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A Ten-year Review of Granular Computing

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Abstract

The year 2007 marks the 10th anniversary of the introduction of granular computing research. We have experienced the emergence and growth of granular computing research in the past ten years. It is essential to explore and review the progress made in the field of granular computing. We use two popular databases, ISI's Web of Science and IEEE Digital Library to conduct our research. We study the current status, the trends and the future direction of granular computing and identify prolific authors, impact authors, and the most impact papers in the past decade.

1 Introduction

The concept of granular computing was initially called information granularity or information granulation related to the research of fuzzy sets in Zadeh's early papers [19, 20, 21]. To the best of our knowledge, the term granular computing first appeared in literature in 1997 [21] as follows, "a subset of computing with words is granular computing." Later in his 1998 paper, Zadeh had a footnote stating that "[t]he label 'granular computing' was suggested by Professor T.Y. Lin" [22]. Therefore, we may consider 1997 as the birth year of granular computing. This year (2007) is the 10th anniversary of the introduction of granular computing research.

Granular computing has been gaining popular in the past ten years [3, 14, 15, 17, 23]. The annual IEEE Conferences on Granular Computing attracted many research papers [10, 24]. It is essential to examine and review the development on granular computing. The goal of this study is to analyze and summarize ten years' research on granular computing. It is hoped that the granular computing community will benefit from this research.

We mainly use two popular databases, ISI's Web of Science and IEEE Digital Library to conduct our research. We will identify prolific authors, impact authors, and the most impact papers in the past ten years. The current status, the trend and the future direction of granular computing could be identified based on the results.

2 Granular Computing

We briefly describe the basic concept of granular computing in this section.

Granular computing is often defined as an umbrella term to cover any theories, methodologies, techniques, and tools that make use of granules in complex problem solving [14, 16]. Granular computing is a new term for the problem solving paradigm and may be viewed more on a philisophical rather than technical level [14]. Zadeh considers granular computing as a basis for computing with words, i.e., computation with information described in natural language [21, 23]. Yao views granular computing as a triangle: structured thinking in the philosophical perspective, structured problem solving in the methodological perspective and structured information processing in the computational perspective [17, 18]. Bargiella and Pedrycz emphasize essential features of granular computing: the semantical transformation of data in the process of granulation and the non-computational verification of information abstractions [3].

The basic ingredients of granular computing are granules such as subsets, classes, objects, clusters, and elements of a universe. These granules are composed of finer granules that are drawn together by distinguishability, similarity and functionality [21]. Based on complexity, abstract and size, granules can be measured in different levels. The problem domain, i.e., the universe, is the highest and coarsest granule. Granules at the lowest level are composed of elements or basic particles of the particular model that is used. If we take the current article as a granule, the finest granules would be the words or letters.

One of the key issues in granular computing for problem solving is granulation. A broad view of granulation could be easy to understand and manageable for granular computing research and applications [14]. Granulation involves the process of two directions in problem solving: construction and decomposition. The construction involves the process of forming a larger and higher level granule with smaller and lower level sub-granules. The decomposition involves the process of dividing a larger granule into smaller and lower level granules. The former is a bottom-up process and the latter a top-down process.

In order to conduct granulation, one has to understand the relationships amongst granules [14]. There are two types of relationships: interrelationship and intrarelationship. Decomposition concerns breaking down a larger granule into smaller granules from which a larger granule can still be formed with construction. Construction concerns grouping smaller granules that share similarity, indistinguishability, and functionality to a larger granule. The relationship involved in the former type of granulation is considered as an intrarelationship, the later an interrelationship.

One of the basic and fundamental relationships is similarity. It is a key to forming an intrarelationship of a granule. Furthermore, it can be used to measure closeness amongst granules. It can also be used to measure the fineness or coarseness of a granule. Refinement and coarsening are another type of relationships. A granule o_1 is defined as a refinement of another granule o_2, or equivalently, o_2 is a coarsening of o_1, if every sub-granule or object of o_1 is contained in some sub-granules of o_2. Partitions and coverings are two simple and commonly used granulations of a universe [15]. A partition of a universe is a collection of its non-empty and pairwise disjoint subsets whose union is the universe. It forms a covering if disjoint is not a condition. The subsets are called covering granules in a covering, and partition granules in a partition.

