consensus for multi-agent systems with Zeno-free triggers	2015	90

TABLE 1. ***(Continued.)*** **Citation classics (the *h*-index is 79).**

Article	Year	#Citations
Hu et al. [108]: Event-driven networked predictive control	2007	87
Zhang et al. [109]: Event-triggered H_∞ reliable control for offshore structures in network environments	2016	87
Li et al. [110]: Event-triggered asynchronous intermittent communication strategy for synchronization in complex dynamical networks	2015	85
Chen et al. [111]: Event-triggered average consensus control for discrete-time multi-agent systems	2012	83
Molin et al. [112]: On the optimality of certainty equivalence for event-triggered control systems	2013	83
Meng et al. [113]: Optimal sampling and performance comparison of periodic and event based impulse control	2012	82
Shi et al. [114]: Event-triggered maximum likelihood state estimation	2014	82
Hu et al. [115]: Distributed event-triggered tracking control of leader-follower multi-agent systems with communication delays	2011	81

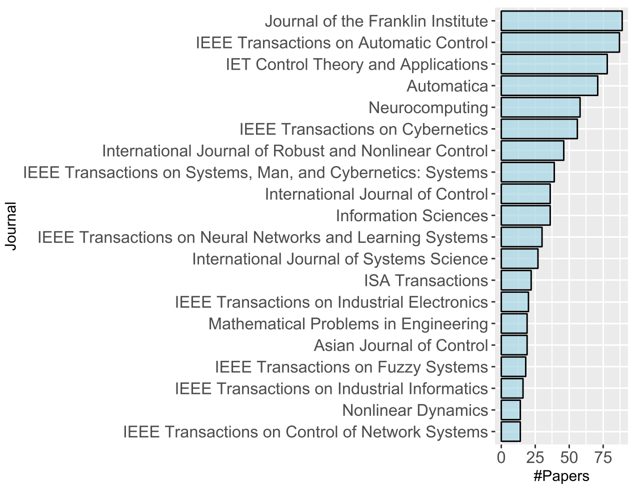

FIGURE 4. Journals that have published the highest number of articles.

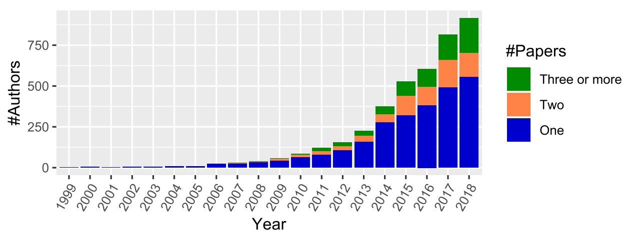

FIGURE 5. Number of authors per year.

Figure 5 depicts the number of authors per year. Each node accounts for a highly cited author. There is an edge linking two nodes when the corresponding researchers have co-authored some paper. Node size and edge thickness are proportional to the number of author's citations and co-authored articles, respectively. Colors distinguish the authors' collaboration networks identified with the Leiden clustering algorithm [116]. Authors appear every year categorized into three groups: color blue represents those sporadic authors that have published only one article in a given year, color orange depicts the moderate authors that have published two papers, and finally color green represents those prolific authors that have published three or more articles in the year.

Figure 6 represents the 5% most cited authors of the paper sample described in Section III-B. Each author is represented by a node, whereas the links represent the papers that two authors have in common. Node size and edge thickness are proportional to the number author's citations and co-authored articles, respectively. Note that the graph is not entirely connected, since there are some isolated authors/groups of authors. Nevertheless, more than 85% of the researchers correspond to the main component of the graph. Regarding the main component of the graph, seven authors' collaboration networks have been identified. Regarding European researchers, Swedish and Dutch Schools lead the two existing networks, and the most prolific authors are Professors Paulo Tabuada, Karl. H. Johansson, Maurice Heemels and Dimos V. Dimarogonas. The other five networks are basically headed by Chinese (or of Chinese origins) scientists (excluding the network colored in pink), some of them are in the list of the Most Cited Researchers developed for Shanghai Ranking's Global Ranking of Academic Subjects 2016 in the area of Electrical and Electronic Engineering, such as Professors Qing-Long Han and Zidong Wang.

B. TIMING

By *timing*, we understand the different ways of how the instants of transmissions are computed. In our analysis, wee have focused on event-triggered and self-triggered approaches. Inside event-triggered, we distinguish between continuous and discrete schemes.

In Figure 7, we can observe that the event-triggered strategies have been much more studied than the self-triggered ones. This is mainly caused because of the ease to design event-triggered schemes, while self-triggered strategies are usually more dependent on the model of the system, and thus theoretical results, such as stability analysis, might be more difficult to be obtained. Therefore, even when self-triggered approaches can produce adequate results in terms of reducing the waste of computation and transmission resources, it has attracted less attention. We also note that the continuous event-triggered schemes are prevailing to the discrete ones, but in the last years, the distance has been reduced.

