IETE Technical Review

ISSN: 0256-4602 (Print) 0974-5971 (Online) Journal homepage: http://www.tandfonline.com/loi/titr20

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To cite this article: Hsiang Cheng, Chi-Tung Chen, Ling-fang Wei, Chu-lien Yen & Mu-Hsuan Huang (2016): Exploring University–Industry Collaboration Trends in Computer Science: A Study on Hardware and Architecture and Software Engineering, IETE Technical Review, DOI: 10.1080/02564602.2016.1185974

To link to this article: http://dx.doi.org/10.1080/02564602.2016.1185974

Published online: 08 Jun 2016.

IETE TECHNICAL REVIEW, 2016
http://dx.doi.org/10.1080/02564602.2016.1185974

Exploring University–Industry Collaboration Trends in Computer Science: A Study on Hardware and Architecture and Software Engineering

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ABSTRACT

This study aims to examine research collaboration between universities and industry in the field of computer science using bibliometric methods. To further understand the impact of individual countries on university–industry (UI) collaboration, data were retrieved from the computer science journal papers included in the Science Citation Index and published during the period 2002–2011. The density, degree centrality, betweenness centrality, and closeness centrality of UI collaborative networks were calculated in order to ascertain the core countries involved in international UI collaboration. This study investigates university–industry collaborative papers (UI papers) at the global and country levels. At the global level, the results show an increasing trend in UI papers and a stable UI collaboration ratio during the last decade. The average number of authors for UI papers is 4.13, which is higher than that for all other papers. Most UI papers result from two-institution collaboration, but we observed an increase in the number of UI papers produced by multiple universities and industrial entities. At the country level, the results also show that international UI paper collaboration has intensified. Meanwhile, the USA is the dominant collaborative partner with many countries and has produced the highest number of UI papers globally.

KEYWORDS

Bibliometrics; Collaboration; Co-authorship; Multiple institutions; University–industry collaboration

1. INTRODUCTION

The relationship between universities and industry has become indispensable in today's knowledge-based society. University–industry (UI) collaboration has become an important pathway to knowledge creation. University–industry collaborative papers (UI papers) are papers authored in collaboration between university researchers and industrial application researchers [1]. The number of UI papers has been increasing [1–6], showing the growing importance of UI collaboration. Tijssen et al. [7] stated that UI papers provide an adequate source for measuring the scale and strength of UI collaboration [7]. As UI papers evidence the majority of output from UI collaboration [8,9] and are employed to evaluate collaboration dynamics [10], UI papers have become established as the data-set most commonly used in studies on UI collaboration. For example, Abramo et al. [3] analysed UI papers in Italy using co-authorship analysis, and Liang et al. [6] used co-authorship analysis to observe UI papers in China during the period 1998–2007. Similar methods have also been used by Kwon et al. [5], Park and Leydesdorff [11], Ponds [2], and Choi [12] to study UI collaboration.

Information technology is now one of the main industries worldwide, with governments devoting resources to technological development for its high economic value. Application and university researchers have also conducted extensive studies on computer-science-related research and development, resulting in substantial growth in the number of papers in computer science. In response to the growing importance of computer science, bibliometric methods have been used to examine its knowledge creation patterns [13–16]. In terms of paper output, there has been an increase in the number of collaborative papers in the field of computer science since the 1980s. Researchers in computer science tend to co-author with two or three other authors to publish papers [17–19]. Domestic and international co-authorial collaborations accounted for 13.2% and 15.8% of all collaborative papers respectively.

Continual research and development is necessary for industrial entities to survive in the market. This is because industrial entities rely on academic knowledge for its high relevance to industrial innovation [20]. Industrial entities establish collaborative relationships with universities to strengthen competitiveness, overcome difficulties in research and application, nurture future talent, and conserve human resources [21]. Previous studies have shown that university researchers are more likely to publish collaborative papers [7,22] in topics that rely heavily on the application of academic

knowledge [23]. This indicates that enterprises that interact with highly technology- and knowledge-intensive topics show closer collaboration with universities.

Considering the contributing impact of computer science in the global economy, trends in UI collaboration represent the current status of scientific research and its knowledge transfer process. Previous UI collaboration studies have primarily analysed the performance of specific countries or several research fields [3,6,11,24], but have not focused on the field of computer science or offered a global analysis. In contrast to previous studies, our study is a country-level global analysis of the field. Through our analysis, the leading countries and their collaboration relations were revealed. Bibliometric methods are used to investigate UI papers and examine trends in research collaboration between universities and industry in computer science. First, it investigates countries that contribute significantly to the number of UI papers, as well as international UI paper trends. Second, the countries in which authors have contributed their papers are analysed to examine the major contributing countries for UI papers. Third, international UI papers are identified from co-authorship between university researchers and industrial application researchers in different countries in order to observe trends in international collaboration in the field of computer science.