3 Methodology and Databases

Much research has been done in identifying research areas, trends, relationships, development and future direction [5, 12, 13]. One of representatives of such research is scientometrics which is the science that measures and analyzes science. Identification of research areas is a key theme of this area [12]. We gain more understanding of a research domain by examining its publications. Studies of this type have been ongoing for decades. For instance, Crane used a logistic curve of publication numbers to describe the growth of research areas [6]. Goffman proposed an epidemic model to predict the growth of research areas [9].

Research impact could be measured by citations. It is suggested that a highly cited paper will have more impact than moderate cited papers. This gives a simple although arguable way to measure the quality and impact of research. A study shows that of the 50 most-cited chemists, seven have been awarded the Noble Prize [8]. In other words, the citation index may be used to predict Noble Prize winners. According to a recent research, citation counts of the publications corresponded well with authors' own assessments of scientific contribution [1]. By analyzing citations, one may predict research influences [7]. Citation is also used as a bibliometric indicator to predict research development [12]. It is suggested that the more recent or current highly cited papers in a research field, the more likely the field will grow rapidly in the near future.

We will examine granular computing research by exploring two main resources in this study: Institute for Scientific Information's (ISI) Web of Science and IEEE's Digital Library. Web of Science (http://isiknowledge.com/wos) is one of ISI's key products in the information age. It features extended functions of ISI's early products Current Content, which collects bibliographic information of research articles of high quality journals selected by ISI. These citation indexes collect not only bibliographic information but also the information of citation relationship amongst research articles. ISI also indexed Lecture Notes in Computer Science (LNCS) as well as Lecture Notes in Artificial Intelligence (LNAI) series for a short period of time. LNCS and LNAI are mainly a collection of conference proceedings. Many computer science-related conferences publish their proceedings through the LNCS/LNAI series.

The IEEE Digital Library (http://ieeexplore.ieee.org) contains more than 120 IEEE journals, magazines, transactions and letters, together with more than 600 IEEE conference proceeding titles dated from 1988. It has a robust search function including full-text search. However, it does not function with citation information thus we only use it for publication count.

4 Search, Research and Results Analysis

4.1 Web of Science

We started with Web of Science to locate granular computing papers that are indexed by ISI. ISI updates its database on a weekly base. The data was collected during the week of April 27 to May 5, 2007. The latest available data was on April 29, 2007. Two basic measures, number of papers and number of citations, are used for popularity and influence of granular computing research.

A granular computing paper is defined as a paper containing granular computing related terms, for instance, "granular computing", "information granularity", "information granulation" or "granular computation". We used the Topic field in Web of Science which is defined as the words or phrases within article titles, keywords, or abstracts.

Results of queries with Topic as "granular computing", "information granularity", "information granulation", and "granular computation" are shown in Table 1. The All column represents the number of granular computing papers with either of the terms, in particular, we use the Or function.

We can see clearly the popular trend of research of granular computing by looking at the All column. One thing that needs to be addressed here is that there are 100 papers using the term granular computing, while about equal

Table 1. Number of Papers Each Year (WoS)

Year	All	Granular computing	Information granulation	Information granularity	Granular computation
1997	5		1	4	
1998					
1999	10	4	2	5	
2000	9	5	4	1	
2001	13	8	9		
2002	18	9	8	6	
2003	19	14	6	2	
2004	28	21	12		2
2005	28	17	13	1	
2006	33	19	16	1	1
2007	5	3	2	2	
Total	168	100	73	22	3

number of papers adopt non-granular-computing terms. In addition, people who adopt the term "granular computing" used different abbreviations. At least four abbreviations, namely, GrC, Grc, GC, and Gc appeared in the literature. It is suggested that a consistent terminology may help promote this domain of study. We suggest to standardize the term of granular computing and use GrC as its abbreviation.

