Bibliometric mapping as a science policy and research management tool

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5 Bibliometric Cartography of Scientific and Technological Developments of an R&D field: The Case of Optomechatronics*

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Abstract

This paper presents the results of an exploration of bibliometric mapping as an analytic tool to study the important aspects of the relation between science and technology, in particular the 'science base' of technology. We discuss a bibliometric (in particular a publication- and patent-based) approach to develop a cartography of science and technology, i.e., the construction of geometrically organized maps in order to visualize the changing internal structure of science and technology. These maps are based on co-occurrences of publication and patent keywords.

We focus on a specific R&D field: optomechatronics. This field is characterized by a strong knowledge transfer between science and technology. We constructed maps for both the science as well as the technology 'side'. Comparison of these two allows the exploration of existing or possible interaction of scientific and technological developments. We identified related subfields (co-word clusters) in the maps of both 'sides' in order to illustrate the interaction between science and technology. Subsequently, we extended the information given by the maps with information on the role and position of a number of countries in the different subfields of optomechatronics, both at the science side as well as at the technology side. This is done by identification of actors in the subfields represented by word clusters in the maps.

Cartography of science and technology allows the observation of the structure (and its changes) of scientific and technology fields. Moreover, it illustrates both existing as well as possible links between science and technology. It therefore presents a powerful tool for science, technology and R&D policy.

5.1 Introduction

5.1.1 Science base of technology

Bibliometric studies on the scientific base of technological development have up till now always been based on direct relations between science (represented by scientific articles) and technology (represented by patents). These direct relations were found in patent references to scientific articles and in inventors publishing scientific papers.

Studies based on the Non Patent Literature (NPL) references in patents (Narin & *Olivastro*, 1988; *Noyons* et al., 1991; *Grupp* and *Schmoch*, 1992), pointed out that these references give an indication of the science relatedness of a technology field. In general, they observe a higher number of NPL references in patents when a technology field is more science-related. It should be noted, however, that this science-relatedness is a clear and direct one. The patents refer directly and unambiguously to the science literature. Furthermore, we know that when a patent document contains a reference to a scientific publication, the knowledge transfer from science to technology has actually taken place (directly via the inventor or applicant or via the patent examiner). This is even better illustrated when an inventor has also published scientific papers (*Rabeharisoa*, 1992; *Korevaar* and *Van Raan*, 1992; *Noyons* et al., 1994). In such cases scientific knowledge appears to have been used directly for technological application.

Methods based on such direct relations, obviously, do not deal with situations in which the relations between science and technology are not so direct and unambiguous. Scientific papers are not always referred to in patents when used for technological application. Sometimes because inventor nor examiner is aware of the scientific work, sometimes because *similar* work has been referred to, and sometimes because a scientific publication is not used directly, but rather via another scientific publication (e.g., follow-up, review). For the inventor-author relation, it takes a closely science-related technology field to find authors being inventors or the other way around. Such direct relations are not to be expected in every technology field.

In *Noyons* et al. (1994), we also observed that the lack of NPL references does not necessarily mean that there is no science link at all. In such cases, we are not able to investigate the science base of technology by using NPL references only. And, in a technological field with no strong interaction between science and technology, we are not able to do so by using the inventor-authored scientific publications.

By using a cartographic approach, we try to deal with short-comings of bibliometric data in such cases, by investigating the science link between science and technology on the basis of a cognitive overlap. We try to identify similar subfields (co-word clusters) in the maps on both 'sides', constructed on the basis of the same definition. Thus we do not identify links between science and technology which are actually present, but rather links which could be there, or even *should be* there. Eventually this approach may prove to be a useful tool for companies to identify research activity for (further) development of products and for research institutes and universities to identify possible application of knowledge.

5.1.2 Basic principles of bibliometric cartography

Science and technology constitute complex, heterogeneous knowledge domains of different fields of activity, characterized by many interrelated aspects. Systematic investigation of this network of interrelations, and with that, the *structure* of science and technology and their *interface*, is a crucial element in the study of R&D. Nowadays, there is an enormous and ever increasing amount of information on science and technology. It is a challenge to develop techniques for extracting well-structured patterns of information from such a rather 'amorphous' mass of data. These patterns may reveal underlying and until now hidden features reflecting cognitive relations. An exciting approach is the development of *bibliometric maps*. There are several important advantages of using such cartographic representations. Visualization of complex masses of data offers a more complete overview in less time. In addition, visual information is more easily remembered. Another important point is the reduction of information. Bibliometric mapping allows the filtering of significant features. Time-series of maps may offer a *dynamic view* of the structural developments of science and technology. For instance, identification of important changes over time in the development of particular fields, such as synthesis of fragmentation of these fields, the increasing importance of specific instrumentation, emerging new activities, or shifts in R&D emphasis of countries and companies. Moreover, comparison of the 'knowledge structure' at the 'science side' of an R&D field with that at the 'technological side' may reveal important information about the 'science base' of technology. The empirical exploration of this hypothesis is the central aim of this study.