2. METHODOLOGY

2.1 Data

We retrieved a data-set of computer science journal articles published between 2002 and 2011 that are indexed in the Science Citation Index. The list of computer science journals was collected from Journal Citation Reports (JCR) database, which divides the field of computer science into seven subfields; then the journal list was searched in Web of Science (WOS) database for collecting the publication data. Initial research showed that the seven subfields consisted of 618 journals and included a total of 351,043 papers. Due to time constraints and a lack of human resources, this paper examines only two subfields of computer science. In order to select these subfields, we extracted the institutional addresses of co-authors to estimate the ratio of UI papers in each subfield. The institutional address includes the authors' names and the name and address of the institution. The papers written by the companies were identified using the keywords appearing in the institutional address (e.g., "corp.," "co.," "ltd.," and "inc."). According to the results of the preliminary review of the data, the difference between the ratios of UI papers in each subfield was relatively small. The subfields "hardware and architecture" and "software engineering" were selected as the research subject. The top 10 impact factor journals of these two subfields were then selected as the research sample. Because two of these journals were categorized by JCR under both "hardware and architecture" and "software engineering", 18 sample journals were selected overall.

After finalizing the list of target journals, papers published between 2002 and 2011 were selected from the WOS database, comprising 12,842 papers. A total of 129 papers without identified author names and institutions were eliminated. The final compilation of papers comprised 12,713 papers, with probability of 0.36, confidence interval of 95%, and sampling error of 0.85%.

2.2 Indicators

The following indicators are used in this paper to examine the trends in UI papers in computer science.

(1) Ratio of UI papers: the proportion of UI papers to the total number of papers selected in a particular timespan.
(2) Ratio of international UI papers: the proportion of the international UI papers to the total number of papers selected in a particular timespan.
(3) Density: density is an indicator of the general level of connectedness of the network. If every node is directly connected to every other node, there is a complete network. The density of a network is defined as the number of links divided by the number of vertices in a complete graph with the same number of nodes.
(4) Degree centrality: degree centrality is easiest to grasp because it is the number of relations a given node maintains. A node with a high level of degree centrality would be located in the centre of a network, with a high likelihood of interaction. The formula for degree centrality is as follows:

$$C_{d(i)} = \sum_j m_{ij}$$

where $m_{ij} = 1$, if there is a link between nodes i and j, and $m_{ij} = 0$ if there is no such link.
(5) Betweenness centrality: betweenness centrality measures the frequency of a node being located on the shortest path between other nodes in the network. It thus measures the degree to which this node functions as a point of control in communication. If a node with a high level of betweenness

centrality were to be deleted from a network, the network would fall apart into otherwise coherent clusters [25]. The formula for betweenness centrality is as follows:

$$b_{ijm} = g_{ijm}/g_{jm}$$
$$C_{b(i)} = \frac{\sum_j^n \sum_m^n b_{ijm}}{\frac{(n-1)(n-2)}{2}}$$

where g_{jm} is the number of shortest paths from node j to node m and g_{ijm} is the number of shortest paths from node j to node m passing through node i.

(6) Closeness centrality: closeness centrality measures the shortest distance of an actor from all other actors in a network that operationalizes the expected reach of a communication [23]. A node with high level of closeness centrality would communicate with other nodes directly. The formula for closeness centrality is as follows:

$$C_{d(i)} = \frac{n-1}{\sum_j^n d_{ij}}$$

where d_{ij} is the number of links in the shortest path from node i to node j.

3. RESULTS AND DISCUSSION

3.1 Global University–Industry Collaboration Trends

Table 1 shows that there were 2434 UI papers published in the field of computer science between 2002 and 2011, which accounts for 19.15% of all papers. The figures indicate an increase in the number of UI papers year on year, except in 2004 and 2010, when the numbers were lower than in the preceding years. Within the 10-year period, the number of UI papers increased from 188 papers in 2002 to 302 papers in 2011, an increase of 160%. This result shows that there was an increase in collaboration between universities and industry. The ratio of UI papers reached its peak in 2008 at 21.56% and its lowest in 2005 at 17.47%.

Table 1: Annual distribution of UI papers

Year	UI paper numbers	All paper numbers	Ratio of UI papers
2002	188	965	19.48%
2003	206	1089	18.92%
2004	195	1035	18.84%
2005	200	1145	17.47%
2006	231	1238	18.66%
2007	242	1301	18.60%
2008	304	1410	21.56%
2009	310	1542	20.10%
2010	256	1448	17.68%
2011	302	1540	19.61%
Total	2,434	12,713	19.15%

Table 2: Average numbers of authors of all papers and UI papers

	Number	Average number of authors	SD	*T*	*p*
All papers	12,713	3.16	1.775	21.184	.000
UI papers	2434	4.13	2.120		

We also calculated the number of authors of UI papers from 2002 to 2011, showing that the average number of authors was 4.13. The annual distribution of UI paper author numbers is shown in Table 2 and Figure 1. There were 672 UI papers with three authors (28.92%), 585 UI papers with four authors (25.17%), and 424 UI papers with two authors (18.24%). There was a total of 1681 UI papers with two to four authors, accounting for 69.06% of the total sample papers. The highest author number for a UI paper was 24 authors. There were 56 UI papers published by more than 10 authors, accounting for 2.41% of all papers. In addition, the annual distribution of number of authors of UI papers shows that collaboration among three people is most common, followed by collaboration among four people. Furthermore, comparison of the number of authors shows that the gap between UI papers with two, three, and four authors was small in 2002; however, the proportion of UI papers with two authors declined gradually, from 21.81% in 2002 to 9.93% in 2011. On the other hand, we see an upward trend in collaborations among four authors, with peaks in 2005 and 2009. Our results indicate that in the field of computer science the author number of UI papers increased, and that collaborations among three to four authors accounted for greatest proportion of UI papers.