Table 2. Most Prolific Authors (WoS)

Name	Papers	Name	Papers	Name	Papers
Pedrycz W	45	Vukovich G	7	Hirota K	4
Oh SK	13	Bortolan G	5	Shi ZZ	4
Skowron A	12	Liu Q	5	Synak P	4
Ahn TC	10	Pal SK	5	Zhang WX	4
Lin TY	9	Park KJ	5	Zhang YQ	4
Yao YY	8	Peters JF	5	Zhong N	4
Bargiela A	7	Stepaniuk J	5	Zhu W	4
Park HS	7	Tsumoto S	5		

It is notable that granular computing research started booming in 1999 based on the results in Table 1. In fact, three of top cited papers by Pedrycz and his collaborators (listed in a later part of this article) were published in 1999.

Web of Science provides a search feature for author and their affiliations. The results are presented in Tables 2 to 5. Table 2 lists the most prolific authors in granular computing in terms of the number of granular computing papers published. The 23 authors listed here published at least 4 granular computing papers. Pedryzy (co)authored about one third of granular computing papers per our definition in this study. There are more than 130 authors recorded in the Web of Science database.

Top 10 countries or territories where authors are located are listed in Table 3. It can be easily observed why Canada is at the top as Pedrycz, Yao and Vukovich reside in Canada. Skowron is from Poland, and Liu, Shi, and Zhang are from China. The top institutions of the authors affiliated are listed in Table 4. Pedrycz is co-affiliated with the University of Alberta and Polish Academy of Sciences. Ahn and Park are with Wonkwang University, South Korea.

Table 3. Top Countries and Territories (WoS)

Countries/Territories	Papers
Canada	62
Poland	55
China	28
USA	26
South Korea	19
Japan	11
Italy	11
Taiwan	9
England	7
India	5

Table 4. Top Institutions (WoS)

Institutions	Papers
University of Alberta	42
Polish Academy of Sciences	33
Wonkwang University	15
University of Suwon	11
University of Regina	10
Warsaw University	10
Chinese Academy of Sciences	9
University of Manitoba	9
Canadian Space Agency	8
San Jose State University	8
Nottingham Trent University	7
Georgia State University	6
Polish Japanese Institute of Information Technology	6
Xian Jiaotong University	6

Table 5. Top Journals (WoS)

Journal Names	Papers
Information Sciences	11
IEEE Transactions on Systems, Man and Cybernetics	10
Fuzzy Sets and Systems	9
International Journal of Intelligent Systems	7
Transactions on Rough Sets	5
Fundamenta Informaticae	5
IEEE Transactions on Fuzzy Systems	4
Soft Computing	4
International Journal of Approximate Reasoning	3
International Journal of Uncertainty Fuzziness and Knowledge-Based Systems	3
Total	61

Journals that publish the most granular computing papers are shown in Table 5. There are another 28 journals published for 34 papers. The remaining papers are published on Spinger's LNCS and LNAI including 13 papers from proceedings of the International Conference on Rough Sets, Fuzzy Sets, Data Mining, and Granular Computing (RSFDGrC), 13 from the International Conference on Rough Sets and Current Trends in Computing (RSCTC), and 9 from the International Conference on Rough Sets and Knowledge Technology (RSKT). The first two conferences are official events organized by the International Rough Set Society (IRSS) and the third one is an IRSS-sponsored conference [11]. This may indicate the close relationship between rough set research and granular computing research.

Table 6. Citation Each Year (WoS)

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Total	Average
Citations	3	7	15	33	43	76	99	120	169	39	604	54.91
All Papers	5	5	15	24	37	55	74	102	130	163		
Citation per paper	0.60	1.67	1.00	1.38	1.16	1.38	1.34	1.18	1.30	0.24		

The second analysis based on Web of Science database is citation analysis. There are 604 citations of 168 granular computing papers. The average citations is 3.60 per paper. Table 6 shows the number of citations each year. Similar to the trend we found in Table 1, the citations are also growing every year, from 3 in 1998 to 169 in 2006. Please note that the figure showed here also includes citations from non-granular computing papers as per our definition. An example is that there were no granular computing papers in 1998 as we can see in Table 1. However, there were three counts of citations in 1998. The citation per year is calculated by the number of citations divided by the number of accumulated papers (All papers). We do not observe any trend for citation per year.

