Project in History of Control: The History of Robot Control

Björn Olofsson and Andreas Stolt

1. Introduction

This report discusses the development of the field of robot control during the past three decades. Robotics is inherently inter-disciplinary in the sense that it combines knowledge from such areas as control, mechanics, and computer science. Further, the collaboration between academia and industry is significant, which will be highlighted in the discussion on the major professional organizations in the field in the next section.

In the middle of the 1980's, the subject of robotics was identified as a separate research discipline by the academic and industrial institutions. The main organizations which have influenced the development of the field are the IEEE Robotics and Automation Society (RAS) and Technical Committee 4.3 Robotics in the International Federation of Automatic Control (IFAC). These organizations arrange the main events in the area of robotics and publishes the influential journals in the area, such as the IEEE Transactions on Robotics. Other organizations influencing the field exists and will be presented in the report.

This report is organized as follows. Firstly, the development of the major organizations, RAS and TC 4.3 of IFAC, are briefly reviewed in Sec. 2. The major journals, conferences and events are identified and put into a historical perspective. To mirror the development of the field of robotics, trends in the subject are analyzed in detail in Sec. 3. In particular, one of the major conferences in the field is analyzed. Trends in paper subjects as well as interest in the conference over the years are discussed. Some of the most influential papers and researchers are also presented. Further, Sec. 4 deals with prominent research labs and robotic companies. Finally conclusions are drawn in Sec. 5.

2. Foundation and development of major organizations

In addition to the major organizations related to IEEE and IFAC in the field of robotics, it can be mentioned that the American Society of Mechanical Engineers (ASME), through the Robotics Committee in the Dynamic

Systems & Control Division, shows interest in the field. Further, the International Federation of Robotics (IFR) [4], founded in 1987, shows interest in robotics. The latter are mainly focused on industrial activities, although research and development are areas of interest as well. The two major organizations in robotics in general, and robot control in particular, will be discussed next.

2.1 IEEE Robotics and Automation Society

The interest of IEEE in robotics as a subject in itself arose in the beginning of the 1980's, which led to the foundation of the Robotics and Automation Council (RAC) in 1984, where George Saridis was the first president. The council was supported by several of the other IEEE societies, among others the Control Systems Society and the Computer Society, showing the interdisciplinary character of robotics.

The background for forming this new council dedicated to robotics was the combined interest from industry in the field, in addition to the increasing number of papers and articles submitted to the conferences and journals of the Control Systems Society, which were directly related to robotics and robot control. The Robotics and Automation Council determined to initially focus on three major activities:

- IEEE Journal of Robotics and Automation, which in 1989 was renamed to IEEE Transactions on Robotics and Automation. In 2004 the journal was split into IEEE Transactions on Robotics and IEEE Transactions on Automation Science and Engineering.
- IEEE RAC Newsletter, which later was transformed into IEEE Robotics and Automation Magazine (RAM)
- IEEE International Conference on Robotics and Automation (ICRA)

The Robotics and Automation Council was transformed into an IEEE society at the 1st of January in 1989. The first president of RAS was Art Sanderson, who was installed in May 1989. However, the work of transforming the RAC to an IEEE society was initiated in 1987 by the president at the time, Dr. Antal K. Bejczy [7]. The reason for transforming the council into a society was the insight that robotics had become a distinctly identifiable discipline at the time. The aim of the Robotics and Automation Society is stated in the Constitution of the RAS as follows [2]

> Its objectives shall be scientific, literary and educational in character. The Society shall strive for the advancement of the theory and practice of robotics and automation engineering and science and of the allied arts and sciences, and for the maintenance of high professional standards among its members[...]

RAS developed fast after its foundation in 1989. As a matter of fact, ICRA already from the beginning in 1984, established as the major conference in the field of robotics. The attendance was doubled from 1984 to 1985, although the participants by then were mainly from North America [6]. It is noticeable that it was not until 1992 that the first ICRA conference was held outside the USA, when the conference was held in Nice in France. Three years later, the first ICRA conference was held in Asia, when Nagoya in Japan hosted the conference. A few years later, the RAS determined that

Figure 1 All former RAS presidents were honored at ICRA 2012. From the left: Kazuhiro Kosuge (president 2010-2011), Bruno Siciliano (2008-2009), Richard Volz (2006-2007), Paolo Dario (2002-2003), TC Steve Hsia (2000-2001), Toshio Fukuda (1998-1999), George Bekey (1996-1997), Norman Caplan (1991), Richard Klafter (1994-1995), Art Sanderson (1989-1990), and TJ Tarn (1992-1993).

