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Four Decades of Multi-Valued Logic –Lists of Highly Cited Papers–

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***Abstract*—This paper surveys research activities in multiple-valued logic (MVL), and focuses on the International Symposium on Multiple-valued Logic (ISMVL). It spans 40 years. Using four different databases, lists of highly cited papers on MVL are shown, and research topics are analyzed.**

***Keywords*-multiple-valued logic, survey, history, citation counts.**

I. Introduction

This paper surveys the history of the International Symposium on Multiple-Valued Logic (ISMVL), and analyzes **highly cited papers** using four databases.

This paper is organized as follows: Section II reviews the history of ISMVL; Section III reviews the research surveys in the past ISMVLs. Section IV shows the method to find highly cited papers from four different databases. Section V shows the result of analysis. And, finally, Section VI concludes the paper.

II. History of ISMVL

As for the research on multiple-valued logic, in North America, the first ISMVL was held in 1971 in New York States, and after that ISMVLs were held in every year. To promote research activities, special issues were published as follows: *Computer* (1974 and 1988), and *IEEE Transactions on Computers* (IEEE TC) (1977, 1981, and 1988). Especially, the papers that appeared in *Computer* were easy to read, and were quite influential. Furthermore, D. C. Rine [15], J. Muzio, T. Wesselkamper [77], J. T. Butler [1], and G. Epstein [4] published monographs.

In this period, in Japan, activities in MVL were done independently. In February of 1970. Prof. T. Hasegawa of Kyoto University organized a workshop on **Multiple-valued Logic and Their Applications**. He organized four workshops up to 1989 [20]. Also, at ISMVLs, Japanese researchers presented papers from the first meeting. Up to 1975, there were only a few Japanese ISMVL papers. However, in 1976, four Japanese papers were published, and after that the number of Japanese papers in ISMVL never decreased. Thus, among the Japanese participants of ISMVL, there were discussions to hold an ISMVL in Japan.

To promote research activities in Japan, **The Japan Research Group of Multiple-valued logic** was organized to hold two domestic meetings in a year. After that, ISMVLs were held in Kyoto in 1983; in Sendai in 1992; Fukuoka in 1998; Tokyo in 2003; and Naha in 2009. Also in 2013, ISMVL will be held in Toyama. Furthermore, in 1989, T. Higuchi and M. Kameyama published a monograph on multiple-valued logic [19] written in Japanese.

III. Survey papers in ISMVL

In ISMVLs, many survey papers were presented: In 1975, T. Kitahashi summarized Japanese activities on multiple-valued research [9]; in 1976, K. C. Smith surveyed research on multi-valued logic circuits [18]; in 1977, D. C. Rine surveyed research on multiple-valued logic design [16]; in 1979, J. T. Butler analyzed research activates using database [6]; in 1986, S. L. Hurst surveyed research in opto-electronics [7]; in 1991, C. Moraga surveyed spectral transformations [12]; in 1992, J. T. Butler analyzed research activates using database again [2]; in 1993, D. M. Miller outlined design tools for multiple-valued logic [30]; in 1997, T. Sasao surveyed ternary decision diagrams [38]; in 2010, C. Moraga surveyed spectral transformation again [13]; in 2012, H. Machida summarized the work of I . G . Rosenberg [10].

Especially, K. C. Smith described as a textbook, D. C. Rine described chronologically. J. T. Butler classified papers stored in INSPEC database by using keywords. He also presented statistical data by years, topics, authors, countries, and affiliations.

IV. Papers with High Citation Counts

In this paper, we use a different survey approach. We are interested in **highly cited papers** in multiple-valued logic.

A. Databases for Analysis

Recently, many papers have become available in digital format. This made analysis using citation counts much easier than before. To find citation counts of papers, we used four databases.

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Web of Science (Fee-based)
This database shows the citations within the papers included in the database of Thomson Reuters only. The number of scientific journals in the database is about 12×10^3. In this database, citations of papers from monographs or small conferences are not counted.

Google Scholar (Free)
This is operated by Google. It also shows citations among monographs, small conferences, and patents. When the documents are in the WEB, informal references other than scientific journal are also counted. On the other hand, papers not available in the Internet are not counted. The service started in Dec. 2004.

Microsoft Academic Search (Free)
This is operated by Microsoft. The database contains 19×10^6 authors and 38×10^6 publications. It also contains papers presented at local conferences. It has many functions and is very convenient to use. In this paper, we used this database to rank most cited papers.

ArnetMiner (Free)
This is operated by the National Science Foundation of China. It started in March 2012. The database contains 1.3×10^6 researchers and 3×10^6 publications. Unfortunately, presently, the database lacks old papers.

B. Influence of Databases

Since four databases have different ranges of coverage, we used these databases to analyze papers. Analysis of many MVL papers exposed the deficiencies of these databases. For example, some papers that are in the top rank in the Google Scholar do not appear in the WEB of Science. In the Google Scholar, patents and informal documents are also counted, while in the WEB of Science, only scientific journal papers that are contained in the database of Thomson Reuters are counted.