In order to understand more on granular computing research, we also identify some top cited papers as follows. The numbers in brackets are total citations and average citations per year.

1. Zadeh LA, Toward a theory of fuzzy information granulation and its centrality in human reasoning and fuzzy logic, *Fuzzy Sets and Systems*, **90**(2),111-127, 1997. (**160, 14.55**)
2. Greco S, Matarazzo B, Slowinski R, Rough sets theory for multicriteria decision analysis, *European Journal of Operational Research*, **129**(1), 1-47, 2001. (**65, 9.29**)
3. Skowron A, Stepaniuk J, Information granules: Towards foundations of granular computing, *International Journal of Intelligent Systems*, **16** (1), 57-85, 2001 (**26, 3.71**)
4. Pedrycz W, Vasilakos AV, Linguistic models and linguistic modeling, *IEEE Transactions on Systems, Man and Cybernetics Part B-Cybernetics*, **29**(6), 745-757, 1999. (**23, 2.56**)
5. Yao YY, Information granulation and rough set approximation, *International Journal of Intelligent Systems*, **16**(1), 87-104, 2001. (**18, 2.57**)
6. Pedrycz W, Fuzzy equalization in the construction of fuzzy sets, *Fuzzy Sets and Systems* **119**(2), 329-335, 2001. (**17, 2.43**)
7. Hirota K, Pedrycz W, Fuzzy computing for data mining, *Proceedings of the IEEE*, **87**(9), 1575-1600, 1999. (**17, 1.89**)
8. Peters JF, Skowron A, Synak P, Ramanna S, Rough sets and information granulation, *Lecture Notes In Artificial Intelligence*, **2715**, 370-377, 2003. (**16, 3.20**)
9. Greco S, Matarazzo B, Slowinski R, Extension of the rough set approach to multicriteria decision support, *INFOR*, **38**(3), 161-195, 2000. (**13, 1.62**)
10. Hirota K, Pedrycz W, Fuzzy relational compression, *IEEE Transactions on Systems, Man and Cybernetics Part B-Cybernetics*, **29**(3), 407-415, 1999. (**13 1.44**)
11. Slowinski R, Greco S, Matarazzo B, Rough set analysis of preference-ordered data, *Lecture Notes In Artificial Intelligence*, **2475**, 44-59, 2002. (**12, 3.00**)
12. Hata Y, Kobashi S, Hirano S, Kitagaki H, Mori E, Automated segmentation of human brain MR images aided by fuzzy information granulation and fuzzy inference, *IEEE Transactions on Systems, Man and Cybernetics Part C-Applications and Reviews*, **30**(3), 381-395, 2000. (**12, 1.50**)
13. Pedrycz W, Bargiela A, Granular clustering: A granular signature of data, *IEEE Transactions on Systems, Man and Cybernetics Part B-Cybernetics*, **32**(2), 212-224, 2002. (**10, 1.67**)
14. Pal SK, Mitra P, Case generation using rough sets with fuzzy representation, *IEEE Transactions on Knowledge and Data Engineering*, **16**(3), 292-300, 2004. (**9, 2.25**)
15. Yao YY, Probabilistic approaches to rough sets, *Expert Systems* **20**(5), 287-297, 2003. (**9, 1.80**)

It is interesting to observe that the total citation ranking is generally consistent with the average citation per year with a few exceptions, e.g. Peters 2003 and Slowinski 2002. Table 7 reveals the ranking of these top papers by total citation and citation per year.