ICRA should be held every other year in North America and every other year in Europe or Asia, establishing the international character of the RAS.

It is also to be noted that the participation from industry and research institutes in the conference initially was higher than from academia, showing the high interest from the industry in the field of robotics. Later, in 2003, RAS started the Industrial Activities Board (IAB) in order to create a forum for industrial relations and committees for standardization. Further, the journal, which was initially a quaterly publication, increased to a bimonthly publication already in 1986, only two years after its first volume. This shows that the interest in the robotics field from the scientific community also increased rapidly in the middle of the 1980's.

2.2 TC 4.3 Robotics of IFAC

Another organization with impact on the development of the field of robotics, especially regarding control of robots, is the Technical Committee 4.3 of the International Federation of Automatic Control. TC 4.3 is part of the Mechatronics, Robotics and Components Cluster.

A clear difference between TC 4.3 of IFAC and the IEEE Robotics and Automation Society is visible in its geographic areas of interest. Whereas RAS started as an American society and later spread to Europe and Asia, IFAC TC 4.3 for a long time focused on Europe as its primary area of interest.

IFAC has no dedicated journal in the field of robotics, but articles concerning robotics are published in the International Journal of Mechatronics. IFAC also has Robotica, a journal dedicated specificly to robotics and automation, as one of its affiliated journals. Furthermore, IFAC TC 4.3 organizes a Symposium on Robot Control (SYROCO) every third year as its primary conference in the field of robotics. The first symposium in this series was held in 1985 in Barcelona in Spain. All subsequent symposia were then held in Europe until 2009, when Gifu in Japan hosted SYROCO [5]. Nevertheless, this focus on Europe has certainly limited the interna-

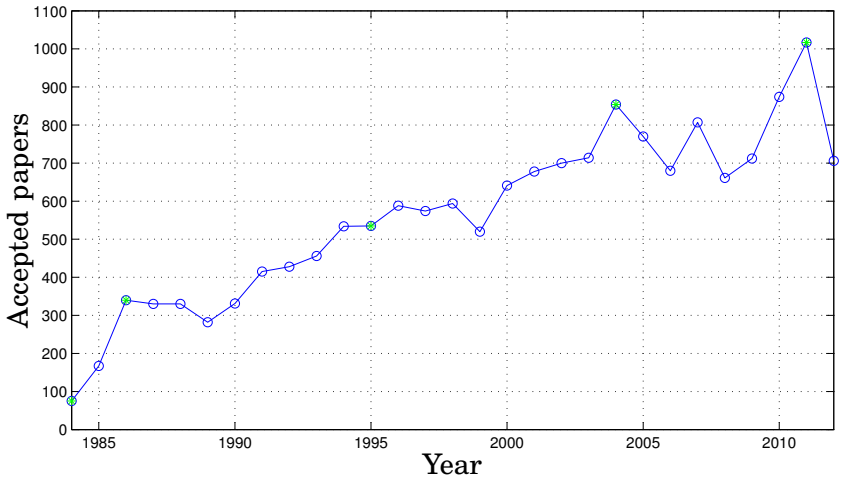

Figure 2 The number of papers presented at ICRA each year since the first conference in 1984. The conferences marked with green * are the ones that have been subject to sampling.

tional spread of the activities of IFAC within the field of robotics. Further, it can be concluded that the interest in the annual IEEE ICRA conferences historically has been higher than for the triennal SYROCO symposia, especially when considered in an international perspective. Especially this year (2012) ICRA recieved more than 2000 submissions and SYROCO approximately 200 submissions[1]. This is most certainly a result of the decision not to organize SYROCO outside Europe for a long time.

3. Analysis of trends in the robot control field

The flagship conference of RAS is ICRA, the International Conference on Robotics and Automation, which is held annually since 1984. In order to analyze the development of the field of robotics the last decades, samples are taken from the past ICRA conferences, both concerning number of accepted papers and the subject of the papers.

The conference has grown steadily over the years and the number of accepted papers each year is displayed in Figure 2. These numbers have been obtained manually by counting the number of papers presented at each conference using IEEE Xplore [3]. A rapid expansion the first few years was followed by five years with almost constant number of accepted papers. A linear growth period then started which lasted for about 15 years, from 1990 to 2005. Thereafter it seems that the conference has reached a new equilibrium (with large fluctuations from one year to another), in terms of the number of accepted papers.