In some cases, a highest ranked paper of a person did not exist. This means that somebody cited the paper incorrectly, and other people copied that citation without verification. In some databases, some of the authors were missing. Thus, for important papers, we downloaded the originals, and confirmed by reading the papers.

C. Citation Counts

For several MVL papers, we carefully analyzed citation counts in four databases. After that, in this paper for convenience, we define **highly cited papers** as follows, where **papers** include books and chapters of books.

Definition 4.1: **A paper with a high citation count** satisfies at least one of the following conditions[1]:

- It is cited by Web of Science at least 25 times.
- It is cited by Microsoft Academic Search at least 30 times.
- It is cited by Google Scholar at least 50 times.
- It is cited by ArnetMiner at least 50 times.

Definition 4.2: **A paper with a very high citation count** is cited by Microsoft Academic Search at least 500 times. **A paper with an extraordinary high citation count** is cited by Microsoft Academic Search at least 5000 times.

Definition 4.3: **A paper on multiple-valued logic** satisfies at least one of the following conditions:

1) Presented at an ISMVL.
2) The title of the paper or a list of keywords contains either **multiple-valued logic** or **multi-valued logic**.
3) It uses a concept of multiple-valued logic.

Papers in Categories 1 and 2 are easy to find by computers, while the papers in Category 3 are found by close inspection by author. Thus, it may not cover all the papers.

V. Result of Analysis

To rank the most cited papers, we used Microsoft Academic Search. A different database may produce different results. The original data was collected in August 2012, and updated in Feb. 2013.

A. Papers Presented at ISMVLs

Category 1 contains papers that appeared in ISMVLs. The second part of the references show the papers with high citation counts. Top ten papers with the highest citations are [30], [37], [21], [40], [36], [29], [23], [32], [26], [22]. Among them, [30], [21], [23] are invited papers.

B. Papers with **multiple-valued logic** or **multi-valued logic** or **multivalued logic** as Keywords

Category 2 contains papers that have keyword **multiple-valued logic** or **multi-valued logic** or **multivalued logic** in the titles or list of keywords[2], which are not in Category 1 The third part of the references show the papers with high citations. The top ten papers with the highest citations are [80], [58], [64], [86], [85], [55], [51], [52], [76]. Among them, [55], [64], [85], [86] are survey papers. In this category, a more than a half of the papers are on circuit realizations.

C. Papers Related to Multiple-Valued Logic

Category 3 contains papers that are related to **multiple-valued logic**, which are not in Categories 1 nor 2. The fourth part of the references show the papers with high citation counts. The top ten papers with the highest citation counts are [91], [96], [92], [94], [100], [99], [95], [93], [90], [97]. In this category, many papers are related to logic synthesis authored by UC Berkeley's people. The references of these papers contain the works that presented at ISMVLs.

[1]Citations contain self citations

[2]Papers with **many-valued logic** are not considered in this analysis.

D. Comparison with Two-valued paper

To show the position of multiple-valued logic to that of two-valued logic, we also investigated most cited papers in top journals and conferences of two-valued logic (Computer Science, Hardware and Architecture). In *IEEE Transactions on Computers (IEEE TC)*, R. E. Bryant's BDD paper [3] has **an extraordinary high citation count**. In *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (IEEE TCAD)*, the paper on waveform analysis by L. T. Pillage et. al [14]; in *IEEE Journal of Solid-State Circuits (IEEE JSSC)*, the paper on low power CMOS circuit design [5]; in *Design Automation Conference (DAC)*, the paper on SAT solver by M. W. Moskewicz et. al [11]; in *International Conference on Computer Aided Design (ICCAD)*, the paper on BDD optimization by R. L. Rudell [17] are most cited papers and have **very high citation counts**.

On the other hand, in the MVL area, we could not find any **paper with an extraordinary high citation count**. The only **paper with a very high citation count** is a monograph on the ESPRESSO logic minimizer by R. K. Brayton et. al [91].

VI. Conclusion and Comments

In this paper, we analyzed MVL papers by citation counts. Papers with high citation counts include ones related to logic synthesis and decision diagrams published by Berkeley people. Many papers with very high citations are related to basic algorithms. These results are used in practical design and verification of VLSI. As for papers on MVL circuits, survey papers have high citation counts [64], [85], [86]. In the MVL system papers, we could not find any paper with high citations.

Current activities in the ISMVL community show that papers on representation of multiple-valued functions (*e.g.,* decision diagrams), emerging technologies (*e.g.,* quantum and reversible circuits, new devices), and new applications tend to be cited more frequently than conventional multiple-valued logic circuits.

In this work, we did not analyze papers on database, fuzzy logic, algebra, or philosophy. Since the authors area is logic synthesis, the analysis may be biased to that area.

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