A Community Analysis of the IEEE IES Industrial Agents Technical Committee

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***Abstract*—At the dawn of the 4th industrial revolution, the use of software agents, service-oriented architectures and related technologies as primary constructs of Cyber-Physical Industrial systems is of high relevance. Current developments in this area have been consistently supported by an active community of researchers and practitioners in the past decades. Most of the main actors in the area are members of the IEEE IES Technical Community on Industrial Agents (TCIA). This work analyzes the evolution of this research and development network. It does so by identifying and investigating specialized sub-communities within the larger umbrella of Industrial Agents, their research interests and directions. In total of 7430 documents from 8045 authors were collected from the Google Scholar profiles of the TCIA members. The analysis reveals different research trends, transitions over the years and the emergence of application and domain foci, that are critically discussed.**

I. Introduction

The IEEE Industrial Electronics Society (IES) Technical Committee on Industrial Agents (TCIA) [1] is composed of international experts and stakeholders who deal with the utilization of software agents, service-oriented concepts, and distributed control in industrial settings. Since its creation more than a decade ago, TCIA continues with its aim to provide a forum where researchers and application specialists can come together to continue the development and application of industrial agents and supporting technologies in production, services (logistics, medical) and infrastructure sectors (power and energy systems, smart buildings, smart cities, etc.).

The core activities of TCIA pertain several areas [2] and are seen as a key enabler for Cyber-Physical Systems (CPS) [3] that are the backbone of the 4th industrial revolution [4]. The core technology of Multi-Agent Systems (MAS) has been generally acknowledged as a convenient paradigm for designing and implementing new generation of intelligent production systems featuring attributes like robustness, scalability and reconfigurability. There are numerous examples of successful deployments of agents in various fields of industrial automation including shop floor control and diagnostics, production planning and scheduling, logistics, building automation, and energy systems [2], [3].

Agent-based software systems are becoming a key management and control software technology for smart production management and control systems [2], [3]. Such systems can offer distributed intelligent management and control functions with communication, co-operation and synchronization capabilities, and also contribute for the behavior specifications of the smart components of the system. The key drivers for this effort are the benefits of agent-based industrial systems, namely robustness, scalability, re-configurability and productivity, all of which translated to a greater competitive advantage.

As a multidisciplinary forum for connecting these questions to state-of-the-art solutions, TCIA also targets the novel and emerging areas driving progress in the industrial sector today – such as industrial ecosystems animated by the next generation Internet [5]. The committee provides a continuous base to many researchers who have been participating in national and international projects building on the knowledgebase created by past and current efforts. Within the IEEE IES, the TCIA aims:

- To develop strategies for supporting systems developments using state of the art technologies and to assist in developing an integrated understanding of future systems needs for the addressed application sectors
- To develop strategies for generating cross-cutting activities with other TCs of the IES
- To provide forums and opportunities for members to exchange ideas, knowledge, experience, learning and results in this area
- To stimulate cross-fertilization of technical and scientific ideas for the advancement of the industrial agents field in tune with latest breakthroughs at the confluence of the ICT and intelligent manufacturing sectors

The aim of this work is to shed some light to the activities of the TCIA, not by looking at the technical contributions, as such aspects have already been discussed in surveys [2], [3], but via the community analysis of the publications of its members. As such, 7430 documents from 8045 authors were collected from the Google Scholar profiles of the TCIA members, and analyzed. This data was used to infer specialized research sub-communities within the larger TCIA community and evaluate globally their research interests and trends. The analysis findings are critically discussed in the context of lifetime of TCIA.

The remaining of this study is organized as follows: section II outlines the applied methodology whereas the results are provided in section III. The paper closes with a discussion of the results (section IV) and the conclusions in section V.

II. Methodology

A. Data Collection and Analysis Procedure

The data supporting the subsequent analysis was collected from the Google Scholar profiles of the IEEE TCIA members with public data. The IEEE TCIA currently has 58 registered members, out of which 35 have a Google Scholar profile. This ensures a 60% coverage of the TCIA publication record. However, the sample is expected to be far more representative since most of the authors, as discussed later, publish as part of tightly connected sub communities within TCIA. Overall the sample contains 7430 paper records, from as early as 1970, from 8045 authors. The data within the individual profiles reflects the public information available by the 5th of May 2017.