The initial growth can be explained by an increasing interest in robotics and automation and the foundation of the robotics field at the time. The conference could not grow too much, however, due to organizational issues.

[1]This number is estimated based on the submission numbers from the papers submitted by PhD-students at the Department of Automatic Control and submission numbers of review requests, since the official number is not public.

1984	Atlanta, Georgia, USA
1986	San Francisco, California, USA
1995	Nagoya, Japan
2004	New Orleans, Louisiana, USA
2011	Shanghai, China

Table 1 The conferences that has been subject to sampling.

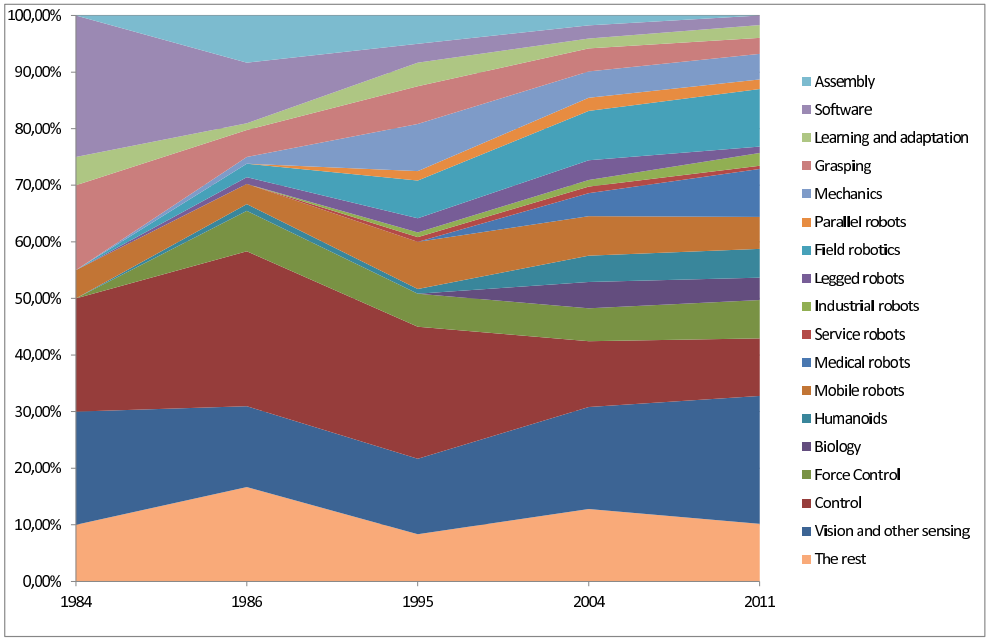

Figure 3 Relative share over time for the subjects considered.

Also, keeping the acceptance rate at a lower number is an indicator of the quality of the presented papers. The interest in the conference is still growing and the number of papers submitted for review the last years has grown to over 2000 [1]. This gives an acceptance rate of less than 50 %.

3.1 Sampled conferences

A number of the ICRA conferences over the years have been investigated, to the purpose of showing its development over time. This has been carried out by sorting the sessions at the conferences according to their subject. The conferences considered are given in Table 1 and the subjects chosen are given in Table 2. It should be mentioned that some sessions could have fitted in more than one of the subjects used, but each session has only been associated with one subject.

3.2 Result of sampling

The result of the sampling is shown graphically in Fig. 3. It can be seen that some subjects have a negative trend, meaning that their relative share of the sessions have decreased, although their share in absolute numbers may not have. Other subjects have emerged and grown rapidly the last few years; these can be considered to be the ”hot” topics in robotics research.

Subject name	*Also contains*
Vision and other sensing	SLAM, human detection, recognition, visual navigation, range sensing, sensor fusion, localization, inspection
Control	Motion and path planning, cooperative control, collision avoidance, manipulation planning, discrete event systems
Force control	Force control, haptics, teleoperation, variable stiffness/flexible arms, impedance control, contact motion
Biology	Biology inspired robots, behavior based systems
Humanoids	Human/robot interaction
Mobile robots	Autonomous navigation, wheeled robots, nonholonomic systems
Medical robots	Surgical robots, rehabilitation robotics
Service robots	Amusement robots
Industrial robots	Industrial automation, factory automation
Legged robots	Walking robots
Field robotics	Aerial robotics, space robotics, underwater robotics, climbing robots, micro/nano robots, surveillance/search/rescue robots, specialized robot systems, UAV
Parallel robots	
Mechanics	Underactuated robots, actuators, robot design, redundant robots, soft material robots, robot design
Grasping	Dexterous manipulation, hands, tactile sensing
Learning and adaptation	
Software	Simulation
Assembly	Assembly skills, assembly planning, assembly applications, manufacturing
The rest	Agent based systems, calibration and identification, modular robots, dynamics and kinematics formulation, distributed robot systems, networked robots, general robotics and applications, robot safety, robotics education

Table 2 The subjects considered when doing the sampling.