As bibliometric maps are based on data in publications and patents, this cartographic approach is independent of single, individual opinions. This is particularly advantageous in the case of broad and heterogeneous fields. This does not mean that bibliometric maps can *replace* opinions of experts. Design and use of bibliometric maps will be optimal in interaction with experts in the field, preferably the 'users' directly involved in the application of the maps.

In bibliometric analysis we may distinguish between *one-dimensional* and *two-dimensional* techniques. One-dimensional techniques are based on *direct* counts (occurrences) of specific bibliographic items (e.g., publications and patents), or particular data-elements in these items, such as citations, keywords, or addresses. We call these techniques 'one-dimensional' as they are in principle represented by *lists* of numbers. Two-dimensional techniques allow the representation of *relational features*. They are based on *co-occurrences* of specific data-elements, such as the number of times keywords or citations are mentioned together in publications or patents in a particular field.

The advantage of the bibliometric method is the possibility to map relationships between *any* co-occurrence of bibliometric data-elements. Thus, a structure of related keywords, or of related references, or a structure generated by combinations of key-words, references and/or classification codes can be made. Each possibility refers to another aspect of the science and technology system and can be applied to different levels of aggregation (varying from R&D groups to entire companies, business sectors, or countries, or even entire fields of science and technology). For a recent review on bibliometric mapping based on different co-occurrence techniques, we refer to *Tijssen* and *Van Raan* (1994).

In this paper we focus on bibliometric mapping based on *word co-occurrences*. Word co-occurrences in a set of publications or patents reflect the network of conceptual relations from the viewpoint of scientists and engineers active in the field concerned. These 'co-word' frequencies are used to construct a co-word map which represents the major themes in a field and their interrelations (*Callon* et al., 1983, 1986). The main advantage of co-word analysis is given by the nature of words: words are the foremost carrier of scientific and technological concepts, their use is unavoidable and they cover an unlimited intellectual domain. An important semantic problem is that the meaning of words is often context-dependent. However, the co-word approach is in fact based on 'words-in-context' (i.e., words placed in relation to relevant other words). Therefore, co-word maps can be regarded as (of course, as yet rather 'primitive') semantic maps.

For a detailed discussion of the main methodological aspects of publication-based science maps and patent-based technology maps, we refer to our recent publications (*Van Raan* and *Tijssen*, 1990; *Engelsman* and *Van Raan*, 1991, 1994; *Peters* and *Van Raan*, 1993). The basic principle is that for each of the keywords the co-occurrence with any other keyword in a set of publications or patents is analyzed, i.e., we count the number of publications or patents having any possible pair of keywords. With matrix-algebra techniques this co-word matrix is displayed in two-dimensional space, and the keywords are positioned in the map according to their mutual relations. This means that the relative distances between research topics indicated by keywords in the map reflect their cognitive relationships from the statistics of the underlying data in publications or patents. The above sketched process of publication- and patent-data collection, composition of co-word matrices, and construction of maps, is highly automated. This enables us to make science and technology maps in a reasonably economic way. A detailed discussion of the co-word methods and techniques to compare scientific and technological developments of specific R&D fields is given in a paper on a parallel study (catalysis and environmental chemistry) by *Korevaar* and *Van Raan* (1992). In this paper, we focus on the bibliometric mapping of the science and technology 'side' of an R&D field, which is considered to be one of the most important new 'generic technologies': optomechatronics.

5.2 Maps of optomechatronics based on expert field definitions

Optomechatronics is an R&D field in which optical, mechanical and electronic technology is combined. It is a field of strongly growing technological importance.

We applied a definition of (opto-) mechatronics as given by a group of European Community experts, the IRDAC (Industrial Research & Development Advisory Committee). The definition is used both to identify relevant publications on the science side and to select relevant patents on the technology side. In earlier work

(*Engelsman* and *Van Raan*, 1991 and 1994; *Noyons* et al., 1991) we used definitions based on specific keywords and patent classification codes.

5.2.1 Method and data

We investigated the 'science side' and 'technology side' of optomechatronics and, more specifically, science as a basis for technology. Particularly, we expect to find in our maps subfields on the science side related to (subfields on) the technology side, and the other way round. Such 'communicating' subfields should be recognized both by specific words in the clusters representing a subfield, and by the (type of) actors found in the clusters.

In the above mentioned IRDAC definition, 6 subfields are distinguished:

1. Mechatronics Systems Design Analysis and Modeling;
2. Sensors;
3. Actuators;
4. Advanced Control Techniques;
5. Interconnection techniques and Standardization Needs;
6. Precision Mechanism and Mechanical Devices.