Table 2 shows the citation classics for the different approaches. The last column in Tables 2-4 follows the notation $[\text{reference}]_{\text{number of citations}}$; e.g., $[22]_{1484}$ means that reference [22] has been cited 1,484 times. In Table 2, we can highlight some important papers. [25] is one of the first articles on event-based control; it establishes a comparison between Riemann (periodic) and Lebesgue sampling, showing the benefits of event-based control. As [2], it ventures the necessity of a theory for event-based sampling analogous to the one for periodic sampling. The basis of this theory is established in [22], which is the most cited paper of event-based control. In [22], conditions for global exponential stability of nonlinear event-triggered control systems

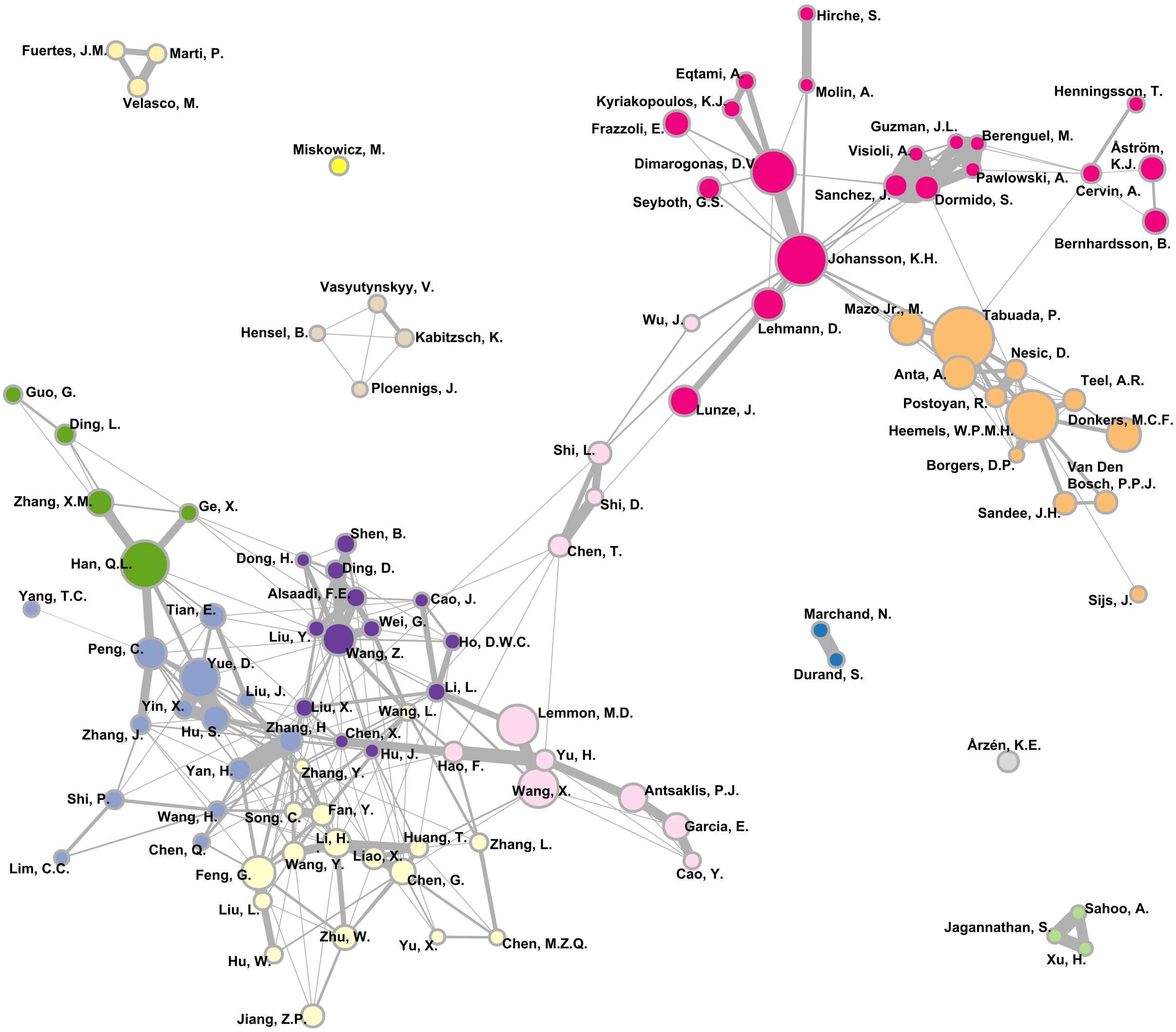

FIGURE 6. Top 5% cited authors.

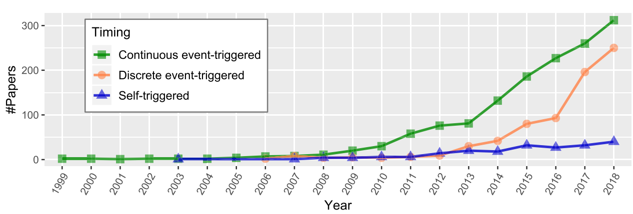

FIGURE 7. Number of papers per year, distinguishing between their timing modalities.

are provided. In addition, minimum inter-event time is guaranteed even in the presence of delays with the proposed event-triggering conditions. These results are also particularized for linear systems. In this category, some of the most important papers for distributed systems are considered. In [55], the effect of disturbances in the performance of the event-based control loop is studied and it is shown the benefits of increasing and decreasing the frequency of the transmissions of information depending on the disturbances. [51], [54], [56] are key papers for the development of distributed systems and are analyzed in that category.

In the discrete event-triggered category, we consider event-triggered control of discrete-time systems, but also continuous frameworks with a periodic verification of the event-triggering condition, the so-called PETC. In this regard, [57], [65] propose the theory of time-delay systems to study systems with PETC and obtain a method not only to guarantee the stability but also to design the feedback gain. On its behalf, [60] extends the results of the seminal paper [52] to consider output-based decentralized PETC using three different approaches: impulsive systems, piecewise linear systems and perturbed linear systems. In [64], a similar analysis is developed but considering a model-based controller.