This study used an independent sample *t*-test to analyse the average numbers of authors of UI papers and of all

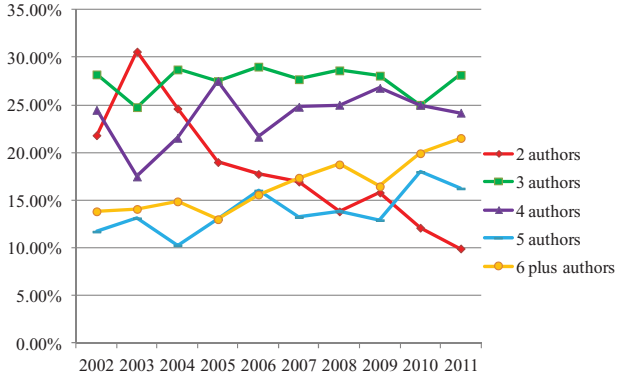

Figure 1: Yearly distribution of UI papers' author numbers

Table 3: Yearly distribution of UI paper institution numbers

Institution numbers	2	3	4	5	6 or more	Average
2002	105 (55.85%)*	48 (25.53%)**	20 (10.64%)	11 (5.85%)	4 (2.13%)	2.77
2003	119 (57.77%)*	48 (23.30%)**	27 (13.11%)	8 (3.88%)	4 (1.94%)	2.69
2004	115 (58.97%)*	60 (30.77%)**	19 (9.74%)	1 (0.51%)	0 (0.00%)	2.52
2005	106 (53.00%)*	66 (33.00%)**	22 (11.00%)	4 (2.00%)	2 (1.00%)	2.67
2006	113 (48.92%)*	79 (34.20%)**	31 (13.42%)	7 (3.03%)	1 (0.43%)	2.72
2007	122 (50.41%)*	81 (33.47%)**	27 (11.16%)	4 (1.65%)	8 (3.31%)	2.76
2008	149 (49.01%)*	103 (33.88%)**	34 (11.18%)	11 (3.62%)	7 (2.30%)	2.79
2009	150 (48.39%)*	104 (33.55%)**	40 (12.90%)	7 (2.26%)	9 (2.90%)	2.85
2010	115 (44.92%)*	82 (32.03%)**	36 (14.06%)	12 (4.69%)	11 (4.30%)	2.96
2011	150 (49.67%)*	92 (30.46%)**	42 (13.91%)	9 (2.98%)	9 (2.98%)	2.84
Total	1244 (53.53%)*	763 (32.83%)**	298 (12.82%)	74 (3.18%)	55 (2.37%)	2.77

Note:
*indicates the highest number of UI papers of the collaborating institutions
**indicates the second highest number of UI papers of the collaborating institutions
The numbers in parentheses indicate the percentages of UI papers from the specific number of collaborating institutions among the overall numbers of UI papers

papers in computer science in order to elucidate the statistical differences between them. Table 2 shows that there is a statistically significant difference in the average author number between the two kinds of paper ($t(31{,}118.647) = 21.184$, $p = .000$). The average number of authors for UI papers is 4.13, which is higher than the average of 3.16 authors per paper for all papers in computer science.

Table 3 shows the annual distribution of UI institution numbers, indicating that the total average number of institutions participate in each UI collaboration was 2.77. Table 3 also indicates the number of institutions participating in UI collaborations increased during the period under study. The average number of institutions reached its peak in 2010 with 2.96 institutions per paper, and was lowest in 2004 with 2.52 institutions. The distribution of collaborating institutions shows that the highest number of UI papers came from two institutions, accounting for 53.53% of all UI papers. That is to say, more than 50% of UI papers were published by authors belonging to a single university and a single industrial entity. The proportion of UI papers produced by three institutions ranked second, accounting for 32.83% of the total UI papers collected. Overall, although the teaming of two institutions remained the dominant trend, there was a gradual decrease in the proportion of such teams, from 55.85% in 2002 to 49.67% in 2011. By contrast, there was an increase in the proportion of UI papers produced by three institutions, from 25.53% to 30.46%. UI papers from four institutions also increased from 2007. These findings show that an increasing number of universities and industrial entities teamed up to conduct research and development. While collaborative teams gradually increased in terms of number of institutions, at the same time universities and industrial entities that share similar research focuses were also extending their partnerships with multiple institutions.

The average number of authors of UI papers was 4.13, which is higher than that of all papers in the computer science field (3.16 authors). The annual distribution of the number of authors of UI papers shows that collaboration among three people was most common, followed by collaboration among four people. There was an increasing trend for four people to produce UI papers, indicating that an increasing number of authors were involved in UI collaboration. However, the main pattern of UI collaboration remained two-institution collaboration, accounting for 53.53% of the total sample papers, followed by collaboration between two universities and one industrial entity or two industrial entities and one university, which ranked second with 32.83%. This study determined an increase in the number of papers co-authored by three or four institutions, showing that UI collaboration is no longer restricted to one-to-one collaboration. As the number of institutions participating in UI collaboration increases, universities and industrial entities become able to interact with multiple institutions.