This IRDAC definition of the field was translated into search terms for both INSPEC and WPIL. Thus, the selection of articles and patents from databases representing both sides (INSPEC for the science side, and WPIL for the technology side) was performed in a comparable way. For each of the two databases we took the most recent 'publication' year, taking into account the entry delay. In INSPEC, we selected articles with publication year 1991, and in WPIL patents with priority year 1989. We stress that the use of the whole WPIL database, yields a severe bias towards Japanese patents. In *Engelsman* & *Van Raan* (1991, 1994) it is argued that Japanese domestic patenting traditions strongly influence the numbers of patents. A possibility to make a more 'realistic' picture of technological activities is the restriction of patent analyses to the US and the European Patent Offices. Important Japanese inventions will be included as most of these inventions lead to patent applications in the US and in Europe. However, exclusion of Japanese domestic patents might push recent developments in Japanese technology into the background. Thus, selection of patents depends upon the type of analysis.

From the set of publications in INSPEC a list of the most frequent controlled terms (CT) and uncontrolled terms (UT) was generated. CT's tend to cover publications with subjects already established within the field, whereas UT's are more 'author related' and possibly cover more new developments (*Van Raan* and *Van der Velde*, 1994). Therefore, we used both CT's (90 most frequent) and UT's (10 most frequent, not already being CT's) as input for the science map. From the WPIL patent set a frequency list of indexed words (IWs) was generated, from which we used the top-100 as input for the technology map.

Both the science as well as the technology map were constructed with help of co-occurrences. We used the above matrices (100 * 100) for multidimensional scaling (MDS) in which word distances on the map are based on the cosine index. For more details of the mapping techniques we refer to *Engelsman* and *Van Raan* (1991, 1994) and to *Noyons* et al. (1991).

Furthermore, the following additional information was included on the maps (a detailed discussion is given in the paper on a parallel study by *Korevaar* and *Van Raan* (1992).

(1) on the basis of distances between words calculated with the cosine index, single-linkage clusters were drawn in the map. If two words have a cosine index above a certain threshold, they are captured in one and the same cluster. The threshold is set to a value which yields a maximum of clusters (of two or more words);

(2) on the basis of 'individual' relations ('pair linkages') between words in the map, in terms of the inclusion index, lines were drawn in the map illustrating these relations as far as the two words are not already captured in one and the same cluster. This is particularly important for words in different clusters, but with a strong 'individual relation'.

For the identified clusters in the map of the science side we applied an 'actor analysis' (see Section 3.2.3). For each major cluster in this map the addresses of the authors of the publications concerned have been analyzed. In particular, we characterized the affiliations by *institute type* (e.g., university institute, company, governmental organization). For this purpose, the list of institutional addresses was matched with an in-house-database with unified and 'cleaned' addresses derived from a large set of scientific publications from most western countries (*De Bruin* and *Moed*, 1990). This 'address master file' also contains information about the *institute type* of most of the covered addresses. In order to match the list of institutional addresses in optomechatronics with the master file, a country name in the address of a publication is essential. As we analyzed publication data with help of INSPEC, the availability of the country name was not a big problem, only in a few cases the country name was not available. But it was much more problematic to match the institute names (as given by INSPEC) with the master file. Eventually, we were able to label 96% of addresses with an institute type. The remaining 4% was either not found in the master file, or not yet labeled in the master file with an institute type.

5.2.2 Results

5.2.2.1 Two maps based on one definition

In the map of the science side (see Figure 1), we observe three main parts. A large network of subclusters containing terms like 'design', 'expert systems', 'adaptive control', 'optimal control', 'stability' and 'control system synthesis'. A second part covers a subfield of 'semiconductors', 'sensors' and 'silicon'. Furthermore, there is a mechanical cluster of 'motors' and 'drives' around 'digital control'. For reasons of clarity we identified, within the large network of (sub) clusters, 5 meaningful clusters for labeling. The resulting breakdown of the major cluster is as follows:

I Design, expert systems, knowledge representation, etc.;

II Stability, control system synthesis, etc.;

III Optimal control, dynamic programming, etc.;

IV Adaptive control, self adjusting systems, etc.;

V Robots and position control;

Next, we have the earlier mentioned two other clusters which appear to be rather 'autonomous':

VI Semiconductor, silicon and sensors, etc. ;

VII A mechanical cluster around digital control.

Cluster I covers research on the design of expert systems including CAD/CAM and manufacturing systems. A major concern of this research is the design of controlling systems. In the surrounding clusters (II, III, IV and V) several closely-related topics are covered, III taking a central position. The latter obviously has a connecting function between all 'control' clusters. Cluster VI covers research of integrated circuit (IC-) technology, sensors and semiconductors. Cluster VII includes research on 'machine control' and, via 'digital control' also 'microcomputer applications' research.

As far as the technological side of the field concerns (Figure 2), we observe a much less complex structure. There are two major clusters to which most other activities are adjacent. First, the *actuator/control techniques* (ACTUATE/CONTROL) cluster, on the right-hand side, is not very large in terms of the applied single linkage clustering, but it attracts all peripheral words and clusters, if we apply inclusion linkage with the word 'control'.