Concerning the self-triggered approach, the most prominent paper, excluding the tutorial [1], is [58], where the first theoretical formalism of self-triggered control for nonlinear systems is provided. In [41], the $\mathcal{L}_2$ stability is proved for

TABLE 2. Citation classics according to the timing's categories.

Timing	#Papers	h-index	Citation classics
Continuous event-triggered	1421	58	[22]$_{1484}$, [54]$_{698}$, [51]$_{654}$, [25]$_{618}$, [55]$_{579}$, [56]$_{514}$, [1]$_{500}$, [3]$_{468}$, [2]$_{451}$, [23]$_{444}$, [59]$_{420}$, [50]$_{359}$, [61]$_{342}$, [62]$_{279}$, [63]$_{271}$, [40]$_{256}$, [66]$_{245}$, [68]$_{210}$, [69]$_{203}$, [70]$_{193}$, [47]$_{181}$, [72]$_{179}$, [48]$_{171}$, [74]$_{166}$, [77]$_{146}$, [78]$_{142}$, [79]$_{139}$, [81]$_{132}$, [82]$_{128}$, [85]$_{112}$, [88]$_{108}$, [49]$_{104}$, [89]$_{103}$, [90]$_{102}$, [91]$_{99}$, [95]$_{95}$, [6]$_{95}$, [98]$_{94}$, [99]$_{93}$, [100]$_{93}$, [102]$_{93}$, [104]$_{91}$, [110]$_{85}$, [112]$_{83}$, [113]$_{82}$, [115]$_{81}$, [117]$_{76}$, [118]$_{72}$, [119]$_{72}$, [120]$_{71}$, [121]$_{71}$, [122]$_{66}$, [123]$_{63}$, [124]$_{63}$, [125]$_{62}$, [126]$_{61}$, [127]$_{61}$, [128]$_{61}$
Discrete event-triggered	732	53	[57]$_{512}$, [60]$_{391}$, [64]$_{264}$, [65]$_{253}$, [71]$_{191}$, [46]$_{181}$, [73]$_{171}$, [75]$_{160}$, [76]$_{147}$, [80]$_{136}$, [83]$_{118}$, [84]$_{117}$, [86]$_{112}$, [87]$_{111}$, [92]$_{99}$, [93]$_{99}$, [94]$_{96}$, [96]$_{95}$, [97]$_{95}$, [101]$_{93}$, [103]$_{92}$, [105]$_{91}$, [106]$_{90}$, [108]$_{87}$, [109]$_{87}$, [111]$_{83}$, [114]$_{82}$, [129]$_{79}$, [130]$_{77}$, [131]$_{77}$, [132]$_{75}$, [133]$_{73}$, [134]$_{73}$, [135]$_{72}$, [136]$_{71}$, [137]$_{70}$, [138]$_{69}$, [139]$_{69}$, [140]$_{67}$, [141]$_{66}$, [142]$_{66}$, [143]$_{64}$, [144]$_{64}$, [145]$_{62}$, [146]$_{61}$, [147]$_{60}$, [148]$_{58}$, [149]$_{58}$, [150]$_{55}$, [151]$_{55}$, [152]$_{55}$, [153]$_{54}$, [154]$_{53}$
Self-triggered	206	29	[54]$_{698}$, [1]$_{500}$, [58]$_{478}$, [41]$_{443}$, [21]$_{268}$, [67]$_{235}$, [48]$_{171}$, [77]$_{146}$, [81]$_{132}$, [102]$_{93}$, [42]$_{90}$, [107]$_{90}$, [111]$_{83}$, [119]$_{72}$, [155]$_{66}$, [156]$_{64}$, [157]$_{58}$, [158]$_{54}$, [159]$_{47}$, [160]$_{44}$, [161]$_{39}$, [162]$_{38}$, [10]$_{36}$, [163]$_{35}$, [164]$_{35}$, [165]$_{35}$, [166]$_{34}$, [167]$_{31}$, [12]$_{31}$

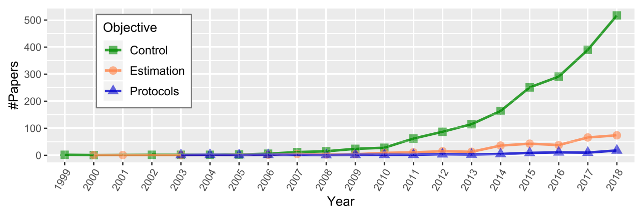

FIGURE 8. Number of papers per year, considering their global objective.

systems sampled with a self-triggering scheme. These schemes are improved for linear systems in [67].

C. OBJECTIVE

This section examines the papers according to their primary objective. In Figure 8, we can observe that most of them are devoted to solving control problems. However, it is essential to remark that we have focused our attention on pure control and estimation problems, but papers centered on signal processing are not considered. In addition, very few papers are focused on the design of protocols and architectures for event-based control systems.

Within the control problem (Figure 9), several approaches can be considered depending on the type of used controller. State-feedback controllers are naturally the most common in the literature since they simplify the theoretical analysis and the implementation. When some states are not available to compute the control input, output-feedback controllers are considered. Hence, output-feedback controllers are a more realistic approach in terms of an actual implementation. For that reason, the extension of state-feedback results to output-feedback is common in the literature.

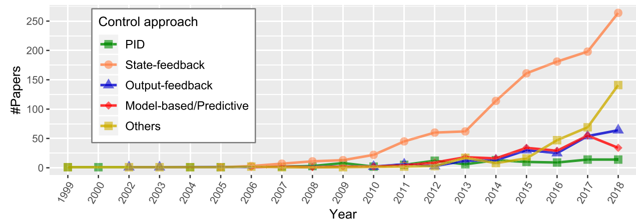

FIGURE 9. Number of papers per year, considering their specific control approach.

