Robotics Narratives and Networks

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Somewhere around 1983, maybe late 1982, there was talk beginning about doing something more formal within IEEE that dealt with robotics and automation. Informally, activity was getting started through the Control Society,...also Systems, Man and Cybernetics, which obviously makes a lot of sense with the telerobotics things and a few others. But we wanted to build a more permanent home for it, so there was one of the first meetings. George Saridis chaired the meeting. I know George Bekey was there, Tony Bejczy, Lou Paul, probably another half dozen people.

And it was decided to form a council within IEEE…We formed a council in robotics and automation…George Bekey started the transactions. At that time it was called a journal…It was the IEEE *Journal on Robotics and Automation*…We started the conferences, the ICRA conference, it started in 1983. The first one was in Atlanta and we participated every year…Once the conference got started there was a great deal of interest. And there were a growing number of papers being submitted every year and rather than having four or five societies trying to compete with each other on all these things, it seemed to make more sense to have a single organization that would be responsible for it.

—Interview with Richard Volz, May 2012

This is how Richard (Dick) A. Volz, the president of the IEEE Robotics and Automation Society (RAS) in 2006 and 2007, describes the founding of the Society and the early days of robotics as a field of scientific study and technological development, a community of practitioners united by a common problem. This, of course, is not the only origin story of the robotics community. In an interview on 18 November 2010, Bernie Roth describes the founding of RoManSy, the first international symposium dedicated specifically to work in robotics, with his friend Aron E. Kobrinsky in 1973.

The conference brought together robotics researchers from all over the world, beginning particularly with those from the west and eastern Europe, enabling an exchange of knowledge and people. Roth remembers meeting a young Oussama Khatib at one of the RoManSy conferences; even though Khatib could not speak English then, the meeting gave him the opportunity to get a postdoctoral position at Stanford University. Khatib's own recollections see the creation of other opportunities for the community to gather:

> Later on, in probably the early 1980s, one of the other early meetings in robotics was called International Symposium of Robotic Research. That was sort of a small meeting that brought all the experts in robotics at the time to meet and discuss the different aspects of robotics from vision to planning, to control, to design, all these different aspects in one meeting.
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> However, the community as a whole comes together in one meeting as we know, and this is ICRA or the IEEE/Robotics Society of Japan International Conference on Intelligent Robots and Systems (IROS). So, at ICRA and IROS all the researchers in robotics and related fields are interested in coming to meet with other researchers to find out about the state of the research but also to interact and especially for Ph.D. students, newcomers to the field [1].

These memories speak of friendships, networking, collaborations, institutionalization, and the cultivation of a group identity for robotics researchers.

Despite its relatively recent origins in the second half of the 20th century, today, robotics is a mature scientific field, making the centuries-long dream of creating autonomous, intelligent machines an increasingly commonplace reality. Its history is long enough that the early participants in the field are no longer all with us. In 2011, in recognition of 50 years of research and development in robotics, the RAS funded a project to collect and analyze information about the rise of robotics as a field of study and its later growth as a community of practice and interdisciplinary problem space. The project involves the collection of oral history interviews with individuals from industry, academia, and other institutions who have done pioneering work in robotics. In addition to the interviews, we have also been analyzing robotics-related publications to show the general, social, and intellectual developments in the field over time. The interview videos and transcripts collected during the

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project are becoming available to the public online this year, so we take this opportunity to introduce the project to the readers of *IEEE Robotics and Automation Magazine*.

Pioneering Narratives

Over 100 participants from all over the world have been interviewed so far in more than 150 h of video as part of the RAS Robotics History Project. The collected interviews represent the experiences of multiple generations of robotics researchers, from those who started working in the field in the 1960s and 1970s to those who joined the field later on in the 1990s and 2000s. The interviews provide a view of robotics from the perspective of its practitioners and document personal experiences that are not part of the written record of the field (See "A Sample Robotics Narrative").