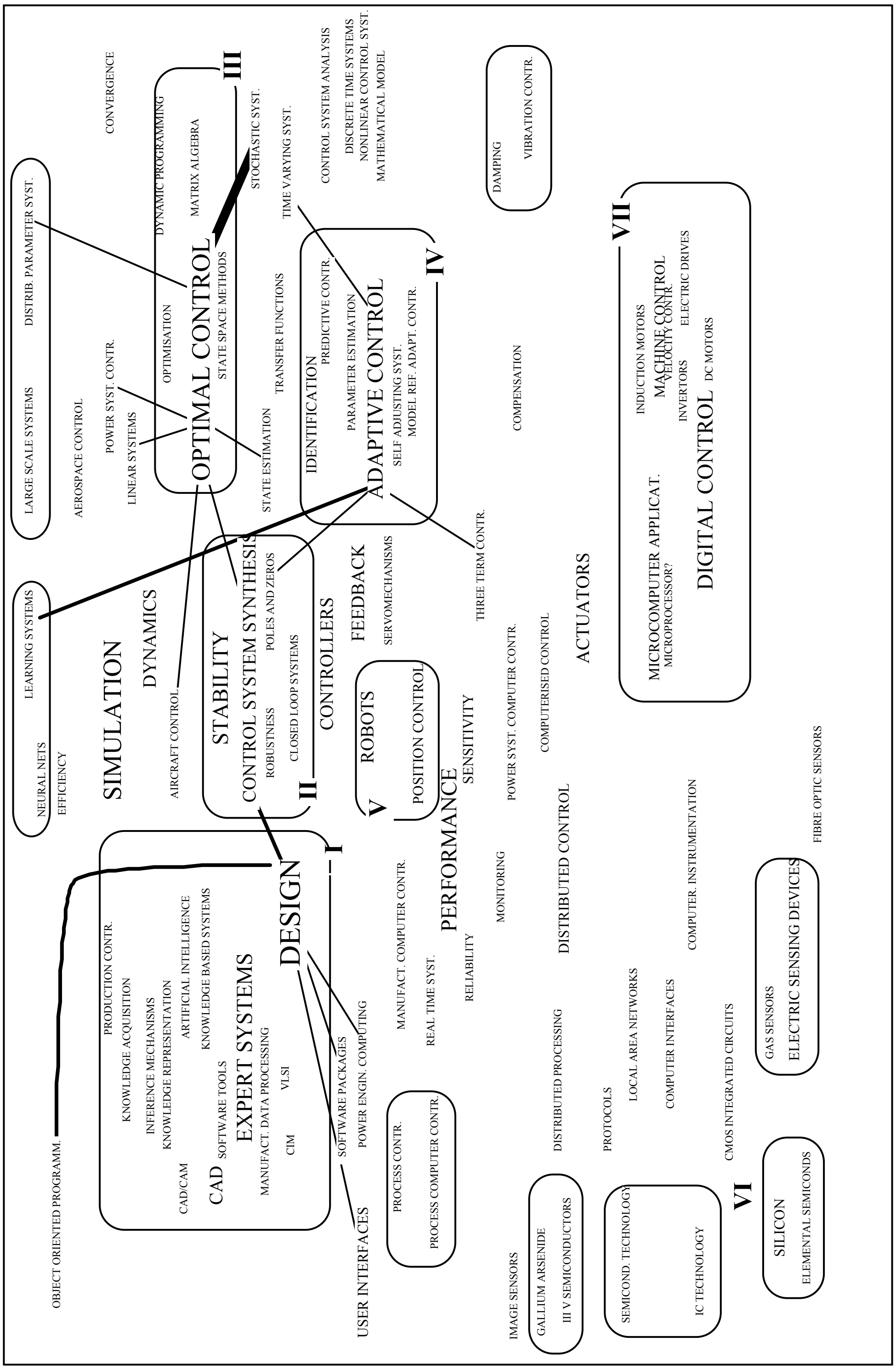

Figure 5-1 Map of the 'science side' of optomechatronics (1991)