Nevertheless, this extension is not straightforward. For example, Zeno behavior may appear using quadratic triggering conditions [84]. It is noticeable that other approaches have attracted attention in the last years while PID and model-based/predictive controllers maintained stable (or even decreased). One of the reasons is the effort of the community to extend the results to nonlinear systems, for which PID and model-based/predictive controllers are not so useful, and new approaches are needed.

Each objective's citation classics are presented in Table 3. The most cited paper on PID control corresponds to the seminal paper [2]. In [104], an event-based PID controller is designed together with a wireless sensor network for greenhouses. This work is one of the first to bring event-based strategies close to real applications. [131] studies the load frequency control for power systems. As [104], it has an applied orientation of the event-triggered control. [100] extends the results presented in [55]. Even when it is not completely devoted to PID control, the proposed formalism can be applied to it, and indeed, the experimental results are obtained using a batch reactor controlled by a PI controller.

State feedback controllers (and their extension to output feedback) are clearly the most used in the literature, and hence, the most cited papers practically correspond to the most cited papers in Table 2. Excluding the papers already analyzed in the previous section, we can highlight [23], which is one of the first articles that derives a formal analysis for event-based controllers. Concerning output feedback control, the first paper that formally analyzes the stability of output-based controllers is [59] (and its preliminary version [99]). Also, in [59] the ETC system is modeled as an impulsive system (this approach would be used later in PETC).

The most cited paper devoted to model-based control is [62], where a model-based event-triggered controller is proposed subject to quantization and time-varying delays. So, it is the first paper that takes into account common issues of networked control systems within the theoretical formalism of model-based controllers. As aforementioned, periodic event-triggered model-based control is developed in [64]. In [88], the model predictive control with event-triggered communication is extended to nonlinear systems.

TABLE 3. Citation classics according to the objective's categories.

Objective	#Papers	h-index	Citation classics
PID control	102	20	[2]$_{451}$, [104]$_{91}$, [131]$_{77}$, [120]$_{71}$, [24]$_{57}$, [168]$_{55}$, [169]$_{54}$, [170]$_{47}$, [171]$_{37}$, [172]$_{34}$, [173]$_{29}$, [174]$_{26}$, [175]$_{26}$, [176]$_{25}$, [177]$_{25}$, [178]$_{25}$, [179]$_{24}$, [180]$_{22}$, [181]$_{21}$, [182]$_{21}$
State-feedback control	1145	58	[22]$_{1484}$, [54]$_{698}$, [51]$_{654}$, [55]$_{579}$, [56]$_{514}$, [57]$_{512}$, [1]$_{500}$, [58]$_{478}$, [23]$_{444}$, [41]$_{443}$, [50]$_{359}$, [61]$_{342}$, [63]$_{271}$, [65]$_{253}$, [66]$_{245}$, [67]$_{235}$, [69]$_{203}$, [70]$_{193}$, [71]$_{191}$, [46]$_{181}$, [72]$_{179}$, [48]$_{171}$, [74]$_{166}$, [76]$_{147}$, [77]$_{146}$, [78]$_{142}$, [79]$_{139}$, [81]$_{132}$, [82]$_{128}$, [83]$_{118}$, [86]$_{112}$, [49]$_{104}$, [89]$_{103}$, [90]$_{102}$, [91]$_{99}$, [94]$_{96}$, [95]$_{95}$, [102]$_{93}$, [42]$_{90}$, [107]$_{90}$, [109]$_{87}$, [110]$_{85}$, [111]$_{83}$, [115]$_{81}$, [133]$_{73}$, [134]$_{73}$, [119]$_{72}$, [121]$_{71}$, [136]$_{71}$, [138]$_{69}$, [155]$_{66}$, [142]$_{66}$, [144]$_{64}$, [156]$_{64}$, [125]$_{62}$, [157]$_{58}$, [183]$_{58}$, [148]$_{58}$
Output-feedback control	211	26	[25]$_{618}$, [59]$_{420}$, [60]$_{391}$, [68]$_{210}$, [75]$_{160}$, [84]$_{117}$, [85]$_{112}$, [93]$_{99}$, [96]$_{95}$, [99]$_{93}$, [100]$_{93}$, [101]$_{93}$, [129]$_{79}$, [137]$_{70}$, [140]$_{67}$, [124]$_{63}$, [127]$_{61}$, [184]$_{53}$, [185]$_{51}$, [186]$_{48}$, [187]$_{42}$, [188]$_{36}$, [165]$_{35}$, [189]$_{33}$, [190]$_{29}$, [191]$_{27}$
Model-based/ Predictive control	207	23	[62]$_{279}$, [64]$_{264}$, [88]$_{108}$, [98]$_{94}$, [108]$_{87}$, [143]$_{64}$, [123]$_{63}$, [192]$_{51}$, [193]$_{47}$, [162]$_{38}$, [194]$_{35}$, [195]$_{32}$, [196]$_{32}$, [197]$_{31}$, [198]$_{30}$, [199]$_{28}$, [200]$_{25}$, [201]$_{25}$, [202]$_{25}$, [203]$_{24}$, [204]$_{24}$, [205]$_{23}$, [206]$_{23}$
Other control	311	25	[3]$_{468}$, [21]$_{268}$, [112]$_{83}$, [117]$_{76}$, [122]$_{66}$, [128]$_{61}$, [207]$_{58}$, [208]$_{57}$, [209]$_{50}$, [210]$_{47}$, [159]$_{47}$, [211]$_{47}$, [212]$_{44}$, [213]$_{43}$, [214]$_{35}$, [215]$_{35}$, [53]$_{34}$, [216]$_{34}$, [12]$_{31}$, [217]$_{28}$, [218]$_{28}$, [219]$_{28}$, [220]$_{27}$, [221]$_{26}$, [222]$_{25}$
Estimation	323	39	[68]$_{210}$, [47]$_{181}$, [73]$_{171}$, [80]$_{136}$, [81]$_{132}$, [87]$_{111}$, [92]$_{99}$, [6]$_{95}$, [97]$_{95}$, [100]$_{93}$, [101]$_{93}$, [103]$_{92}$, [105]$_{91}$, [106]$_{90}$, [113]$_{82}$, [114]$_{82}$, [130]$_{77}$, [132]$_{75}$, [135]$_{72}$, [139]$_{69}$, [141]$_{66}$, [145]$_{62}$, [126]$_{61}$, [146]$_{61}$, [149]$_{58}$, [223]$_{57}$, [224]$_{55}$, [154]$_{53}$, [225]$_{53}$, [226]$_{52}$, [185]$_{51}$, [209]$_{50}$, [227]$_{47}$, [228]$_{46}$, [229]$_{44}$, [230]$_{43}$, [231]$_{42}$, [232]$_{42}$, [233]$_{40}$
Protocols	73	14	[1]$_{500}$, [40]$_{256}$, [47]$_{181}$, [90]$_{102}$, [234]$_{50}$, [235]$_{37}$, [236]$_{34}$, [237]$_{32}$, [238]$_{26}$, [239]$_{26}$, [240]$_{20}$, [241]$_{18}$, [242]$_{17}$, [243]$_{16}$