For each individual profile and for each paper within that profile the following information was collected from the profiles: title, author list, place published, publication year and number of citations. In addition, the abstracts were also collected, but only in partial form as only a percentage of it is made available by Google Scholar.

The dataset was pre-processed by harmonizing the author list of each paper to eliminate repetitions e.g., by lower and upper-case letter combinations, accents, or other aliases used by the authors within the TCIA. The paper title was converted to lower case to eliminate search ambiguities. Each author's list was used to infer the community network across different time spans. The resulting networks were abstracted as undirected graphs whereby any pair of authors (nodes) that have co-authored a paper are linked. The community detection algorithm detailed in [6], implemented in the Gephi Toolkit library [7], was used to identify specialized communities within the larger TCIA community umbrella for the different time spans. For each network, the top ten most connected authors were identified (where the size of the community exceeds 10, otherwise all the authors were included). This list of hubs was then subsequently used to select their publications and, through the analysis of the frequency of words in the papers' titles, infer the core research directions and trends of that sub-community. Simultaneously, a similar word frequency analysis was carried out on the abstracts of the community's most influential papers. A paper was considered influential if it had overall more than 10 citations and if it was attracting more than 10 citations per year. Common conjunctions, verbs, articles, pronouns and non-domain specific words were removed on all the word frequency analysis.

The co-author network analysis is sensitive to the time spans addressed. The TCIA network has therefore been analyzed in two ways: *(i)* in two-year periods, from 2006 to 2017, to understand smaller variations in the multiple research directions and *(ii)* in aggregated form, featuring three periods; the first half of the TCIA existence (2006–2011), the second half (2011–2017) and its full activity timespan (2006–2017).

B. Limitations

The work carried out has several known limitations. The analysis considers only members of TCIA with Google Scholar profiles. As such, some member contributions are not included in this analysis, although most highly publishable authors are. A future work could utilize additional sources e.g., other online libraries to acquire the complete works of those authors.

The analysis assumes the correctness of the Google Scholar public profiles parsed. It has to be pointed out though, that since most Google Scholar profiles are automatically maintained (by bots), sometimes they will include works that do not belong to the author (e.g., due to similar name) or documents that are not officially published etc. The analyzed sample is specially affected by these unintended additions for papers whose publication year is prior to 2000. In this context, the analysis is restricted to the activity period of TCIA i.e., 2006–2017, where the data contains less outliers.

Finally, as already mentioned, this work pertains the activities of the TCIA members, and not the Industrial Agents at large; as such, other work within the scope of the Industrial Agents published by non-TCIA members is not included.

Figure 1: TCIA co-author network (2011–2017)

III. Result Analysis

The data shows the TCIA community is currently composed by 23 sub-communities as shown in Figure 1. There, each sub-community is represented in a different color and proximity denotes closer ties among them.

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A. Co-Author Network Analysis

Considering the number of members in TCIA, this reveals that the majority of them are simultaneously active in more than one. The measurements taken across the entire activity timespan, as well as the first half of TCIA's activity, show two additional communities that became part of the network due to weak links arising from one of the TCIA hubs. However, these communities have developed work in areas unrelated to TCIA (e.g., Biology, Biochemistry and Cancer research) and the weak connections were lost in the recent years. These communities have also been excluded from further analysis in this work.