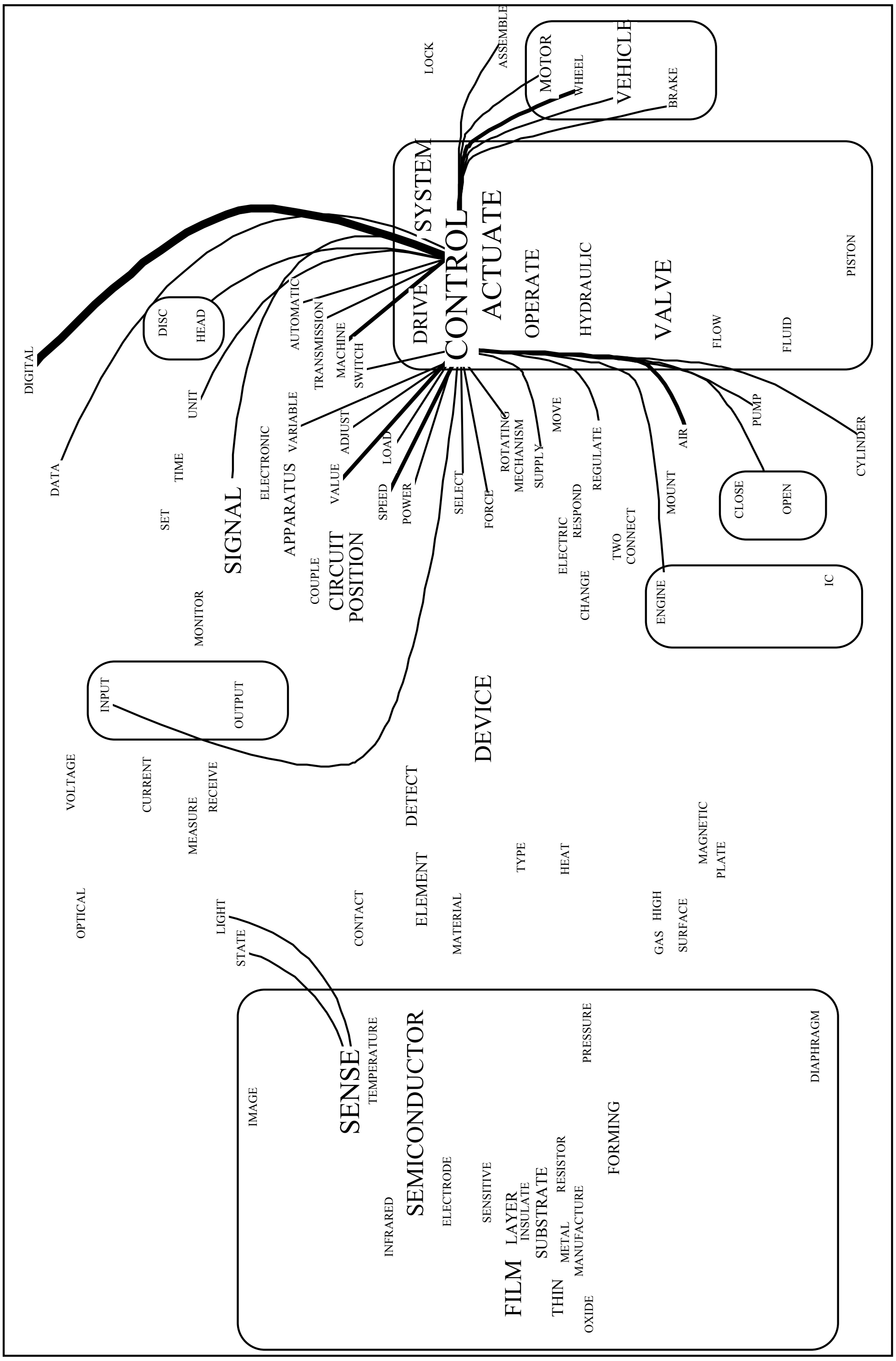

Figure 5-2 Map of the 'technology side' of optomechatronics (priority year = 1989)

Second, on the left-hand side, we observe the larger sensor (SENSE) cluster. In fact, this cluster looks larger as it contains more words, but actually it covers less publications than the *actuator/control techniques* cluster. The *sensor* cluster containing words like 'semiconductor', 'gas', and 'sensing', corresponds to cluster VI of the science map. The *actuator/control techniques* cluster corresponds to cluster VII of the science map. The other clusters of the science map are not directly related to clusters in the technology map. In other words, only very few terms from other clusters in the science map are found again in the technology map. In these scientific clusters (I-V), however, a lot of research is involved that has resulted in computer software. Therefore, as software cannot be patented as such, it is not expected to appear in the technology map based on patent applications.

In a recent report (*Noyons* and *Van Raan* 1993) we extensively compare our results as presented in this paper (and based on the IRDAC definition) with our earlier maps (*Engelsman* and *Van Raan* 1991, 1994; *Noyons* et al. 1991). In main lines, we reach the following conclusions. Optomechatronics, being an important, strongly developing R&D field in which the integration of several already highly developed fields take place, can be defined in different ways. Each definition emphasizes particular aspects of the field. We also observe that different definitions cover different links in the chain from scientific research to technological application. Our science map (Figure 1) based on the IRDAC definition of (opto-) mechatronics appears to cover scientific research in the most basic sense (i.e., most basic for the field). Here the different kinds of control systems are included. Moreover, there is a specific cluster of mechanical control applications, and a cluster of sensors, semiconductors and integrated circuit technology. These clusters are the most prominent composing parts of the field. The typical optical R&D takes its position more or less at the center of the map. *Busch-Vishniac* (1991) discusses the techniques used for micro-automation, which is positioned at this point of the map. These techniques supported by sensor and actuator technology is represented by words like: controllers, feedback, servomechanisms, position control, manufacturing, actuators, sensors and fibre optics.