Table 7. Rank of Top Cited Papers (WoS)

	Total Citation		Citation Per Year
1	Zadeh 1997	1	Zadeh 1997
2	Creco *et al.* 2001	2	Creco *et al.* 2001
3	Skowron *et al.* 2001	3	Skowron *et al.* 2001
4	Pedrycz *et al.* 1999	4	Peters *et al.* 2003
5	Yao 2001	5	Slowinski *et al.* 2002
6	Pedrycz *et al.* 2001	6	Yao 2001
7	Hirota *et al.* 1999	7	Pedrycz *et al.* 1999
8	Peters *et al.* 2003	8	Pedrycz *et al.* 2001
9	Greco *et al.* 2000	9	Pal *et al.* 2004
10	Hirota *et al.* 1999	10	Hirota *et al.* 1999
11	Slowinski *et al.* 2002	11	Yao 2003
12	Hata *et al.* 2000	12	Pedrycz *et al.* 2002
13	Pedrycz *et al.* 2002	13	Greco *et al.* 2000
14	Pal *et al.* 2004	14	Hata *et al.* 2000
15	Yao 2003	15	Hirota *et al.* 1999

According to Web of Science, 80 of 168 papers were cited at least once by other researchers. In other words, half of granular computing publications have some level of research impact. There were 604 citations in total. However, almost half of the citations are from the top 5 papers. To be exact, the top 5 papers count for 292 citations.

We identify the most influence authors in the next step. As the Web of Science does not facilitate author citation count of selected papers. We manually count 81 granular computing papers that have at least one citation. Table 8 lists the most impact authors whose granular computing papers received citations more than 10 times. Zadeh published one granular computing paper with citation count as 160. Pedrycz has four highly cited papers with total citation numer as 80. Together with his other papers, his total citation number is 130. Accordingly, Zadeh was identified as a Highly Cited Researcher in Computer Science and Pedrycz in Engineering by ISIHighlyCited.com.

Table 8. Impact Authors (WoS)

Name	Cites	Name	Cites	Name	Cites
Zadeh LA	160	Synak P	31	Kobashi S	14
Pedrycz W	130	Peters JF	26	Hirano S	12
Greco S	90	Vasilakos AV	23	Kitagaki H	10
Matarazzo B	90	Ramanna S	22	Mitra P	10
Slowinski R	90	Bortolan G	17	Mori E	10
Skowron A	78	Vukovich G	17	Pal SK	10
Stepaniuk J	41	Lin TY	15	Zhang YQ	10
Yao YY	37	Bargiela A	14	Zhong N	10
Hirota K	32	Hata Y	14		

4.2 IEEE Digital Library

We mainly conducted granular computing paper count for IEEE Digital Library. The search to All Fields of IEEE Digital Library was conducted in early May, 2007. The results are shown in Table 9. The "All Field" of IEEE Digital Library stands for Full text, Document title, Author, Publication title, Abstract, Index theme, and Affiliation. It is obvious that the terms we used will not appeare in the fields of author and affiliation. The Document title is the same as Article titles in Web of Science.

The tricky field is Publication Title which includes conference titles. As a result, all papers included in the proceedings of IEEE International Conferences on Granular Computing (IEEE GrC) are retrieved. However, not all papers published in these proceedings are granular computing papers based on the criteria we used in selecting papers in Web of Science database. It is observed that there are 157 IEEE GrC'05 and 180 IEEE GrC'06 papers collected in the IEEE Digital Library. The number in Table 9 with brackets is the number of granular computing papers that are not from IEEE GrC proceedings.

The IEEE Digital Library treats research papers and other types of publications equally. For example, our query results contain several announcement of special issues on granular computing that appeared in IEEE Computational Intelligence Society journals. Prefaces, indexes, and even breaks of the proceedings of IEEE GrC were also appeared in our research results. We excluded these items.

With these considerations and explanation, we may conclude that the criteria we used in searching the IEEE Digital Library are very similar to the search of Web of Science. Due to the different scopes of collections between Web of Science and IEEE Digital Library, the results are not very consistent. The former collects mainly journal articles with an exception of the LNCS/LNAI, the latter collects many conference proceedings. We cannot easily identify a clear trend for granular computing papers as we do in the previous section. Other than some IEEE transactions, the majority of collections of the IEEE Digital Library are IEEE conference proceedings. It is noted that granular computing papers are scattered in different IEEE conference proceedings. Quite often, granular computing papers were published as special session papers to conferences. This would make the number fluctuate from year to year.