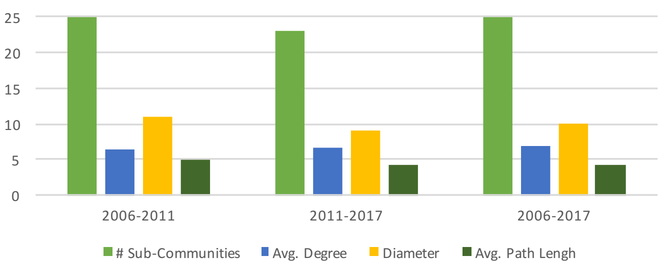


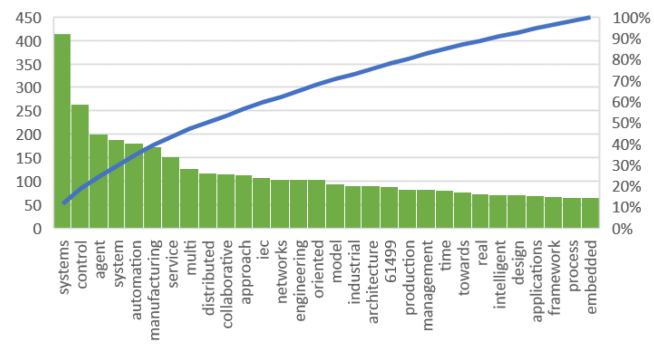
Figure 2: Overview of the TCIA network evolution over time.

The collected data also shows that the network is strongly connected with an average degree of 6,649, a diameter of 9 and an average path length of 4,1802 in 2011–2017. Not surprisingly, each subgraph, pertaining the different communities, denotes higher connectivity values. Certain communities are also closer to each other than others as qualitatively pointed out in Figure 1).

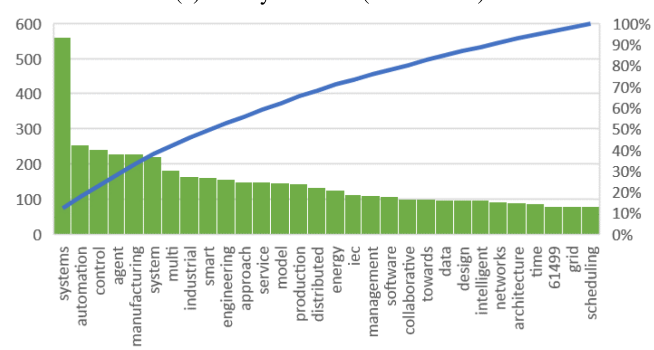
Figure 3: Word cloud of TCIA titles (2006–2017).

For each community, and across the aggregated time spans (2006–2017) there is a consistent set of top authors emerging in the data which re-assures the stability of that community, its underlying research interests and directions. A more in-depth analysis of the early (2006–2011) and later (2011–2017) period sub-communities clearly reveals them. However, as we focus on the characteristics and not the explicit authors, such matters are not further in-detail presented in this work.

Word clouds are considered an effective way to visualize data. Figure 3) shows the key words for the whole period in discussion (2006–2017), while the font-size indicates correlates to the word frequency. Comparing the relative positions of the top words, one can see clearly some predominant ones that pertain both periods. Generally words, such as system(s), control, manufacturing, smart, distributed and (multi-)agent, occur very frequently in published paper titles on the early (see Figure 4a) and later (see Figure 4b) period communities as well on the whole period from 2006–2017 (see Figure 3), which shows still a global and predominant effort in control of manufacturing systems at multiple levels.



(a) "Early" Period (2006–2011).



(b) "Later" Period (2011–2017).

Figure 4: Top–30 title words in TCIA community publications

However, considering discretely the two periods, looking only at the words of the titles, we can witness a transit in interests. Some have significantly gained interest e.g., smart, software, energy, power, data, self[-X], industrial, engineering, production, scheduling, grid, physical etc. Similarly, others seem to have decreased in interest e.g., collaborative, networks, architecture, environment, holonic, virtual, embedded, web, ontology, mobile, reconfigurable, soa, etc. It has to be pointed out though, that this view is purely based on the

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absolute position of the frequencies of the words, and as it is not linked to any semantics, it may or may not necessarily be linked to concrete approaches or domains. The latter may be described with other keywords or be more specific. An example is the integration of agents and devices; where in the early period the term "machine" was used, in the later period we see mostly the word cyber or physical (referring usually to CPS). A more detailed view on the basis of communities (and not the words per se) is provided later and summarized in Table I and Table II.