Participants have discussed a variety of questions regarding their experiences, including: 1) how they got involved in robotics, 2) their aims and aspirations in doing robotics research, 3) the important institutions and events that affected their work, 4) challenges and successes they had over the years, 5) people, things, and animals that inspired them, 6) their connections with others in the robotics industry and outside of it, 7) the social and cultural factors that affected their work, and 8) how technological capabilities had an impact on the problems they chose to tackle. These interviews provide a series of unique and rich narratives from different periods in robotics that identify individuals, institutions, events, technologies, and ideas that have significantly influenced the developmental trajectory of robotics through the years. They put a human face on the development of a scientific field, showing the experiences, career trajectories, collaborations, mentorships, and friendships of participants. Such information can be particularly useful in revealing how individual values and actions have shaped robotics, how social relationships supported the development and growth of the field, and how particular past experiences are shaping present-day actions and values.

The collected interviews have been transcribed and are publicly available through the IEEE History Center archive [2]. This archive will continue to be updated in future years as the opportunity for more interviews presents itself, and it can be used as a record of the disciplinary history and development of robotics or a unique data set for the scientific study of robotics. Along with

A Sample Robotics Narrative

When I was first got into the graduate school laboratory (as one of two new students), my thesis advisor said to us: I want one person to work on mechanical vibration, the other on automatic control. The vibration question is related to the regular vibration of the train. So, that is important but I think I almost know about the regular vibration of the train. So, I do not like that and I ask my friend: Why don't you do that? He said yes. One week later my advisor professor Fuji said to me, you know, would you like to build a mechanical hand to turn a crank? When I heard that, I could not understand what it means, but it is very, very attractive, the mechanical hand and so on. I said yes without knowing anything and that is the instant I started studying robotics. I tried to make a hand and to add the sensors to control it, the mechanical controls and so on. I just enjoyed doing that. I did this for my masters. In that time, I have no computers.

When I proceeded to the doctor course, I really thought to change my topic to adaptive control for airplanes. Controlling subsonic states to keep the stability of the airplane, that is also a very important topic of that day. But, I found the most important point of airplane dynamics depends on the characteristics of the wing. And the wing shape is completely determined by an American standard. Therefore, if I go this field, I cannot have complete freedom, so I stopped doing it and decided to return back to the mechanical hand and started again. And I tried to find some manipulator.

I found some company that tried to make manipulators, not a robot, but a bilateral manipulator to handle nuclear isotypes or something. I told my professor, I want to use this machine which some company developed, is it possible? The professor asked to the company and it turned out the company person is a student of this professor and they said "yes, we finished the manipulator, and we are not using it. If you like, you can use it." So we borrowed it for free. And after that, the hardest thing is to get a computer. Computer at that time is very, very difficult to get in Japanese areas. The medical department at the University of Tokyo had one computer that is hooked to control the artificial heart for goat. So, I planned to use it but unfortunately, at that time, University of Tokyo had some serious events with radical students and they opposed some part of the medical school and closed the university for one year… Therefore, that project was done and laboratory was also closed, so I also lost everything. But after that is settled down, that is spring of 1968, when the radical students got out and the university returned back to the normal, I started again.

At that time, professor, my thesis advisor, tried to purchase computers to control my mechanical arm. But unfortunately, the computer would be arriving to my laboratory about six months later, which is after I have to finish my thesis. But I was very lucky that the computer company kindly lent me another computer before that, but the contract is just on the six months. During that time, I changed interface and did the program and completed my project. And that is how I worked on my first robot hand.

—Interview with Hirochika Inoue, August 2011.

the transcripts, IEEE.tv is presenting an archive of videos collected in the course of the study, which can serve as a resource for educators to present robotics research and careers to students of all ages.

Robotics Networks

Oral history interviews are grounded in the memories of individuals and are, therefore, a subjective and partial reconstruction of events in the past. To provide a more general understanding of the development of robotics as a field of research and development, the project combines oral history interviews with the study of the social networks of actors in the field using bibliographic data available in online databases, such as the Web of Science and IEEE *Xplore*. Robotics is a field that traverses disciplinary and national boundaries, supported by a heterogeneous network of scientists, users, and institutions. Constructing and analyzing the social and cognitive networks of robotics through bibliometric and network analysis allows us to place the experiences of interviewees in a broader context.