The category of other control approaches includes event/self-triggered schemes specifically designed for controllers different from the most common ones. For example, an impulsive control is designed in [3], [25]. In [112], [122] optimal event-triggered controllers are studied. Sontag's Universal Formula is used within the perspective of event-based control in [117]. Adaptive control under event-triggered communication is studied in [208]. Ternary controllers [159], sliding-mode control [212] and many others are proposed in an event-triggered framework. However, the results for self-triggered are much more limited, which can be an interesting and unexplored research field. Note also that papers like [21], [209] consider control inputs in their scheme, but the design of the controller is left open. Therefore, they are included in this category.

Traditionally, the estimation problem has received less attention than the control under the perspective of the event-based approach. However, several papers have proved its potential to improve the estimation results. In [47], it is shown how the event-triggering threshold provides a trade-off between communication rate and estimation quality. In [87] and [73], an event-based H_∞ filter is proposed to save communication resources while the quality of the estimation is maintained. This approach is extended to the distributed case in [80].

Architectures and communication protocols have received limited attention compared to control and estimation problems. In spite of that, it is necessary to establish these protocols to bring the advantages of event-based control to real cases. In this sense, [40] compares periodic and send-on-delta sampling and studies the communication bandwidth and data acquisition requirements. [90] is the first paper that analyzes the system performance of an event-based controller under different medium access control protocols, showing that the best results are obtained using a *Carrier Sense Multiple Access*.

D. OTHER CATEGORIES

This section discusses other categories neither included in *timing* nor *objective*. In Table 4, we can observe a high overlap between distributed and multi-agent systems, which makes sense as multi-agent systems are the natural application field of distributed control. So, [54] is the basis for distributed multi-agent systems, since it proposes frameworks for centralized and distributed event-triggered, and self-triggered approaches for linear systems. In [56], the ideas of the previous paper are extended to a more complex case (the agents do not know the consensus point), and more realistically implementable (the continuous monitoring of neighbors is not required and absence of Zeno behavior is proved). In [51], distributed event-triggered control is addressed for nonlinear systems.

In nonlinear systems, the most cited papers correspond to those where theoretical frameworks are established, such as [22], [50], [51] for event-triggered control, [58] for self-triggered control or [97] for event-triggered estimation. Other papers, as [71], transform the nonlinear system into a Takagi-Sugeno fuzzy system to be able to apply the techniques developed for linear systems. PETC has also been studied for nonlinear systems since the seminal paper [255], but considerably less than for linear systems. Classical problems like time-delays or quantization have not been studied enough, and many nonlinear processes do not fit in the current theoretical frameworks. Therefore, this is still an open research line.

According to Table 4, experimental results are scarce in the literature. In general, we can observe two types of papers in this category: theoretical ones whose contributions are supported by experimental results in academic examples, and articles that show event-based control working on real industrial processes. In the first group, we can highlight (i) [83],

TABLE 4. Citation classics concerning other minor categories.