3.2 University–Industry Collaboration Trends at the Country Level

For this study, we calculated the number and the proportion of UI papers for individual countries in order to identify the countries in which authors produced UI papers and to better understand related trends. Table 4 lists the top 20 countries by numbers of UI papers in two five-year windows. By splitting the analysis of UI papers into two stages, we can determine whether there is a changing trend in the top 20 countries. Through a comparison between the two stages, the growth and decline in the number of publications in each country can be determined. The top three contributors in 2002–2006 and 2007–2011 were the USA, China, and Germany, with the USA outnumbering the others significantly. The

Table 4: Top 20 countries/regions for UI papers

Country	2002–2006	2007–2011	Total
USA	793 (77.75%)	1018 (71.99%)	1811 (74.40%)
China	75 (7.35%)	165 (11.67%)	240 (9.86%)
Germany	68 (6.67%)	113 (7.99%)	181 (7.44%)
UK	63 (6.18%)	84 (5.94%)	147 (6.04%)
Canada	49 (4.80%)	88 (6.22%)	137 (5.63%)
Switzerland	33 (3.24%)	76 (5.37%)	109 (4.48%)
France	34 (3.33%)	61 (4.31%)	95 (3.90%)
Spain	22 (2.16%)	50 (3.54%)	72 (2.96%)
Italy	28 (2.75%)	47 (3.32%)	75 (3.08%)
Israel	33 (3.24%)	34 (2.40%)	67 (2.75%)
South Korea	21 (2.06%)	41 (2.90%)	62 (2.55%)
Japan	25 (2.45%)	37 (2.62%)	62 (2.56%)
India	17 (1.67%)	38 (2.69%)	55 (2.26%)
Taiwan	21 (2.06%)	28 (1.98%)	49 (2.01%)
Singapore	11 (1.08%)	35 (2.48%)	46 (1.89%)
The Netherlands	14 (1.37%)	31 (2.19%)	45 (1.85%)
Greece	23 (2.25%)	21 (1.49%)	44 (1.81%)
Austria	11 (1.08%)	30 (2.12%)	41 (1.68%)
Sweden	14 (1.37%)	27 (1.91%)	41 (1.69%)
Australia	19 (1.86%)	18 (1.27%)	37 (1.52%)
Finland	13 (1.27%)	18 (1.27%)	31 (1.27%)
Belgium	10 (0.98%)	18 (1.27%)	28 (1.15%)
Other countries	61 (5.98%)	108 (7.64%)	169 (6.94%)
Total	1020 (100%)	1414 (100%)	2434 (100%)

growth rates in UI papers show that only Greece (−8.70%) and Australia (−5.26%) experienced negative growth in their numbers of UI papers. Overall, the number of UI papers showed an increase; Singapore showed the highest growth rate at 218.18%, with Austria (172.73%) and Switzerland (130.3%) ranked second and third. This also shows that UI collaboration became increasingly popular.

Table 5 also shows the ratio of UI papers of the top 20 countries in 2002–2006 and 2007–2011. This result shows that the number of UI papers produced by the USA accounted for 70% of all UI papers, outnumbering second-ranking China. The cumulative number of the other countries in the top 20 accounted for less than 10%, indicating that USA was the most important source of UI papers. Comparing the country rankings of UI papers for 2002–2006 and 2007–2011 shows that although the USA, China, and Germany ranked first, second, and third, respectively, the USA and China showed opposing trends; while the USA showed a decline from 77.75% to 71.99%, China experienced growth from 7.35% to 11.67%, indicating the emergence of China in terms of UI collaboration.

Table 5: Annual distribution of international UI papers and average number of countries

Year	Number of international UI papers	All paper numbers	Ratio of international UI papers	Average number of countries
2002	63	965	6.53%	2.13
2003	68	1089	6.24%	2.31
2004	55	1035	5.31%	2.16
2005	73	1145	6.38%	2.14
2006	84	1238	6.79%	2.29
2007	85	1301	6.53%	2.21
2008	124	1410	8.79%	2.26
2009	126	1542	8.17%	2.26
2010	102	1448	7.04%	2.40
2011	150	1540	9.74%	2.33
Total	930	12,713	7.32%	2.26

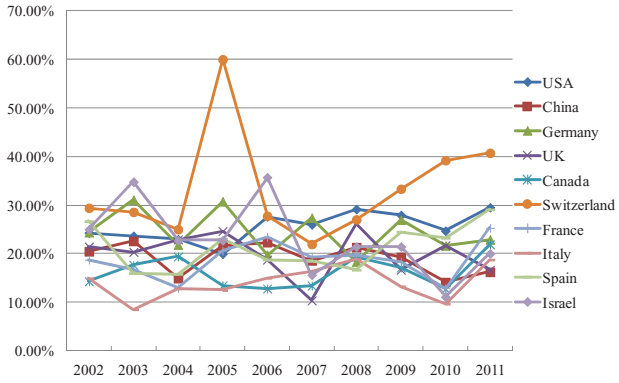

Figure 2: Ratio of UI papers of the top 10 countries

The ratio of UI papers is the proportion of UI papers to the total number of papers selected in a particular timespan. For this study, we calculated the ratio of UI papers of the top 10 countries, as illustrated in Figure 2. Most of these countries showed ratios of 20%–30% in their UI collaboration. Switzerland showed the highest proportion of UI papers, and Italy the lowest. The annual ratios of UI papers in Switzerland remained consistently above 25%, and experienced rapid growth after 2007. It is noteworthy that the ratio of UI papers in Switzerland was 60% in 2005; this was due to a general decrease in the number of collaborative articles between universities and industry. Yet even excluding 2005, Switzerland still outnumbered other countries in terms of UI collaboration ratio, even exceeding that of USA. In 2011, Switzerland's ratio of UI papers reached more than 40%, showing that such collaboration has become an important source of knowledge formation in Switzerland.