Beyond the common wording, the 25 "early" communities (2006–2011) where clustered based on their specific research interest in 12 different groups (Table I). Three of the clusters were removed since their research was unrelated to TCIA but showed in the data due to the weak links mentioned earlier.

Word frequency and clustering analysis suggest that three communities, A, B and C, in *cluster 0*, were developing work that had a product centric perspective with ties to information and knowledge representation. Communities D, E and F (*cluster 1*) had a special orientation towards real-time and application oriented research and development. The data also suggests additional specializations in code generation for embedded devices and scheduling of transportation systems. *Cluster 2* shows communities focused on control problems. Here sub-specializations include energy grids, mobile development, enterprise and device integration (community G), and AI-oriented research with focus on autonomy and consciousness (community H). *Cluster 3*, with two communities (I and J) shows a clear specialization in the development of IEC-61499 and its applications particularly in power/energy related research including simulation, design and possibly test cases in baggage handling. *Cluster 4* (communities K and L), focused in models and formal methods for software design. Community K converged to PLC oriented research, while community L adhered to more software design oriented research using aspects. *Cluster 5*, with just one community, denoted strongly bio-inspired research in evolutionary industrial systems, also including development of service oriented architectures. *Cluster 6*, also with one community, denoted a focus on holonic and heterarchical architectures for flexible systems with a particular emphasis on routing. *Cluster 7* was more focused on researching agency principles with two likely specializations: ontologies and knowledge representation (community O) and coordination, self-* properties, planning and execution (community P). *Cluster 8* specialized in collaborative networks positioning itself more at enterprise level and further away from control oriented research. *Cluster 9* had a clear focus on maintenance including analytical and predictive methods.

In Table II the "later" TCIA communities(2011–2017) are reflected. The first evident change is that communities C, E and L have disappeared and communities T, U, V, W, X and Y have emerged. As a note, one community was removed due to developing TCIA-unrelated research. The hub of community L occurs now as part of community A. Communities T and V members were not featured as top authors in the earlier communities. Community U now includes two core members previously from communities M and A as well as new members (that did not show in the data before). Community W results from a member previously from community I and includes an all-new set of members not previously present in the analyzed data. The same is verified with community X that developed from a M member. Two members from community J originated from community Y.

Table II also shows a more concentrated research effort when considering the different research affinities with a bigger cluster of communities developing around the distributed control approach IEC 61499 (*cluster 1*) denoting sub-specializations in agent-orientation, standards for the integration of intelligent electrical equipment (based on IEC 61850) and its applications (including simulation) and the implementation of IEC 61499 compliant development environments.

In parallel, *cluster 0* and *cluster 5* further specialize in agent-based systems. Cluster 0 denotes high application oriented research in areas such as: transportation, health-care, energy and collaborative issues such as trust and emotion management while cluster 5 research seems more manufacturing oriented while in parallel exploring other particular aspects of agents such as self-properties, decision theory and learning. While community N has retained most of its research words, community M seems to have discontinued the use of the words "bio", "soa", "robot" and "monitoring" in favor of learning and decision theory related words.

In comparison to Table I there is still a relevant cluster on modeling aspects that includes the same main researchers but has lost one community. These communities are still involved in formal aspects of modeling, PLC code generation and field agents, but have also incorporated the research in emerging knowledge representation standards such as SysML.

Community S is still focused in maintenance, but the data indicates the adoption of new practices such as big data exploration and analytics. An extension of application domains towards health care and wind turbines are now more frequently observed.

Cluster 7 now incorporates the more enterprise oriented research that previously was spread among several clusters. These communities are now linked by the use of services, either on a technical or conceptual plane, as a base to develop their research. Aligned with *cluster 7*, *cluster 3* seems to specialize in technical aspects and IT infrastructure development. It is also the first community to more consistently adopt the word "cyber" in their recent work. Along with the words cloud, architecture and migration this denotes a trend of this community to develop research in line with the cutting-edge trends in IT technology.