In our technology map (Figure 2) we observe applications of sensors and semiconductors on the one hand, and mechanical control techniques on the other. The conclusion that 'expert systems' and other aspects of control techniques as represented in the science map are not found again in the patent-based technology map, is probably due to the fact that the application of this subfield concerns mostly software, which is not patentable. Furthermore, the technology map lags somewhat behind in time as compared to the science map. Our technology map, therefore, represents particularly the science and technology interface (not surprisingly, the contents of our earlier science and technology 'interface map' (see Figure 11 in *Engelsman* and *Van Raan* 1994) is almost fully covered in this map). The specific micro- (and macro-) automation techniques are positioned in between the two major clusters in our technology map. Relevant words are: sense, semiconductor, layer, plate, magnetic, surface, optical, control actuate, position, circuit, speed and others (see Busch-Vishniac, 1991). We also find the inclusion of optical techniques, which is hardly covered by the earlier maps.

5.2.2.2 The role of actors

For the clusters in the science maps based on the IRDAC definition (Figure 1 and Figure 2), we applied an actor analysis. We identified the institutes responsible for the publications as represented by the word clusters in the map.

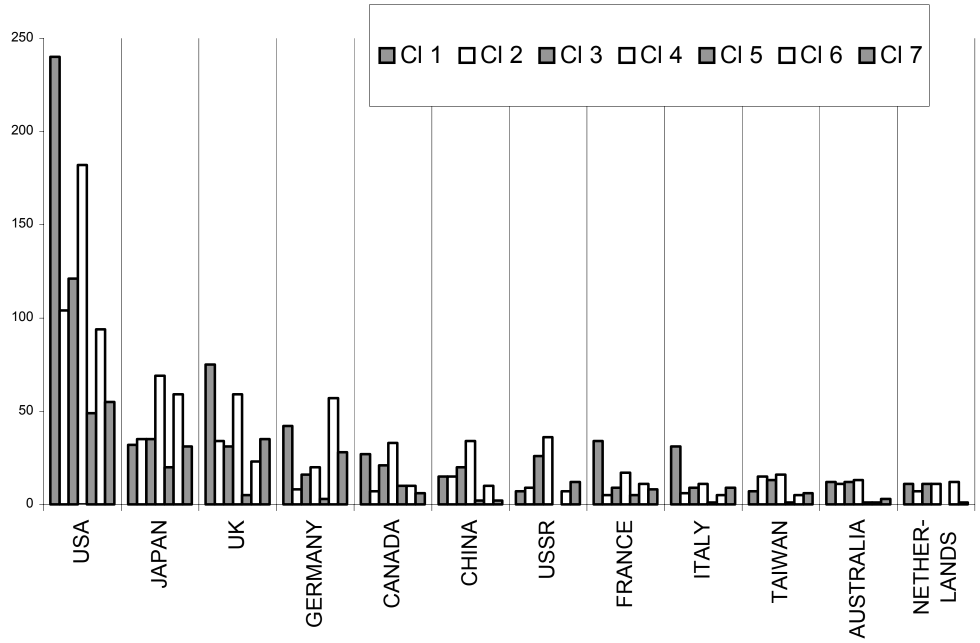

Figure 5-3 Number of publications per country per cluster, 'science side' of optomechatronics

The seven clusters of the science map are separately analyzed with help of the INSPEC database, by combining all possible word co-occurrences within a cluster (e.g., for cluster X with words A,B and C we use the combination [A*B] + [A*C] + [B*C]). For the resulting set of publications we identified the institutes involved (i.e., affiliations of authors). For each cluster a frequency list of active institutes was generated. This list was touched up with additional information if country or city names were missed in the database. Thus we were able to determine the most active countries per cluster. In Figure 3, the results are plotted for the 13 most active countries.

Not very surprisingly, the USA is the most active country in all 7 clusters. Only in cluster VI and VII they are more or less approximated by Japan and Germany, in cluster VII also by the UK. Another remarkable finding is that Japan appears to have such a relatively small activity in cluster I, which is the main subfield for almost all other countries. Apparently, Japan focuses more on cluster VI, and on cluster IV which, however, is also important for most of the other countries. The Netherlands also has its main focus of activity on cluster VI, has no 'measurable' activity in cluster V, and hardly any in cluster VII.

The institutes active in each cluster have been characterized by type. A large in-house database (with affiliations of scientific authors in a unified address structure) was used for this purpose. This database includes, among other, information about the *type* of the affiliations. In this 'CWTS address master file', seven types of institutes are distinguished:

1. Universities (U)
2. Colleges etc. (E)
3. Companies (C)
4. Governmental institutes (G)
5. Research institutes (R)
6. Hospitals (H)
7. International Institutes (I)

As some of the addresses in the master file are not yet labeled with an affiliation type, and some addresses were not found in the master file, we introduced an eighth type (X) attached to those not identified. Moreover, as we found it difficult in many cases to determine U or E, these two institute types are joined together in our analysis.