Category	#Papers	h-index	Citation classics
Distributed systems	752	49	[54]$_{698}$, [51]$_{654}$, [56]$_{514}$, [57]$_{512}$, [60]$_{391}$, [50]$_{359}$, [61]$_{342}$, [63]$_{271}$, [64]$_{264}$, [66]$_{245}$, [68]$_{210}$, [69]$_{203}$, [72]$_{179}$, [48]$_{171}$, [77]$_{146}$, [80]$_{136}$, [81]$_{132}$, [86]$_{112}$, [49]$_{104}$, [89]$_{103}$, [91]$_{99}$, [99]$_{93}$, [102]$_{93}$, [110]$_{85}$, [111]$_{83}$, [115]$_{81}$, [132]$_{75}$, [133]$_{73}$, [121]$_{71}$, [138]$_{69}$, [139]$_{69}$, [142]$_{66}$, [123]$_{63}$, [145]$_{62}$, [126]$_{61}$, [146]$_{61}$, [128]$_{61}$, [157]$_{58}$, [207]$_{58}$, [148]$_{58}$, [151]$_{55}$, [152]$_{55}$, [153]$_{54}$, [244]$_{53}$, [192]$_{51}$, [185]$_{51}$, [245]$_{50}$, [234]$_{50}$, [246]$_{50}$
Multi-agent systems	634	40	[54]$_{698}$, [51]$_{654}$, [56]$_{514}$, [50]$_{359}$, [61]$_{342}$, [63]$_{271}$, [66]$_{245}$, [68]$_{210}$, [69]$_{203}$, [72]$_{179}$, [77]$_{146}$, [82]$_{128}$, [89]$_{103}$, [91]$_{99}$, [93]$_{99}$, [102]$_{93}$, [107]$_{90}$, [111]$_{83}$, [115]$_{81}$, [121]$_{71}$, [138]$_{69}$, [142]$_{66}$, [145]$_{62}$, [126]$_{61}$, [128]$_{61}$, [147]$_{60}$, [151]$_{55}$, [153]$_{54}$, [244]$_{53}$, [185]$_{51}$, [245]$_{50}$, [246]$_{50}$, [247]$_{49}$, [248]$_{49}$, [210]$_{47}$, [249]$_{42}$, [250]$_{42}$, [251]$_{42}$, [252]$_{41}$, [253]$_{40}$
Non-linear systems	618	37	[22]$_{1484}$, [51]$_{654}$, [58]$_{478}$, [50]$_{359}$, [71]$_{191}$, [78]$_{142}$, [79]$_{139}$, [81]$_{132}$, [84]$_{117}$, [88]$_{108}$, [94]$_{96}$, [97]$_{95}$, [42]$_{90}$, [130]$_{77}$, [117]$_{76}$, [119]$_{72}$, [135]$_{72}$, [136]$_{71}$, [139]$_{69}$, [124]$_{63}$, [125]$_{62}$, [183]$_{58}$, [208]$_{57}$, [254]$_{56}$, [152]$_{55}$, [184]$_{53}$, [255]$_{49}$, [256]$_{48}$, [193]$_{47}$, [227]$_{47}$, [211]$_{47}$, [257]$_{44}$, [213]$_{43}$, [187]$_{42}$, [232]$_{42}$, [258]$_{39}$, [259]$_{37}$
Experimental results	142	21	[2]$_{451}$, [83]$_{118}$, [108]$_{87}$, [120]$_{71}$, [168]$_{55}$, [247]$_{49}$, [260]$_{43}$, [172]$_{34}$, [167]$_{31}$, [197]$_{31}$, [261]$_{29}$, [173]$_{29}$, [262]$_{29}$, [200]$_{25}$, [178]$_{25}$, [201]$_{25}$, [263]$_{24}$, [264]$_{24}$, [265]$_{24}$, [180]$_{22}$, [266]$_{21}$

where PETC is applied to singular systems with delays and quantizations, and it is tested on an inverted pendulum on a cart; (ii) [108], where event-triggered predictive control is applied to a servo system; (iii) [247], where an event-based estimation algorithm is experimentally tested, and (iv) [167], where the benefits of self-triggered control in a communication network are studied. In an intermediate point between the two groups, we may consider [120] where the experimental results are carried out on a pilot chemical plant of 8 tanks. Finally, we can observe than industrial cases are even more scarce. In [197], event-based predictive control is applied to a greenhouse to minimize the actuation and reduce production costs. A similar idea is applied in [200] to reduce the maintenance cost of a photobioreactor plant.

E. CATEGORY COVARIATION

This section analyzes the covariation among the different categories; only the comparisons where there is a significant variation will be discussed.

In Figure 10, we observe the percentage of publications that address control or estimation problems versus the timing used. Naturally, the majority of the papers consider an event-triggered approach independently of the objective. However, it is noticeable that the percentage of articles devoted to self-triggered estimation is much more reduced (only 2.5%), so this may be an interesting field for future research. Within the event-triggered strategy, the continuous event-triggered approach represents 70.9% of the control papers, while the discrete event-triggered approach represents 74.5% of the estimation articles. These results are foreseeable since discrete models are more common in filters and estimators.

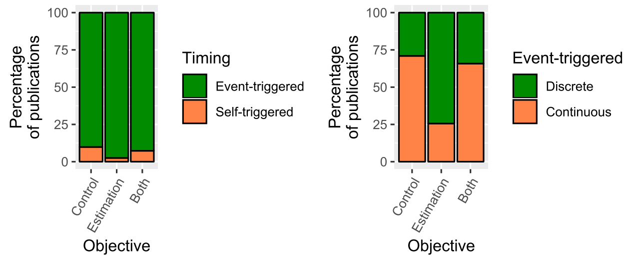

FIGURE 10. Covariance of ***objective*** and ***timing***.

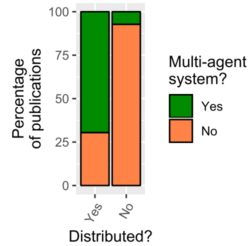

FIGURE 11. Covariance of ***distributed*** and ***multiagent***.