Table 9. Number of Papers Each Year (IEEE)

Year	All	Granular computing	Information granulation	Information granularity	Granular computation
1996	2		2		
1997	8		4	4	
1998	3		2		
1999	6	5	1	2	
2000	12	6	5	2	
2001	19	10	10	2	
2002	14	12	4		
2003	11	4	6	2	
2004	8	5	2	1	2
2005	172 (15)	169 (12)	6	3	
2006	207 (27)	201 (21)	7		
2007	3	3			
Total	465 (135)	415 (135)	49	16	2

It is interesting to know that there are a number of granular computing papers in the early year. This reflects the fact of the long publication cycle for journal papers. New ideas are normally published in conference proceedings. It is clear to see that we have a larger number of granular computing paper due to the launch of the IEEE International Conference on Granular Computing in 2005. The IEEE Digital Library does not provide a search feature to find or count granular computing papers within the IEEE GrC proceedings as per our definition. We thus cannot get the actual number of granular computing publications in 2005 and 2006. We will conduct a detailed study for IEEE GrC proceedings in the future.

4.3 Research Trends and Interaction

Figure 1 shows the growth of granular computing publications in terms of cumulative numbers. The label WoS stands for the cumulative number of papers published each year in ISI selected journals and proceedings. IEEE represents cumulative paper numbers on IEEE's publications. All is the total publications in IEEE Digital Library and Web of Science (We did only a simple addition but did not consider redundant counts). We can see from Figure 1 that all three lines are close to linear, i.e. the granular computing publications has a linear growth rate.

Scientific growth is a diffusion process [6]. It is suggested that this happened when members of a research area has less interaction with each other and with scientists who are not in the area [6]. In the areas where researchers are aware of each other's existence, and mutual influence and communication occurred, the curve of cumulative growth of publications and of authors entering the field follows a logistic pattern [6]. Our findings of most impact papers confirm this. By examining the titles, we may find that all granular computing papers are fuzzy sets and rough sets related

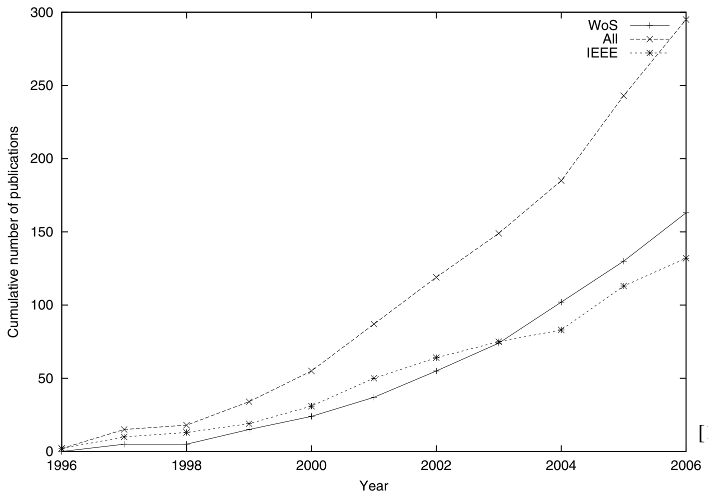

Figure 1. Publication Growth and Trends

except for papers 3, 4 and 13. With a detailed examination of the remaining three papers, we found that paper 3 is rough sets and papers 4 and 13 are fuzzy sets related. We may conclude that the most influential papers are fuzzy sets and rough sets related. In other words, the granular computing community has a lesser relationship and minimal interaction with other research communities.

5 Concluding Remarks

We have reported trends and development for research on granular computing during the past ten years by examining two popular databases. Prolific authors, impact authors, as well as most impact papers were identified. It is suggested that a unified term of granular computing should be used in order for researchers to locate granular papers easily from research databases. It is observed that the growth of granular computing is in a healthy manner. However, there is evidence showing that the granular computing community has less interaction with other research communities other than fuzzy sets and rough sets. It is time to interact and communicate with other research communities in order to promote the research of granular computing. We will conduct a detailed analysis and study on classification, different school of thoughts, and remaining problems in future articles.

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