Here, we present a few demonstrative examples of how one can use bibliographical information on journal articles published in robotics journals to portray the social and cognitive structure of robotics. This approach is particularly effective for surveying the landscape of the discipline and identifying potentially interesting individuals, articles, and terminology. We analyzed the bibliographic records of robotics-related research published in nine journals: *Advanced Robotics, IEEE Robotics and Automation Magazine, IEEE Transactions on Robotics* (including the *IEEE Journal of Robotics and Automation* and *IEEE Transactions on Robotics and Automation*), *Industrial Robot (an international journal), International Journal of Robotics Research, Journal of Field Robotics* (including the *Journal of Robotic Systems*), *Journal of Intelligent and Robotic Systems,* and *Robotics and Autonomous Systems*. The 14,590 records were downloaded from the Web of Science on 22 November 2014 and cover the period from 1983 to 2014. There are 16,875 authors and 52,017 links among those authors in the data set. The average number of collaborators per author is 6.165. Only 2.5% of the authors have not collaborated. The author with the largest number of collaborators (83) is Vijay Kumar.

The network analysis of robotics publications shows how the field has developed into a discipline over its 50-year history. The connectivity of a network is an important indicator of the development of a field. One of the basic ways to identify the existence of these cohesive subgroups of researchers is through the components. The sizes of the components are expressed in percentages of the total number of connected nodes. Understanding the distribution of components and particularly the emergence of the giant component (covering 50% or more of all the nodes) has been used

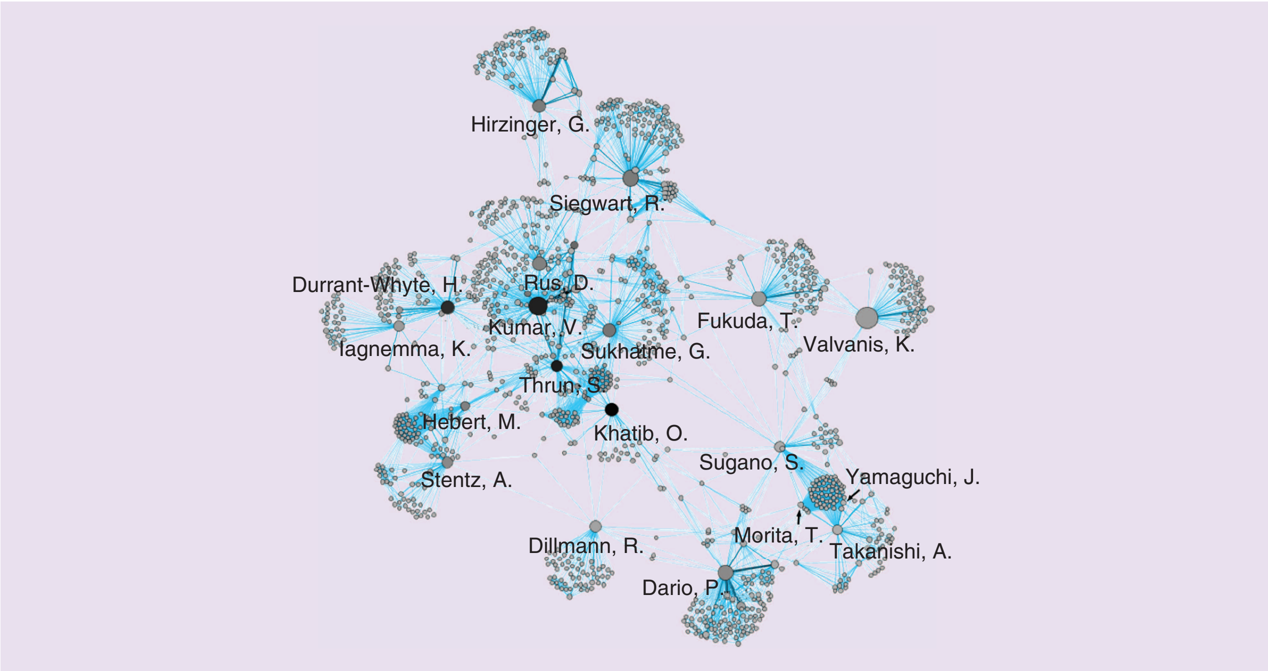

Figure 1. The collaboration network of 19 robotics researchers identified as central by one of the four centrality measures (V. Kumar, P. Dario, R. Siegwart, G. Sukhatme, K. Valavanis, T. Fukuda, H. Durrant-Whyte, D. Rus, R. Dillman, G. Hirzinger, A. Takanishi, S. Thrun, A. Stentz, S. Sugano, M. Hebert, T. Morita, J. Yamaguchi, O. Khatib, and K. Iagnemma) and all of their collaborators. The author nodes are size-colored by the number of papers per author and color coded by the total times these papers are cited. The edges are color coded and weighted by the number of times two authors collaborate.