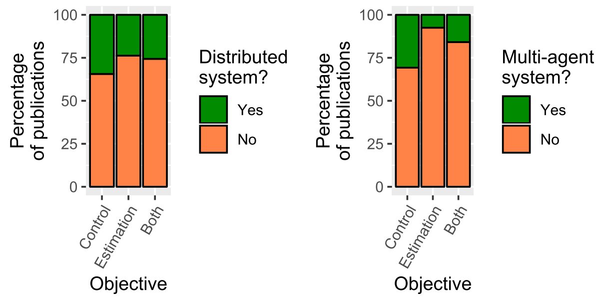

FIGURE 12. Covariance of ***objective*** and ***distributed/multi-agent***.

In Figure 11, we can observe the correlation between distributed and multi-agent systems. Practically all multi-agent systems (92.8%) consider distributed control. Despite that, 30.6% of papers dedicated to distributed systems are not targeted for multi-agent systems. These papers are mainly devoted to wireless sensor/actuator networks, large-scale systems, and other systems where there is an exchange of information.

Not only there is a larger production of papers dedicated to distributed systems than to multi-agent systems, but also there are differences in their objectives. Figure 12 displays the objective of the papers versus distributed and multi-agent systems categories. In both cases, distributed control has been studied more than estimation. However, this difference is even more substantial in multi-agent systems, where only 7.5% of the papers study estimation problems in multi-agent systems.

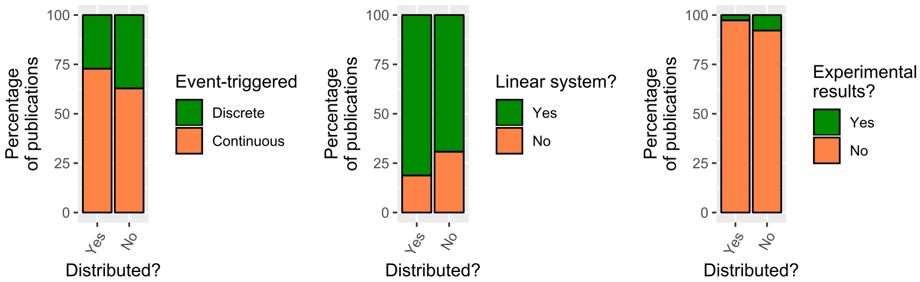

FIGURE 13. Covariance of ***distributed*** and ***event-triggered/linearity/results***.

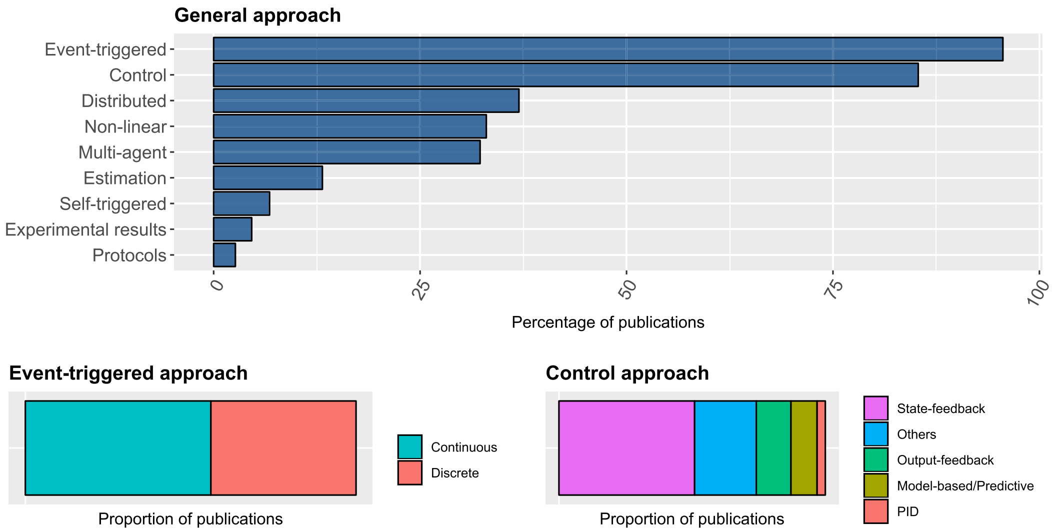

FIGURE 14. Present and future.

In Figure 13, the last bunch of comparisons is depicted. We can note that discrete event-triggered schemes are less common in distributed systems. Similarly, nonlinear distributed systems have been studied less frequently than linear systems. Finally and as mentioned above, there is a lack of experimental results, being this deficiency particularly pronounced in distributed systems, where only 2.7% of the articles report any type of empirical validation.

In general, these figures allow us to confirm that there are several areas in event-based control that have not been exploited yet, remarkably in distributed systems, since many of the problems have been solved only for the centralized case.

F. PRESENT AND FUTURE

As Figure 2 shows, the production of papers on event-based control has undergone exponential growth in the last years. 46.24% of all papers have been published in the last two years. This has a clear foundation. The new paradigm created by the networked control systems and the cyber-physical systems attracted the attention to the event-based control, especially in the last decade. Once the general framework was established, and once it was proved that the event-based control could produce important benefits in this new paradigm, it was needed to translate all the well-established control theory of continuous systems and periodic discrete systems to consider aperiodic transmissions of information.

For these reasons, we note that more complex frameworks and problems have started to be considered in the last years. So, while continuous state event-triggered control for linear systems is the most common topic in the historical review, discrete schemes, nonlinear systems and other control methods have closed the gap in the last years, as we can see in Figure 14, and also in the temporal evolution depicted in Figures 7 and 9.