B. Influential Paper Analysis

While the previous analysis uncovers the overarching research direction of TCIA, the analysis of the most influential papers suggests more immediate trends and highlights the importance and maturity of specific research thematics. For the sake of space, the data from 2006–2011 and aggregated

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Table I: “Early” clusters and communities with their research interests (2006–2011)

Cluster	Communities	Strong Shared Words	Weak Shared Words
0	A	Product, Management	Web, Knowledge
	B		Information, System
	C		
1	D	Real-time, Applications	Embedded, Generation, Distributed, Code, Learning, Reality
	E		Indoor, MIMO
	F		Scheduling, Transportation, Clustering, Scheduler, Car, Technology, Magenta
2	G	Systems, Control	Things, mobile, Grid, Devices, Energy, Internet, Integration, Enterprise
	H		Autonomous, Consciousness
3	I	IEC 61499, Formal, Reconfiguration, Automation, Architecture	Future, Application, Simulation, Power, Description, Design
	J		Smart, Block, Mechatronic, Interoperability, Baggage, Implementation, Standard, Handling, Function, Controllers, Verification, Modelling
4	K	Model	Plant, Statecharts, PLC, UML, Evaluation, Software
	L		Aspect, Join, Point, Oriented
5	M	Roadmap, Socrades, Bio, Robot, Industrial, Shop-floor, Evolvable, Infrastructure, Model, SOA, Service, Support, Production, Monitoring	
6	N	Manufacturing, Routing, Holonic, Heterarchical, Products, Open, FMS	
7	O	Towards, Agent	Automatic, Ontology, Assembly, Electronic, Agents, Modular
	P		MAS, Self, Coordination, Planning, Engineering, Delegate, Execution, Autonomic
8	R	Inheritance, Creation, Modelling, Environments, Enterprises, Organization, Networked, Virtual, Collaboration, ECOLEAD, Framework, Indicators, Collaboration, Value, Process, VBES	
9	S	Maintenance, Analysis, Life, Bearing, Assessment, Prediction, Performance, Intelligent, Feature, Machine, Prognosis, Services, Methods, Data, Prediction	

Table II: “Later” clusters and communities with their research interests (2011–2017)

Cluster	Communities	Strong Shared Words	Weak Shared Words
0	F	Agent, Future, Management	Transportation, truck, Models, Adaptive, Real-time, Cargo
	T		Assistance, Coordination, Mobile, Medical, Emergency
	U		Energy, Process, Integrating, Process, Organized
	O		State, Trust, Emotional, Operations
	V		Internet
1	J	Intelligent, IEC 61499, Automation, Scheduling, Execution, Control, Applications, System	IEC 61850, Function Logic, Semantic, Blocks, Formal
	I		Development, Environment
	W		Electric, Simulation, Grids, Power,
	P		MAS, Production, Delegate, PROSA
2	A	Plant, Industrial, Automatic, Evolution, Automated, Generation, Software, Machine,	Requirements, Technology, Knowledge,
	K		Information, Modelling, PLC, UML, Field, SysML, Evaluation, Challenges
3	G	Sensor, Distributed, Wireless	Smart, SOA, Migration, Grid, Cyber, Architecture, Impact, Cloud, Prosummer, Assessment,
	D		Model, Network, Remote, Analysis,
4	X	Localization , PCA	
5	M	Self, Approach	Evolvable, Performance, Learning, Selection, Framework, Decision, Detection
	N		Hybrid, Flexible, Dynamic, FMS, Holonic
6	S	Big data, method, Battery, Systematic, Advances, Clustering, Physical, Study, Analytics, Turbine, Wind, Prognostics, Health	
7	Y	Support, Service, Services, System	Factory, Web, Manufacturing
	B		Complex, Product, Intelligence, Engineering
	R		Business, Enterprises, Networks, Virtual, Collaborative, Support, Ecosytems
	H		Emotion

data from 2006–2017 are not detailed. They are however, well-aligned with the word frequency analysis of the paper titles for the corresponding periods (see Figure 4a and Figure 3).