By comparing the number of institute types in each cluster, we were able to characterize the kind of research in a subfield (cluster), as represented by its 'institute type'. The results are shown in Figure 4.

In the above we are dealing with the science side of optomechatronics. Therefore, it is not surprising that most research in all clusters is done at universities and in colleges. In cluster VI and cluster VII, however, significantly more companies are active than in any other. In clusters I to V, the number of companies involved hardly exceeds the share of research institutes.

Apparently, industry takes higher interest in the research of cluster VI and VII. This will be further supported by our findings for the technological side of the field (see next section).

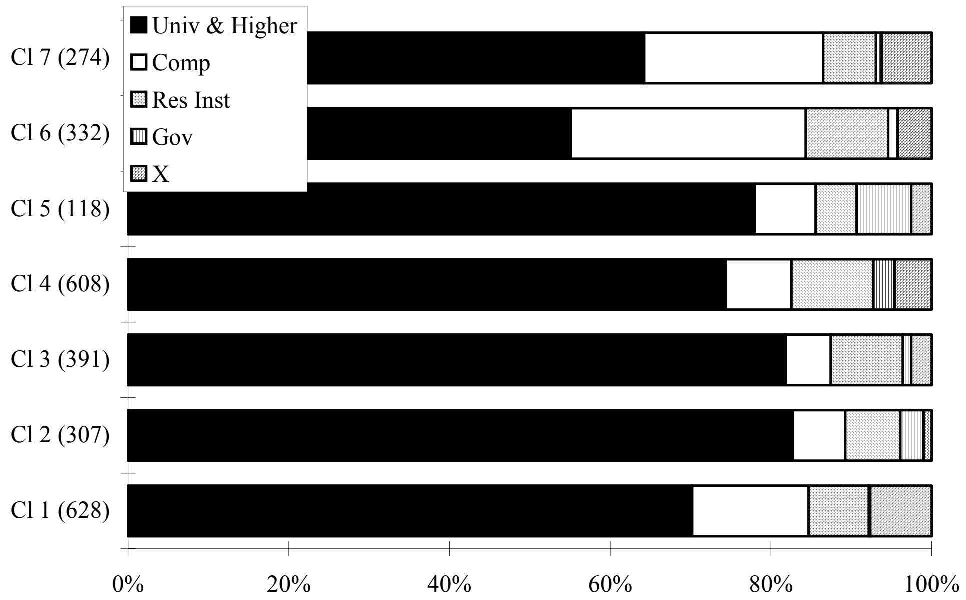

Figure 5-4 Percentage of institute types per cluster, 'science side' of optomechatronics

Subsequently, a profile of 13 most active countries with respect to number of institute types is made (see Figure 5). In most countries, universities and colleges have the largest share. In Taiwan even 100% is academic. Only in the USSR, research institutes (in particular the *Ukrainian Academy of Science* (ACAD SCI UKSSR) in Kiev, and The *Institute of Control Science* (INST CONTROL SCI) in Moscow) outnumber universities. This, however is characteristic for all Soviet scientific activities (*Piskunov* & *Saltykov*, 1992). The number of not identified institutes is never more than 5% except for France. More than 25 % of the addresses from this country could not be labeled with a type. Not surprisingly, in Japan the share of companies involved is larger than in any other country, although they do not exceed universities and colleges. The most active companies from Japan are *Fujitsu LTD*, *Hitachi LTD*, and several departments of *Nippon TT*. The UK is traditionally more academic-oriented.