The first ICRA conference in 1984 was rather small, compared to the rest of the sampled conferences, and this means that many of the considered subjects were not represented at all. This conference is therefore in some sense treated as an outlier in the following analysis.

Decreasing trends The most obvious example of a negative trend is shown for the software subject. The reason for this is probably that the computation power has grown exponentially for quite some time now. In

Decreasing trend	*Constant*	*Increasing trend*
Software	Learning and adaptation	Parallel robots
Assembly	Grasping	Field robotics
Control	Mechanics	Biology
	Service robots	Vision and other sensing
	Mobile robots	Medical robots
	Legged robots	Humanoids
	The rest	Industrial robots
		Force control

Table 3 Division of the subjects according to how their popularity has developed over the years.

the 1980's it was really interesting to make efficient software, in order to be able to do all the required computations in real-time on the hardware available. When the computers became faster, this probably became almost a non-issue, and the interest in these research questions have thus decreased.

The subject of control also shows a distinct negative trend, but this is probably not the complete truth. A large share of the sessions associated with the other subjects with increasing trends would also have fitted in the control subject, and a reasonable guess is therefore that control as a subject at least is not decreasing its share of the sessions, probably it is increasing[2]. For example, the Force control subject exhibits an increasing trend, which shows that the subject of robot control has divided into several sub-disciplines the last decade, which explains the results of the sampling.

The third subject that has a negative trend is assembly. Some of the decreased share of the sessions might be explained by that the assembly related papers have been assigned to other types of sessions[3]. The assembly subject seems to have been a hot topic some years ago (10 % of the sessions at ICRA1986), which further seems to have cooled down in the last years.

Increasing trends Some subjects have increasing trends, such as Medical robots, Field robotics, and Humanoids. The common denominator for these subjects are that they all are specialized robotic subfields. The growing interest in these areas can be explained by the fact that the general knowledge of how to build and control robots has increased over the years, and thus made it possible to, *e.g.*, build reliable and safe robots to be used in surgery. This trend will most likely continue, as there exists very many potential applications that can be robotized.

Another subject with an increasing trend is the Biology subject. To mimic human (and animal) behavior seems to be a promising way to build smart and efficient robots. The subject Vision and other sensing is also increasing its share of the sessions. This can be explained by the fact that

[2]This would have been investigated closer when the sessions were associated to the subjects if this issue had been known beforehand. But it is probably not worth the effort to redo the counting to confirm this suspicion.

[3]As an example, Andreas presented two assembly related papers at ICRA2011, but the conference contained no special session for assembly. Consequently, one paper was put in a session about Industrial robots and the other in a Force control session.

advanced perception is necessary to be able to make robots smart and autonomous.

The last three subjects that have been put in the increasing trends category are Force control, Industrial robots, and Parallel robots. These subjects are hot locally here in Lund, and this gives an indication that our lab[4] is focusing on topics which have a growing interest in the robotics community.

Constant trend subjects Most of the subjects considered seem to have reached an equilibrium in the share of the sessions at ICRA. As the conference has been growing over the years, this actually means that the actual number of sessions for each subject have been growing.

The subjects in this category are all kind of basic research areas, and not so specialized as some of the subjects in the increasing trends category. The conclusion to draw from this can therefore be that there is a steady interest in the basic robotic subjects, and that new challenging areas exhibit an increasing interest, such as Medical robots and Humanoids. To summarize, it seems as advanced applications of robotics is the current trend at the ICRA conference.

3.3 Most cited articles in the field

In order to investigate the most influential articles and papers in the field, the database SciVerse Scopus[5] is utilized for retrieving citation numbers. This database indexes a majority of the journals and conferences in the field. It should be noted, though, that the papers from the International Federation of Automatic Control (IFAC) are not included in this database.