The analysis of the period 2011–2017 is more interesting

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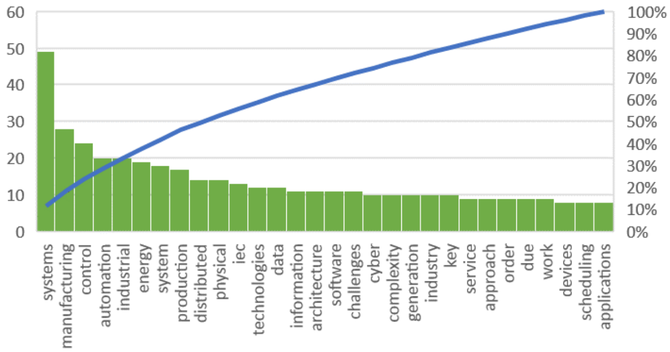

Figure 5: Abstract words of influential papers (2011–2017).

since it denotes a higher discrepancy between word titles analysis and trendy or influential research directions. The data shows a pronounced interest in energy related research and the emergence of cyber-physical systems. Words such as "complexity" and "information" also suggest an increased trend in research beyond just control aspects. At the same time words such as "application" and "devices" suggest a generalized interest in demonstration activities and a better interconnection and interplay between system level research and the target mechatronic systems.

IV. Discussion

Conventional survey papers often offer a rather constrained perspectives of the work on a given field. By relying on the automated parsing as utilized in this work, a much larger dataset of publications can be investigated, and a potentially more representative overview may emerge. In this context, the analyzed data contains important insights on the work of the IEEE IES TCIA community. Some are confirmatory of previous traditional surveys while other expose trends whose extension has been somehow elusive.

As a community, TCIA seem to be steadily adjusting and reinventing itself, by focusing its research is different areas, by recruiting new members, creating influencers and spawning new specialized sub-communities pursuing distinct but complementary research. TCIA is highly dependent on software aspects, and as such it is only logical that it follows strongly the rapid changes and trends witnessed in software industry.

Automation and control issues in manufacturing are still the main research subjects of TCIA. Such research line is deeply embedded in TCIA's culture and was partly the motivation for its creation. However, energy related research has gained important traction in the past five years, largely following the more global trend of amalgamating software approaches with key power grid elements and applications. Within TCIA, energy related research exists as a specialized separate focus-line but also deeply connected to development and implementation of advanced automation solutions.

The analyzed data also confirms the tradition of researching at a more systemic level. This means that the research within this community rarely focuses on specific machines/equipment but rather focuses on their usage as part of a more harmonized automation infrastructure cutting across all levels of the automation pyramid. This ambitious direction has motivated an important activity related to system modeling and standardization. Especially with respect to standardization efforts, TCIA members seem to be particularly involved in the development of IEC-61499 related approaches.

The identified trends can be interpreted as the maturity, in the required aggregated form, of some of other technologies being relatively low while, at the same time, they could be used interchangeably to express or demonstrate the same set of concepts and approaches and therefore their relative importance is low. An example can be found on the emergence of "cyber-physical systems" and "cloud" as a design metaphors whereby the details of different technologies are not so relevant at the systemic level where most of the TCIA research develops.

V. Conclusions

This work has presents new insights on the TCIA community as this is captured by the analysis of the information captured by Google Scholar profiles of the TCIA members. The collected 7430 documents from 8045 authors were analyzed both at word level in titles and abstracts, as well as the networks that emerge from the co-authorship of the papers. The results reveal the communities that are formed within TCIA, the research aspects that their work pertains, as well as evolution of research over time. The clusters are investigated in two periods i.e., the "early" (2006–2011) and the "later" (2011–2017) and the transition of the interests within TCIA is critically discussed.

Collectively the TCIA community seems in a decisive trajectory to close the gap between industrial systems and the emerging global challenges put upon them. As such, the work carried out in TCIA is pertinent, and has consistently adjusted to cover technology and concept trends. However, key pieces of this complex knowledge puzzle still denote an important fragmentation and while research diversity is fundamental, Figure 1 still shows research islands that may need to better collaborate in order to increase their impact.

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