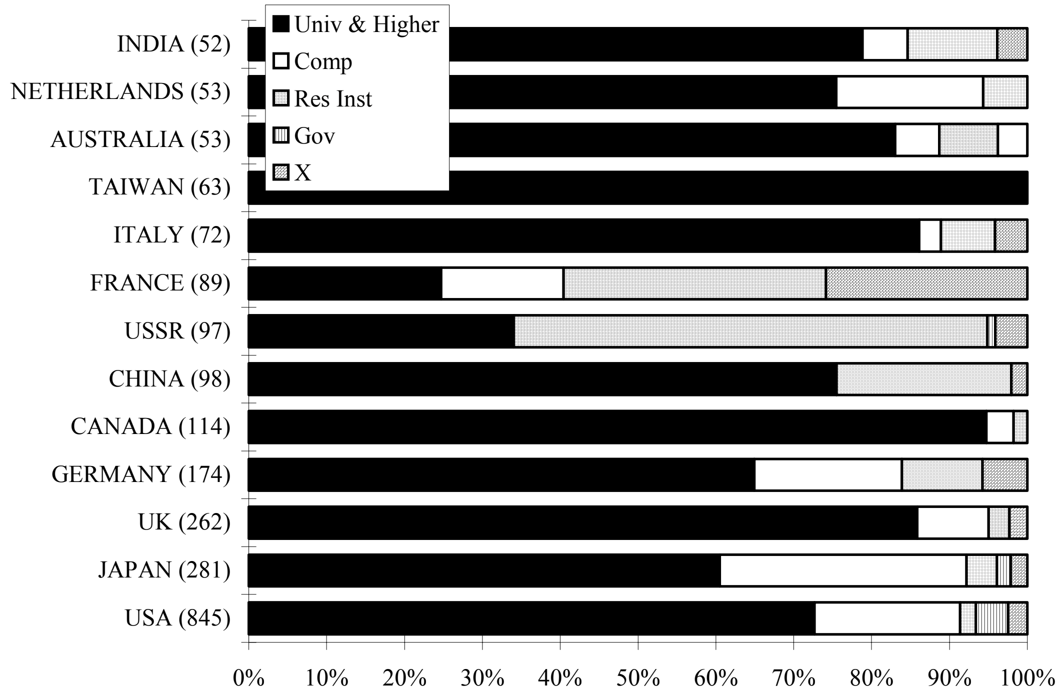

Figure 5-5 Percentage of institute types for 13 most active countries, 'science side'

The large amount of active research institutes in France is due to the fact that CNRS institutes are identified as such. It may, however, well be argued that most of the publications from these institutes are in fact academic.

In the Netherlands no deviant pattern is observed, with universities being the most active institutes (particularly the *University of Technology at Delft* (TECH UNIV DELFT), followed by companies (*Philips*) and research institutes.

For the technology side, ongoing work is devoted to identify actors in terms of inventors as well as applicants.

5.3 General conclusions and discussion: overview of possibilities and limitations

Bibliometric cartography based on publications and patents is a powerful tool to analyze the structure of science and technology. Mapping of R&D fields offers the possibility to visualize the internal structure of these fields. In fact, a geometrical structure in abstract space is constructed, reflecting the cognitive relations covered by the statistics of the data in publications and patents. This reveals centers of invention activities which can be analyzed further in terms of countries, companies, R&D laboratories involved, etceteras.

Time series of maps allow an impression of important temporal changes. A more detailed discussion is given by *Noyons* & *Van Raan* (1993). We found that recent developments are based on the main lines of preceding periods. This means that on the basis of the contours and patterns visible in the most recent maps, medium-long term predictions about future developments can be made.

In this paper, we have presented the results of an analytical, 'cartographic' study of science as a base of technology. As a starting point we used the bibliometric maps representing the field of optomechatronics. For the science map of the field we performed an *actor analysis* by identifying the countries and institutes or companies involved in the publications representing clusters (subfields) in the map. We found that this bibliometric actor analysis is a useful tool to determine the relative activity of countries and/or companies, in comparison to the activity in the same cluster by other countries and companies, or to the activity in other clusters.

In the maps we implemented a method to relate the science and technology side. The selection of field-specific patents and publications was based on the same definition (IRDAC definition). The resulting maps (Figs 1 and 2) show, in main lines, the same cluster structure. Though there is no *direct* connection between the related clusters in the science map on the one hand and the technology map on the other, we conclude that the research activities represented by the corresponding clusters in the science map can (or should) be considered as a science base for the two technology clusters. Thus, the institutes active in these science (base) clusters perform research which is, or could be, important for applications represented by the patents in the corresponding technology clusters.

We found that the used databases (INSPEC and WPIL) are quite appropriate for our purposes, but that there still are several shortcomings. One basic problem is related to the use of any patent database. In the most recent science map we identified about five clusters on several aspects of *control*. These clusters were not identified in the technology map because most of these techniques involve software which is not patentable. By using a patent database, we miss such technological applications. In view of the problematical jurisdiction around patenting software, we do not expect much progress on this point in the near future. Given our experiences with maps based on data from COMPENDEX (*Van Raan* and *Van der Velde*, 1994), we expect that such a typical engineering database may provide a useful combination of (applied) scientific, technological and software developments.

As far as our 'actor analysis' concerns, we conclude that on the 'science side' of optomechatronics the USA , Japan, the UK and Germany are the leading countries. In Japan a significantly large share of research is done in companies. Furthermore, it is striking to see that Taiwan and China take such high interest in the optomechatronics research. In these two countries almost all work is done in universities and research institutes (of course, as far as our bibliometric approach can reveal). For the Netherlands we observed a high interest for Cluster VI (*sensors and semiconductor technology*). The emphasis on research in this subfield is also found in Germany and Japan. These two countries are also interested in cluster VII (*mechanical and digital control*), which is not the case for the Netherlands. Most of the other countries are more active in cluster I-V (research on several *control techniques*).

A possible enrichment of the cartographic analyses is an investigation of the direct links between science and technology in terms of patent citations to non-patent literature. If such relations are actually present, it would be interesting to find out if they refer to the links found in this study. In future research we will elaborate on this.

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