Landmark articles Using the search pattern ”robot control”, the database Scopus provides the most cited articles in the robot control field. The five most cited articles are

1. R. A. Brooks (MIT Artifical Intelligence Lab, MIT): ”Robust Layered Control System for a Mobile Robot”, IEEE J. of Robotics and Automation, 1986.
2. O. Khatib (Stanford University, USA): ”Real-Time Obstacle Avoidance for Manipulators and Mobile Robots”, Int. J. of Robotics Research, 1986.
3. S. Julier (IDAK Industries), J. Uhlmann (Oxford University, UK), and H. F. Durrant-Whyte (University of Sydney, Australia): ”A new method for the nonlinear transformation of means and covariances in filters and estimators”, IEEE Trans. on Automatic Control, 2000.
4. T. McGeer (Simon Fraser University, Canada): ”Passive dynamic walking”, Int. J. of Robotics Research, 1990.
5. T. Balch (Carnegie Mellon University, USA) and R. C. Arkin (Georgia Institute of Technology, USA): ”Behavior-based formation control for multirobot teams”, IEEE Trans. on Robotics and Automation, 1998.

[4]The Robotics Lab shared by the Department of Automatic Control and Computer Science at LTH.

[5]http://www.scopus.com

It can be concluded that a majority of the five most cited articles are connected to control of mobile robots, but also the article by Julier *et al.* on estimation and filtering can be noted. This article discusses applications of the Extended Kalman Filter and variants thereof, such as the Unscented Kalman Filter, in the context of mobile robotics, and has influenced the whole field of control.

Further, on the top twenty list of the most cited articles, the landmark articles given below can be mentioned:

- M. H. Raibert (Boston Dynamics, USA) and J. J. Craig (Stanford University, USA): ”Hybrid Position/Force Control of Manipulators”, Trans. of the ASME J. of Dynamic Systems, Measurement and Control, 1981.
- O. Khatib (Stanford University, USA): ”Unified Approach for Motion and Force Control of Robot Manipulators: The Operational Space Formulation”, IEEE J. of Robotics and Automation, 1987.
- J.-J. E. Slotine and L. Weiping (MIT, USA): ”On the Adaptive Control of Robot Manipulators”, Int. J. of Robotics Research, 1987.

All of these articles have had a major influence on the field of robot control, which is clearly shown by their citation numbers. Especially the article by Raibert *et al.*, in combination with the articles in 1985 by N. Hogan (MIT, USA) on impedance control for robots, founded the subject of force control for industrial manipulators. Further, the ideas presented in the article by Khatib on task-space control formed a new subfield in the robot control field, which has influenced the development of robot control for decades.

Influential researchers in the field Using the database Scopus introduced in the previous section, interesting information on the number of articles and papers published by different researchers in the field is extracted. With the search pattern ”robot control”, the following researchers are the five most productive in terms of published material.

1. T. Fukuda (Nagoya University, Japan)
2. K. Ohnishi (Keio University, Tokyo, Japan)
3. G. Hirzinger (Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany)
4. S. Arimoto (Riken, Wako, Japan)
5. D. M. Dawson (Clemson University, USA)

It is clear that the list is dominated by researchers from Japan and USA. Nevertheless, G. Hirzinger, who is heading the DLR institute in Germany, qualifies for the position as the third most productive researcher in the field.

4. Prominent labs and companies in the robot control field

4.1 Successful robotics lab

DLR, Munich, Germany The Robotics Lab at DLR in Munich is one of the most recognized and successful labs in Europe, with the current head Prof. Gerd Hirzinger. Other well-known robotic researchers within this lab are Alin Albu-Shäffer, who has made significant contributions to the area of impedance control for robots, and Patrik van der Smagt. Some of the recent results from the lab are

- A light-weight arm. It is a seven degree-of-freedom industrial manipulator with built-in joint torque sensors. DLR has licensed the production of the robot to KUKA Robotics.
- The DLR Hand II. A human-like robotic hand which is considered as one of the most advanced and complex artificial hands in the world.
- Rollin' Justin. A humanoid robot with a rolling base. The arms consists of two light-weight robots, and each arm contains a four finger hand. The "head" has stereo cameras, to the purpose of vision-based control.

KAIST, Yuseong-gu, South Korea The Korean Institute of Advanced Science and Technology (KAIST) has a well-known robotics lab. One famous result of the research at the lab is the humanoid robot Hubo-II, developed by the group lead by Prof. Jun Ho Oh. It is an impressive walking robot that even can run.