in collaboration studies to study the emergence of disciplines. Increases in the size of the largest connected component signify the transition from a relatively unorganized group of researchers into a scientific field. The existence of a giant component is also considered important for the exchange of ideas and diffusion of knowledge. There are 1,276 connected components in the robotics collaboration network. The largest connected component contains 13,523 authors, i.e., 80.1% of all the authors in the data set. The size of the largest connected component has changed over time. It was only 2.8% in the earliest time period (1983–1989) and has been increasing since to 11.1% (1990–1994), 38.5% (1995–1999), 44.2% (2000–2004), 64.2% (2005–2009), and 65.7% (2010–2014). This progression shows how robotics researchers have coalesced over the years.

The important actors in the field can also be identified through social network analysis, which can be compared with the list of interviewees to understand our coverage of the field. One of the most popular network measures in scholarly networks is centrality. Centrality measures try to answer the question of who are the most central nodes in a network. One of the simplest

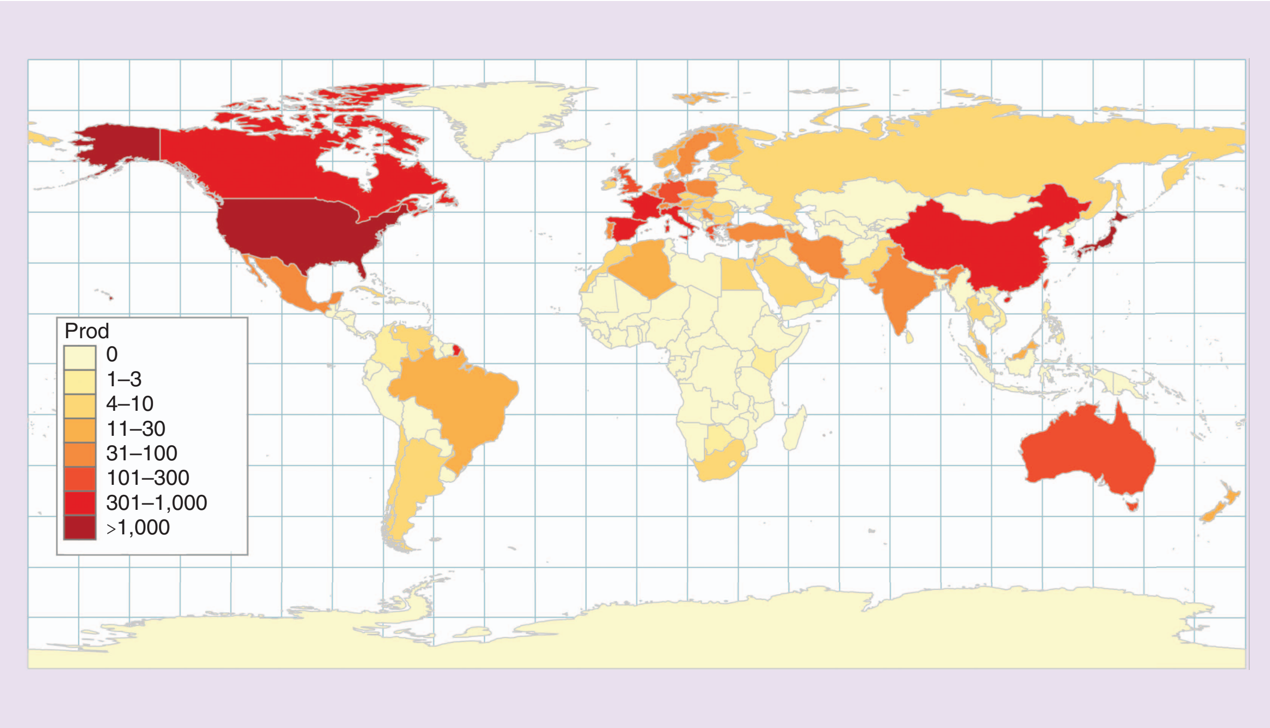

Figure 2. The distribution of the number of papers published in the robotics journals (1983–2014) per country.