3.3 *International University–Industry Collaboration Trends*

For this study, we analysed UI papers between countries in order to examine the trend of international UI papers worldwide in the field of computer science. Annual distributions of international UI papers are shown in Table 6. The results show a total of 930 international UI papers during 2002–2011, accounting for 7.32% of the total sample papers. Table 5 shows that 2011 had the highest ratio of international UI papers, at 9.74%. The second-ranking year was 2008 with 8.79%. The lowest ratio of international UI papers was in 2004 with 5.31%. Overall, there was an upward trend in UI collaboration

Table 6: Top 20 countries/regions for international UI papers

Country	2002–2006	2007–2011	Total
USA	263 (76.68%)	422 (71.89%)	685 (73.66%)
China	47 (13.70%)	104 (17.72%)	151 (16.24%)
Germany	48 (13.99%)	88 (14.99%)	136 (14.62%)
UK	52 (15.16%)	70 (11.93%)	122 (13.12%)
Canada	37 (10.79%)	73 (12.44%)	110 (11.83%)
Switzerland	28 (8.16%)	68 (11.58%)	96 (10.32%)
France	27 (7.87%)	54 (9.20%)	81 (8.71%)
Israel	27 (7.87%)	31 (5.28%)	58 (6.24%)
Spain	15 (4.37%)	42 (7.16%)	57 (6.13%)
Italy	20 (5.83%)	37 (6.30%)	57 (6.13%)
India	12 (3.50%)	29 (4.94%)	41 (4.41%)
South Korea	17 (4.96%)	24 (4.09%)	41 (4.41%)
Greece	19 (5.54%)	21 (3.58%)	40 (4.30%)
The Netherlands	12 (3.50%)	26 (4.43%)	38 (4.09%)
Singapore	5 (1.46%)	31 (5.28%)	36 (3.87%)
Austria	7 (2.04%)	29 (4.94%)	36 (3.87%)
Japan	14 (4.08%)	20 (3.41%)	34 (3.66%)
Australia	17 (4.96%)	15 (2.56%)	32 (3.44%)
Taiwan	14 (4.08%)	15 (2.56%)	29 (3.12%)
Sweden	6 (1.75%)	22 (3.75%)	28 (3.01%)
Belgium	8 (2.33%)	15 (2.56%)	23 (2.47%)
Finland	9 (2.62%)	14 (2.39%)	23 (2.47%)
Other countries	46 (13.41%)	97 (16.52%)	143 (15.38%)
Total	343 (100%)	587 (100%)	930 (100%)

between countries. The ratio of international UI papers during 2002–2007 was 5%–7%, while that in the period 2008–2011 was 7%–9%, slightly higher than in the previous window. The average number of countries participating in UI papers increased from 2.13 in 2002 to 2.33 in 2011, showing an increase in the number of countries conducting UI collaboration with others (Table 5).

Each country prefers a different collaboration type for UI papers (different collaboration style). While some countries favour international UI papers, some prefer domestic UI papers. Table 6 shows the 20 countries with the highest number of international UI papers during 2002–2011. This research shows that the three countries with the highest numbers of international UI papers were the USA, China, and Germany, with international UI papers in the USA outnumbering those of other countries significantly. We also calculated the growth rates of international UI papers during 2002–2006 and 2007–2011. The results show that the number of international UI papers continued to increase over the years under study, with Australia (−11.76%) being the only country experiencing negative growth. Singapore's number of international UI papers experienced fivefold growth, while that of Austria also grew by more than 300%, showing closer international UI collaboration.

For this study, we compared the ratio of international UI papers with the ratio of UI papers in individual countries, as shown in Figure 3. The results indicate that different countries may prefer different modes of UI collaboration. UI collaboration in Greece, Switzerland, and Austria was mainly international collaboration. The