Looking at Table 5 with the top 2% cited papers in the last two years, without considering the two overviews [10], [86] as they refer to past articles but are not research papers itself, we note that 75% of the papers consider a discrete framework, which is a sign of the importance that these schemes have achieved. In spite of that, the natural absence of Zeno behavior in discrete-time systems, which facilitates the theoretical development in some cases, might also be a reason for the increment in the number of papers in this topic. Concerning the objective of the papers, we can observe that 75% of the articles are devoted to controlling problems, while the rest are dedicated to estimation problems, so the historical tendency is maintained over the last years.

TABLE 5. Top 2% cited papers in the last two years.

Article	Year	#Citations
Zhang et al. [86]: An overview and deep investigation on sampled-data-based event-triggered control and filtering for networked systems	2017	112
Wu et al. [129]: Event-triggered sliding mode control of stochastic systems via output feedback	2017	79
Zhang et al. [134]: Event-triggered sampling control for stability and stabilization of memristive neural networks with communication delays	2017	73
Zhang et al. [136]: Event-triggered H_∞ control for a class of nonlinear networked control systems using novel integral inequalities	2017	71
Ding et al. [142]: Observer-based event-triggering consensus control for multiagent systems with lossy sensors and cyber-attacks	2017	66
Dolk et al. [124]: Output-based and decentralized dynamic event-triggered control with guaranteed $\mathcal{L}_p$-Gain performance and zeno-freeness	2017	63
Ge et al. [145]: Event-Based set-membership leader-following consensus of networked multi-agent systems subject to limited communication resources and unknown-but-sounded noise	2017	62
Ge et al. [147]: Distributed formation control of networked multi-agent systems using a dynamic event-triggered communication mechanism	2017	60
Shen et al. [149]: Event-triggered state estimation for discrete-time multidelayed neural networks with stochastic parameters and incomplete measurements	2017	58
Cheng et al. [94]: An asynchronous operation approach to event-triggered control for fuzzy Markovian jump systems with general switching policies	2018	96
Ding et al. [10]: An overview of recent advances in event-triggered consensus of multiagent systems	2018	36
Wu et al. [196]: Event-triggered control for consensus of multiagent systems with fixed/switching topologies	2018	32
Yan et al. [267]: Event-triggered asynchronous guaranteed cost control for Markov jump discrete-time neural networks with distributed delay and channel fading	2018	31
Shen et al. [221]: Finite-time event-triggered H_∞ control for T-S fuzzy Markov jump systems	2018	26
Wu et al. [268]: Event-triggered Control for consensus problem in multi-agent systems with quantized relative state measurements and external disturbance	2018	24
Wang et al. [269]: Finite-time state estimation for recurrent delayed neural networks with component-based event-triggering protocol	2018	23
Li et al. [270]: Model-based adaptive event-triggered control of strict-feedback nonlinear systems	2018	22
Ren et al. [271]: Event-triggered finite-time control for networked switched linear systems with asynchronous switching	2018	22
Zhang et al. [272]: Event-based robust control for uncertain nonlinear systems using adaptive dynamic programming	2018	21
Liu et al. [273]: Event-Triggered H_∞ state estimation for delayed stochastic memristive neural networks with missing measurements: The discrete time case	2018	20

It is also important to mention that 40% of the papers consider nonlinear systems, which is a remarkable growth with respect to the historical review. This is a logical step in the evolution of event-based control, since many of the techniques developed for linear systems need to be extended to nonlinear systems to be applied in many fields, such as robotics, autonomous vehicles or industrial processes. This drift to nonlinear systems also has an impact on control strategies. While 53% of the papers present still a state-feedback controller, other approaches are attracting more and more attention, as shown in Figure 14.

Table 5 also shows that every top 2% cited papers consider event-triggered control, while none is devoted to self-triggered control. This reveals the upward trend of event-triggered control, while self-triggered control is comparatively halted. It is known that self-triggered control schemes are harder to design, especially for nonlinear systems, since it is necessary to estimate when the next event will be triggered. This might be a sign not only of why researchers have focused on event-triggered control, but also of that the research in self-triggered control might not be halted because the topic is exhausted, and that groundbreaking advances may produce a blow-up similar to the experimented by the event-triggered control.

Remarkably, none of the top 2% cited papers present experimental results. On the one hand, experimental results are pretty scarce in general, as aforementioned in the historical review. On the other hand, papers with experimental results are generally focused on a specific system or process, which makes them less citable than general theoretical papers.

Concerning multi-agent systems, all of them consider distributed control strategies, which is logical in the sense that many distributed solutions have already been proposed in the literature, and consequently, a centralized scheme might be seen as a step back. From Table 5, the 30% consider distributed schemes, which is consistent with the data from the historical review. Nevertheless, we have to take into account that normally the advances are produced for a centralized scheme, and after that, extended to the distributed case. Therefore, it is expectable that this percentage grows up when researchers start extending the aforementioned recent results for nonlinear systems and discrete event-triggered control to distributed multi-agent systems.

V. CONCLUSION

Since the first articles published in 1999, and as a result of its proved benefits for NCSs, the production of scientific papers on event-based control has grown dramatically, covering not only many classical problems in control theory, which only have been studied under continuous or periodic sampling, but also new challenges intrinsically related to NCSs, such as bandwidth limitation, transmission delays or cyberattacks.

Using a systematic methodology, 2,299 papers on event-based control have been analyzed to uncover the main motivations and researched themes, together with their interrelations. As a result, important open-problems and research gaps have been detected, being particularly serious the scarcity of actual industrial applications that empirically prove the potential benefits of event-based control. Additionally, and to facilitate browsing the available literature, we have identified the most influential articles, authors, institutions, and journals.

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