measures of centrality is degree centrality. This measure is tied to the idea of social capital. According to this measure of centrality, the most prominent nodes are the ones that have most ties to other nodes in the network. According to degree centrality, the ten most central authors in robotics are: 1) Roland Siegwart, 2) Paolo Dario, 3) Vijay Kumar, 4) Gaurav Sukhatme, 5) Atsuo Takanishi, 6) Sebastian Thrun, 7) Toshio Fukuda, 8) Anthony Stentz, 9) Shigeki Sugano, and 10) Martial Hebert. Another measure of centrality, called betweenness, *describes* a researcher's ability to broker between groups or the likelihood that information originating anywhere in the network will reach a particular node. According to the betweenness centrality, the ten most central authors are: 1) Vijay Kumar, 2) Paolo Dario, 3) Roland Siegwart, 4) Gaurav Sukhatme, 5) Kimon Valavanis, 6) Toshio Fukuda, 7) Hugh Durrant-Whyte, 8) Daniela Rus, 9) Ruediger Dillmann, and 10) Gerd Hirzinger. The collaboration map (Figure 1) shows the relations among the 19

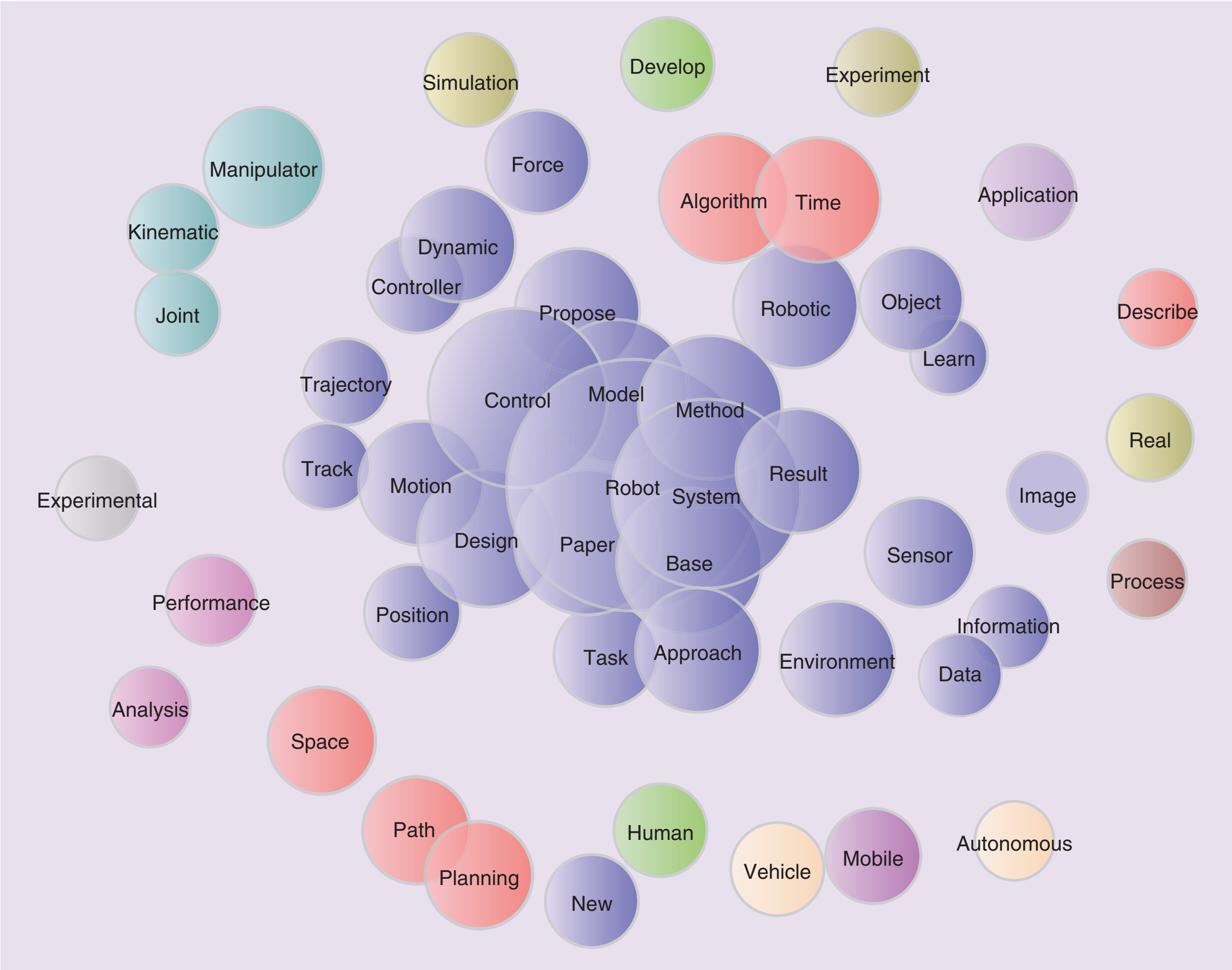

Figure 3. The 50 most commonly used words in the titles of robotics articles.

researchers identified as central by one of the four measures of centrality described earlier. It is interesting that all of the authors are connected. Most of them have direct ties, and quite a few have only a few researchers between them.

As can be seen in collaboration networks, robotics researchers collaborate widely across borders. Robotics is truly an international endeavor. The distribution of robotics papers across the world is shown in Figure 2. Researchers from 80 countries have published papers in the nine major robotics journals. The top ten contributors are: 1) the United States, 2) Japan, 3) Canada, 4) France, 5) Italy, 6) Spain, 7) South Korea, 8) China, 9) Germany, and 10) England.

Bibliometric analysis also allows us to map some of the conceptual features and changes in the robotics field. The main words used in paper titles in the field and their clusters based on co-occurrence are shown in Figure 3. How the conceptual focus of the field has changed through the years is shown in Figure 4. The word *manipulator* was specific to the early years of robotics (1983–1989), which we also trace in our interviews describing the development of robotic arms. The vocabulary used at that time was very different from the later periods. The only outlier is the year 1984, which is much closer to the vocabulary of the 1990s than any other year from the 1980s. The term that is a bridge between 1984 and the 1990s is *kinematic*. The specific focus of the early 1990s (1991–1993) was on: 