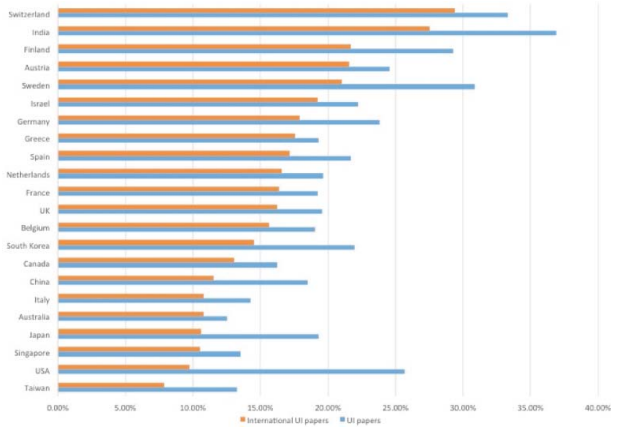

Figure 3: Ratio of international UI papers and UI papers by country/region

USA, Japan, and Taiwan are countries/regions that showed a greater preference for domestic UI collaboration. Switzerland had the highest ratio of international UI papers at 29.36%, and India ranked second with 27.52%. Greece had the highest proportion of international UI collaboration with a total of 40 international UI papers, accounting for 90.91% of its total UI papers. Switzerland ranked next with a total of 96 international UI papers, accounting for 88.07% of its total UI papers. Note that USA, with the highest number of international UI papers, had the lowest percentage of international UI papers, accounting for only 37.82%, showing that USA mostly experiences domestic collaboration between institutions. Furthermore, except USA, all other countries in Figure 3 exhibit percentage greater than 50% in their international UI papers share in the field of computer science.

During 2002–2011, there were 930 international UI papers in the field of computer science. To understand trends in UI collaboration between countries, this study pairs countries that show international UI collaboration relationships. Table 7 shows the 20 pairs with highest number of UI papers published. The pair "USA and China" ranks top, accounting for 12.26% of international UI papers; "USA and Germany" accounted for 7.31% of all international UI papers; "USA and UK" ranked third, accounting for 7.20% of all international UI papers. Except for "Germany and Switzerland", all of the remaining top 20 country pairs involved the USA as a partner. Therefore, this study shows that the USA plays a dominant role in international UI collaboration.

Among the 151 international UI papers in which China participated, the USA co-authored 114 papers, accounting for 75.50% of all international UI papers from China; 50% of international UI papers that Germany

Table 7: Top 20 international UI collaboration country/region pairs

Rank	Number of international UI papers (share)	Country pairs (country's total UI papers, international UI papers as % of total)	
1	114	USA (685, 16.64%)	China (151, 75.50%)
2	68	USA (685, 9.93%)	Germany (136, 50.00%)
3	67	USA (685, 9.78%)	UK (122, 54.92%)
4	66	USA (685, 9.64%)	Canada (110, 60.00%)
5	61	USA (685, 8.91%)	Switzerland (96, 63.54%)
6	49	USA (685, 7.15%)	Israel (58, 84.48%)
7	40	USA (685, 5.84%)	France (81, 49.38%)
8	30	USA (685, 4.38%)	South Korea (41, 73.17%)
9	28	USA (685, 4.09%)	Spain (57, 49.12%)
10	27	USA (685, 3.94%)	Italy (57, 47.37%)
11	26	USA (685, 3.80%)	India (41, 63.41%)
12	19	USA (685, 2.77%)	Australia (36, 59.38%)
13	19	USA (685, 2.77%)	Taiwan (29, 65.52%)
14	19	USA (685, 2.77%)	Japan (34, 55.88%)
15	17	USA (685, 2.48%)	Greece (40, 42.50%)
16	16	USA (685, 2.34%)	The Netherlands (38, 42.11%)
17	16	USA (685, 2.34%)	Singapore (36, 44.44%)
18	16	USA (685, 2.34%)	Sweden (28, 57.14%)
19	15	Germany (136, 11.03%)	Switzerland (96, 15.63%)
20	13	USA (685, 1.90%)	Finland (23, 56.52%)

participated in were in collaboration with the USA; 54.92% of international UI papers that Germany participated were in collaboration with the USA. Overall, most of the countries published more than 50% of their international UI papers with the USA. However, the USA showed a much lower percentage in its participation in international UI papers with other UI partner countries. Except for China, the international UI paper share for the USA with other countries was lower than 10%. These findings show that the USA is the most important partner in international UI collaboration, while the USA also collaborates with diverse countries.

To understand international UI collaboration from the perspective of individual countries and to ascertain the impact that each specific country has on the collective network, for this paper we employed UCINet in two five-year time frames to examine the international UI collaboration network. The density, degree centrality, betweenness centrality, and closeness centrality of the UI collaboration network were calculated to determine the core countries involved in international UI collaboration.

Figure 4 shows the international UI collaboration network from 2002 to 2006, with a network density of 0.485; Table 8 shows the data of the centrality of the top 20 counties. In this figure, each country is represented by a node, and the size of each node represents the number of international UI papers. The larger the node, the higher the number of international UI papers. The links between nodes represent UI collaboration, while the width of the links represents the frequency of collaboration between the two countries. The figure shows that

Figure 4: International UI collaboration network, 2002–2006

the USA is at the centre of the international UI collaboration network. The USA ranks first in three kinds of centrality, and the value of centralities outnumber other countries. The results show that the USA is at the centre of UI collaboration network. Among the 42 countries included in the network, the USA has the biggest node, having collaborative relations with most of the countries included, and establishing particularly extensive international UI collaboration relations with China, Germany, the UK, Canada, and Israel. China, the UK, and Germany also frequently co-authored with other countries. Besides their UI collaborative relationship with the USA, these countries also collaborated with neighbouring