Nagoya University, Nagoya, Japan The lab at the Nagoya University, lead by Prof. Toshio Fukuda, is another successful lab. The research performed here is among others in medical robotics, intelligent systems control, bio-inspired robot control, and nano-robotic systems. The lab is productive in terms of published articles in the area of robotics, *cf.* the list of the authors with the largest number of published articles in the previous section.

JPL[6], Los Angeles, California, USA This lab is a NASA field center and is mostly involved with space research. The robotics group is headed by Richard Volpe, and the research performed spans from making autonomous robots to be run on Mars, to creating airships that can fly through the atmosphere on planets like Venus.

MIT[7], Boston, Massachusetts, USA There are several robotics groups at MIT. One of the well-known is the Eric P. and Evelyn E. Newman Laboratory for Biomechanics and Neurorehabilitation, which is headed by Prof. Neville Hogan. The research direction of this lab is, *e.g.*, to restore function for impaired or aging persons combining robotics and neuroscience. It is also to be noted that the area of impedance control for robots, was the result of pioneering research by Prof. Hogan.

[6] Jet Propulsion Laboratory
[7] Massachusetts Institute of Technology

The Artifical Intelligence (AI) lab at Stanford, San Fransico, California, USA The robotics group at the AI lab is headed by Prof. Oussama Khatib. Research performed in this lab is, *e.g.*, on humanoid robots, haptic interaction, and on neuromuscular control. Earlier research results are in the area of walking robots and task-space control.

4.2 Robot companies

Robotics is a subject where collaboration with industry is common, and several examples of research results from the academic institutions which have been transferred to industry and successful products exists. This section gives a brief overview of some well-known companies and some of their products.

Industrial robot manufacturers There are many companies which manufactures industrial robots today. One of the most influential is *ABB Robotics* (Sweden/Switzerland), with its headquarters in Shanghai and production in Västerås and Shanghai. Another very large robot manufacturer is *KUKA Robotics* (Germany), with headquarters in Augsburg, Germany. Both ABB and KUKA are famous for their orange robots. Other large manufacturers that can be mentioned are *Motoman* (USA/Japan), *Comau* (Italy), *Reis* (Germany), and *FANUC* (Japan).

Other robot companies The vacuum cleaner robot Roomba is a successful product from the American company *iRobot*. They also produce other types of household robots, but also robots for military use. *Willow Garage* is another American robot company, which is devoted to personal robotic applications. They have developed and maintain the open source software project ROS (Robot Operating System) and manufactured the robot PR2 (Personal Robot 2). The PR2 mobile robot platform is today one of the widely used mobile robots for implementation of control applications. A third well-known American robotics company is *Boston Dynamics*, who for instance has developed the four-legged walking robot Big Dog. The humanoid robot ASIMO is a well-known product from *Honda* (Japan).

5. Conclusions

The major organization for robotics is the IEEE RAS, and this has been the case ever since the foundation in 1984. The interest in robotics research has been growing over the years, and this trend seems to continue, with an increasing interest in ICRA, the main conference.

The investigation of the ICRA conferences has shown that the overall size of the conference has grown rapidly from the start in 1984 with 20 sessions to 177 sessions at the conference in 2011. The sampling of the session topics at the conferences has shown that some subjects show a decreasing trend, such as Software and Assembly, and others increasing trends, such as Field robotics and Medical robots. The overall conclusion is that the attention of the community is directed towards new areas to use robots in, *e.g.*, subjects like the two already mentioned but also Humanoids and biology-inspired robots.

6. References

[1] Acceptance letters from ICRA, 2010–2012.

[2] IEEE Robotics and Automation Society Constitution, 2011. http://www.ieee-ras.org/uploads/secretary/documents/ieee-ras-constitution-oct-2011.pdf.

[3] IEEE Xplore Digital Library, April 2012. http://ieeexplore.ieee.org/Xplore/home.jsp.

[4] International Federation of Robotics, April 2012. http://www.ifr.org.

[5] SYROCO 2012 History, April 2012. https://www.syroco2012.org.

[6] Antal K Bejczy. The Birth of the RAS. *Robotics & Automation Magazine, IEEE*, 14(1):104–108, 2007.

[7] Antal K Bejczy. The IEEE Robotics and Automation Society History. In *IEEE Conference on the History of Technical Societies*, pages 1–7. IEEE, 2009.