1) space, 2) joint, 3) force, 4) trajectory, and 5) dynamic. The period from 1994 to 1997 had a specific focus on: 1) position, 2) controller, 3) control, 4) path, and 5) planning. The late 1990s and early 2000s focused on: 1) mobile, 2) force, 3) image, and 4) sensor. The period from 2007 to 2014 shows a shift to issues related to: 1) human, 2) learn, 3) environment, 4) information, 5) autonomous, 6) simulation, 7) algorithm, 8) design, 9) time, and 10) vehicle. Similar topical changes can be seen in the collected interviews, with early narratives focusing on the development of robotic manipulators, followed by more development of mobile robots, and most recently, attention to the application of robotic technologies in everyday environments and robots' interaction with people.

A New Resource for Robotics

The Robotics History Project funded by the RAS collects information on the personal experiences of robotics researchers in the field and supplements them with

(continued on p. 146)

on the organizing committee. In addition, usually the women on the team are one of a small group of senior women in the field, with the same ones being included over and over. When we ask the organizers why they do not include a few additional women, they say they have trouble identifying other qualified women with conference organizational experience.

Thus, my goal with this all-female organizing team is to raise the visibility of women in robotics around the world. I want to provide them the opportunity to gain experience on the organizational team so that other conference organizers in the future can draw from this field and then include more women in the leadership of the field. We have several senior women on the ICRA 2015 team, but we also have a large number of earlier-career women who are outstanding researchers; these earlier-career women are perhaps not well known outside their research specialties. I am hopeful that by serving on the organizational team, they will become better known to the broader robotics community and, thus, will be called on more in the future.

This activity is especially important for increasing the visibility of women in robotics in parts of Asia and the developing countries, as women in these regions typically find many more roadblocks to their professional advancement than do women in the Western world. My hope is that this step will also encourage young female students in robotics, giving them many strong female role models to follow. Hopefully, they will then become leaders of the field and we can help address the disappointingly low numbers of women included in robotics leadership within the ICRA/IROS communities.