Table 8: Top 20 countries/regions of centrality, 2002–2006

Country	Degree centrality		Betweenness centrality		Closeness centrality	
	Rank	Centrality	Rank	Centrality	Rank	Centrality
USA	1	290	1	523.17	1	93.18
UK	2	61	5	39.91	3	63.08
Germany	3	58	2	71.47	2	65.08
China	4	45	9	6.64	7	55.41
Canada	5	42	7	20.82	5	57.75
France	6	34	6	34.50	4	59.42
Switzerland	7	30	12	2.75	11	53.95
Israel	8	27	21	0.50	21	51.25
Greece	9	23	8	7.07	6	56.16
Italy	9	23	10	4.87	8	54.67
Spain	11	20	3	46.70	8	54.67
South Korea	12	19	4	41.87	11	53.95
Taiwan	13	15	13	2.50	13	52.56
Japan	14	14	11	3.68	11	53.95
Australia	14	14	14	1.57	13	52.56
The Netherlands	16	13	16	1.30	16	51.90
Sweden	17	12	26	0.24	16	51.90
India	17	12	15	1.53	21	51.25
Finland	19	11	19	0.73	13	52.56
Belgium	20	8	25	0.25	21	51.25
Austria	21	7	27	0.13	16	51.90
Norway	21	7	17	1.15	16	51.90
Singapore	21	7	20	0.58	21	51.25
Brazil	24	6	18	0.83	18	51.90

Figure 5: International UI collaboration network from 2007 to 2011

countries/regions such as China with South Korea, Taiwan, Japan, and Singapore, and collaboration between the UK, France, Germany, and Spain in Europe.

Figure 5 illustrates the international UI collaboration network from 2007 to 2011, showing an increase in the total number of nodes from 42 to 53. Table 9 shows the data of the centrality of the top 20 counties. The density of the UI collaboration network also increased from 0.485 to 0.574. This result illustrates an upward trend in UI collaboration across countries. The USA maintained its position as the biggest node among the 53 countries included, with increasing collaborative partners. The value of centralities still outnumbers the other countries. It shows that the USA is still the very centre of the network. Beside existing partners such as China, Germany, the UK, Canada, and Israel, USA intensified its international UI collaboration with Switzerland, France, South Korea, India, and Spain. Other countries that collaborate frequently include China, Germany, and the UK, though their nodes are smaller than the USA's in size. The network also illustrates that these countries also began to collaborate with partners in other continents, such as Germany with India, China with Germany, and the UK with Japan. In contrast with the network from 2002 to 2006, the number of smaller nodes has increased, growing to include countries such as Cyprus, Serbia, Sri Lanka, and Kuwait. These countries have only published one international UI paper each, mostly collaborating with countries such as the USA, China, Germany, and the UK. This finding shows that the diversification of the main UI collaboration countries has contributed to the growth in the number of the countries that participate in UI collaboration. It also illustrates that developing countries have begun to collaborate with technologically advanced countries.

Table 9: Top 20 countries/regions of centrality, 2007–2011

	Degree centrality		Betweenness centrality		Closeness centrality	
Country	Rank	Centrality	Rank	Centrality	Rank	Centrality
USA	1	513	1	704.16	1	85.25
Germany	2	125	3	162.45	2	65.00
China	3	112	11	15.57	9	55.32
UK	4	86	2	165.66	3	62.65
Canada	5	75	4	134.15	4	59.09
France	6	72	10	19.76	5	57.78
Switzerland	6	72	13	13.82	5	57.78
Spain	8	52	12	14.17	9	55.32
Italy	9	43	14	9.84	9	55.32
The Netherlands	10	36	6	61.62	7	55.91
Israel	11	34	28	0.40	20	50.49
India	12	33	9	21.04	12	54.47
Austria	13	31	5	64.58	7	55.91
Singapore	14	29	23	2.09	24	49.52
Sweden	15	26	15	8.55	12	54.17
Greece	15	26	21	2.19	14	52.53
South Korea	17	23	20	2.21	27	48.60
Japan	18	20	19	2.70	16	52.00
Australia	19	17	18	3.18	19	51.49
Finland	20	16	17	3.83	14	52.53
Ireland	20	16	22	2.12	16	52.00
Belgium	20	16	24	1.06	16	52.00
Norway	23	14	16	8.35	20	50.49
New Zealand	28	5	7	26.08	26	49.06
Venezuela	34	3	8	24.92	27	48.60

By examining the degree centrality of the UI collaboration network, we aim to measure the number of partnerships each country has with other countries. The higher the degree centrality is, the higher the number of collaborative relationships a country has with other countries. Higher degree centrality also entails more exposure and more opportunities to interact with other countries. Betweenness centrality measures the degree to which the node under study functions as a point of control in the communication. The higher the betweenness centrality is, the greater influence the country has. Closeness centrality measures independence of UI collaboration. A node with a high level of closeness centrality would communicate with other nodes directly. Our research shows that the USA ranked first in degree centrality, betweenness centrality and closeness centrality throughout the 10-year period under study, showing its strong influence and dominant role in global UI collaboration. The Netherlands, India, Austria, New Zealand, and Venezuela increased markedly in terms of their degree centrality, betweenness centrality, and closeness centrality, showing the growing influence of international UI collaboration. Yet Greece and Japan showed significant decreases in their centrality measures, and Spain experienced a lowered betweenness centrality and lower ranking, showing that these three countries became less influential in international UI collaboration.

Table 10: Correlation between number of UI/international UI papers and centrality of top 20 countries/regions

Type	Year	Degree centrality	Betweenness centrality	Closeness centrality
UI Collaboration	2002–2006	0.987*	0.988*	0.940*
	2007–2011	0.988*	0.954*	0.895*
International UI Collaboration	2002–2006	0.999*	0.976*	0.967*
	2007–2011	0.998*	0.957*	0.927*

*$p < .001$.

We also analysed the correlation between UI papers and international UI papers and determined that the two variables are highly correlated ($\gamma = .990$, $p < .001$). The countries from which numerous UI papers have been authored are the same ones from which numerous international UI papers have been authored as well. This result shows that the countries that are active in UI collaboration may also be active in collaborating with other countries. We further analysed the correlation between the number of UI and international UI papers and centrality of the top 20 countries and regions. As shown in Table 10, both UI and international UI collaborations were highly correlated with three types of centrality. This indicates that the countries from which more UI papers have authored are also the countries centrally located in the network. The countries from which more UI or international UI papers have been authored may interact closely with other countries and dominate cross-country communication in computer science.

4. CONCLUSION

UI papers provide an adequate information source for measuring the scale and strength of UI collaboration. Bibliometric methods were employed in this paper to examine trends in UI collaboration in computer science by analysing UI papers. There were 2434 UI papers in computer science between 2002 and 2011, accounting for 19.15% of the total sample papers. Overall, the number of UI papers increased over the 10-year study period, indicating that industrial and university researchers have become more likely to collaborate in the field of computer science. In other words, the relevance of UI collaboration in computer science has grown, and scientific research and its applications in this field have become interdependent. This increasing trend coincides with the results of previous UI collaboration studies of fuel cells [26] and biomedical research [27].

This study found an increasing trend in the numbers of authors and numbers of institutions involved in UI collaborations. The average number of authors of each UI paper was 4.13, which is higher than that for all papers in computer science (3.16). The annual distribution of the number of authors of UI papers shows that collaboration among three people is most common, followed by collaboration among four people. There is an increasing trend for four people to produce UI papers, indicating an increasing number of authors are involved in UI collaboration. However, the main pattern of UI collaboration remains two-institution collaboration, accounting for 53.53% of the total sample papers, followed by collaborations between three institutions (two universities and one industrial entity or two industrial entities and one university), which rank second with 32.83%. This study found an increase in the number of papers co-authored by three or four institutions, showing that UI collaboration was no longer restricted to one-to-one collaboration. As the number of institutions participating in UI collaboration increased, universities and industrial entities became able to interact with multiple institutions.

There was also an increasing trend in the number of countries participating in frequent UI collaboration. There were 930 international UI papers between 2002 and 2011, accounting for 7.32% of the total sample papers. The ratio of international UI papers also increased from 6.53% to 9.74%. The international UI collaboration networks for the two windows of 2002–2006 and 2007–2011 show that the total number of nodes increased from 42 to 53, with density increasing from 0.485 to 0.574. This shows that international UI collaboration became more common.

Among individual countries, the USA had the most outstanding performance. Across 2002–2006 and 2007–2011, USA consistently published the highest number of UI papers, accounting for more than 70% of the total UI papers, and outnumbering the number of UI papers published in China. The UI collaboration networks for 2002–2006 and 2007–2011 are centred on the USA, showing an increasing number of countries collaborating with the USA. Overall, most of the countries published more than 50% of their international UI papers with the USA. The USA is a leading country of technology research and development and has a long history of governmental and industrial investment in computer science research. Its profound influence on the field coincides with the results of this study. However, the USA showed a much lower percentage in its participation in international UI papers with other UI partner countries. This result shows that the USA was the most productive country in UI collaboration, and the dominant partner of most countries in their international UI collaboration.

China, the second-ranked country for UI paper authorship, has shown substantial growth in the authorship of

both UI papers and international UI papers between the two 5-year windows. This result accords with that of Liang et al [6]. In addition, studies by Kwon et al. [5] and Park and Leydesdorff [11] have shown that there is also an increasing trend in the ratio of UI collaborations from South Korea. Our results show that the numbers of both UI and international UI papers from South Korea have increased, but the ratio of international UI papers to UI papers has decreased. Summarizing our study and previous studies, besides China and South Korea, the growing trend of authoring UI and international UI papers is also evident in Japan, India, Taiwan, and Singapore, indicating the emergence of UI collaboration in Asia.

The growing trend of UI collaboration is observable across different research areas and countries and regions. In other words, collaboration between universities, government, and industries may become more intimate in the future. The results of this study provide information on the development of joint contributions between universities and industries in computer science and may serve as a reference for administrative departments involved in policymaking.

Because of time and human resource limitations, we analysed only the top 10 impact factor journals in two subfields of computer science. This study obtained an overview of UI papers in computer science and further explored the output performance of each country. Future studies should perform further analysis at the institutional level, or broaden their scope to other subfields of computer science or other research areas of natural science. An institutional-level analysis may provide a more thorough understanding of the UI collaboration in computer science. Through a subfield comparison, UI collaboration in the field of computer science can be fully outlined, and through a comparison of the results from different research areas, the characteristics of UI collaboration in each research area can be determined.

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