We have received much positive feedback from the IEEE Robotics and Automation Society for taking this step.

HISTORY *(continued from p. 142)*

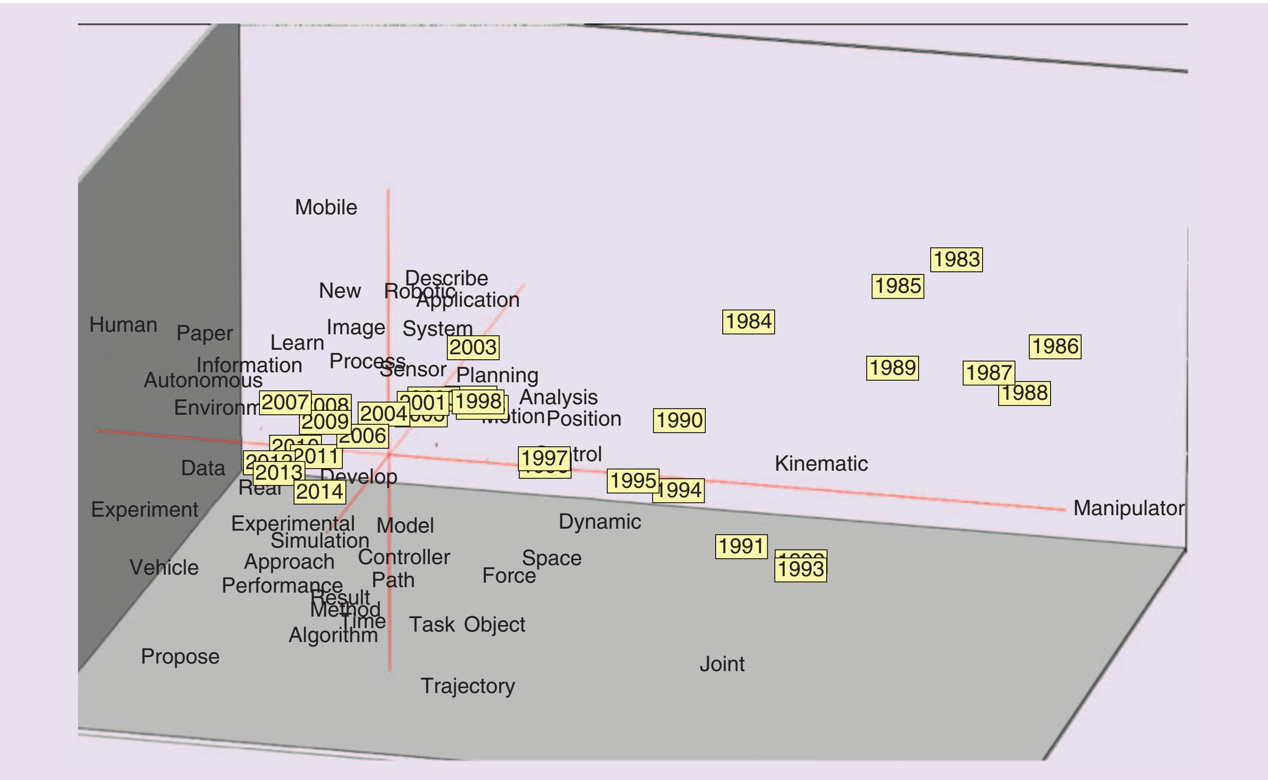

Figure 4. The multidimensional scaling diagram between the terms and publication time periods.

digitally available information on robotics publications from the past decades. This provides an unprecedented opportunity for scholars and the public to learn about the changes in this quickly developing field of scientific and technological innovation. At the same time, these narratives can provide inspiration and guidance to new robotics researchers and educators, making this technically complex field more approachable, understandable, and human. Time will show the various exciting uses that will be found for this new resource for understanding robotics.

References

[1] Interview with Oussama Khatib, Apr. 2013.

[2] [Online]. Available: http://www.ieeeghn.org/wiki/index.php/Oral-History:Robotics_History:_Narratives_and_Networks