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ORIGINAL ARTICLE

The evolution of large-scale dimensional metrology from the perspective of scientific articles and patents

Fiorenzo Franceschini · Domenico Maisano

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Abstract In the last two decades, there has been a great development of the measuring systems in the field of large-scale dimensional metrology (LSDM), as also proved by the significant growth of the scientific literature. The aim of this paper is to analyze the LSDM scientific literature, from the dual perspective of scientific articles and patents, and estimate their impact in terms of amount of documents and relevant citations. In detail, this study investigates similarities and differences between articles and patents, as regards their dominant technologies and temporal distribution, and identifies (1) the major scientific journals and conference proceedings containing LSDM articles and (2) the major assignees of LSDM patents. Two main results emerge from the analysis: (a) important inventions concerning new LSDM systems were deposited before the end of twentieth century, while scientific articles have "bloomed" only in the last decade, and (b) the vast majority of patents concern inventions related to the laser-interferometry technology, while articles are divided more evenly among available technologies, with an important role played by the less accurate but more affordable ones, such as photogrammetry or structured-light scanning.

Keywords Large-scale dimensional metrology · Large volume metrology · Scientific publications · Patent literature · Citation impact · Dominant technology

F. Franceschini (✉) · D. Maisano
DIGEP (Department of Management and Production Engineering), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
e-mail: fiorenzo.franceschini@polito.it

D. Maisano
e-mail: domenico.maisano@polito.it

1 Introduction

In the last two decades, there has been a rapid growth of large-scale dimensional metrology (LSDM) instruments, for measuring medium- to large-sized objects (i.e. objects with linear dimensions ranging from tens to hundreds of meters [1]), where accuracy levels of a few tenths of a millimetre are generally tolerated [2, 3]. These systems usually support the assembly phase and/or dimensional compliance test on large volume objects, in situ. Table 1 sketches the evolution of the major LSDM instruments, with a brief description of their characteristics. For more information on LSDM instruments and their technologies (e.g. technical features, usual applications, metrological performance, cost, etc.), we refer the reader to the extensive reviews [3–6].

The aim of this paper is a wide-range analysis of the existing scientific literature, from the dual perspective of (1) scientific publications, which reflect the interest of the (academic) scientific community, and (2) patents, which reflect the well-established (at industrial level) technologies or the emerging ones [7].

The analysis tries to delineate the technological and scientific evolution of LSDM systems in the last 20–30 years, by comparing these two types of outcomes and highlighting similarities and, more interestingly, differences and counter-tendencies.

We emphasize that the academic literature—which generally consists of journal articles, conference proceedings, book chapters and monographs—and the patent literature are not necessarily dependent on each other, as also evidenced by the relatively low incidence of patent citations in scientific publications and vice versa [8, 9]. This is the key reason for which combining these two analysis perspectives may lead to interesting results.

In the literature, there are many cases in which scientific publications and patents are investigated in conjunction, for instance, the contributions by Van Looy et al. [10], Czarnitzki

Table 1 List of the main LSDM instruments, with a brief description of their features

Instrument	Introduction time	Short description
Tapes/sticks	Thousands years ago	Reference artefacts used for measuring the length of an object directly.
Theodolite	≈1,700	It consists of a movable telescope mounted within two perpendicular axes—a horizontal and a vertical one. When the telescope is pointed at a target point of interest, the angles with respect to each of these axes can be measured with large precision.
Contact-probe coordinate measuring machine (CMM)	1960s	This device is used for measuring the geometrical characteristics of an object. It is generally composed of three moving axes, which are orthogonal to each other in a typical three dimensional coordinate system. Measurements are defined by a mechanical contact-probe attached to the third moving axis.
Total station	Early 1970s	It is a sort of theodolite integrated with an Electronic Distance Meter (EDM) to read angles and distances from the instrument to a point of interest. System setup is partially automated and, when measuring, there is no need for an assistant staff member, as the operator may control the total station from the observed point.
3D scanners based on structured light, laser or photogrammetry	1990s	These instruments measure the three-dimensional shape of an object by processing images—taken by two or more cameras—of (1) encoded light patterns, (2) laser beams or (3) targets projected on the object surface. Measurements are characterized by a high level of automation.
Optical-probe CMM	1990s	It is a classical CMM equipped with a contactless optical-probe, which allows the localization of a high density cloud of points on the object surface. Measurements are less accurate but considerably faster than those carried out with a contact-probe.
Laser tracker, tracer and radar	1990s and early 2000s	These instruments allow the accurate localization of a target on the surface of the object of interest, by measuring mutual angles and distances. Distance measurements are generally based on the laser-interferometric and/or Absolute Distance Meter (ADM) technology.
Distributed LSDM systems	2000s	Unlike the previous instruments, which can be classified as "single-station", these ones consist of a network of devices distributed around the measurement volume. The spatial coordinates of targets, in contact with the object of interest, are determined by two localization techniques: (1) multilateration (based on distances between targets and network devices) and (2) triangulation (based on angles between targets and network devices). Distributed systems may rely on different technologies (e.g. ultrasonic, photogrammetric, optical, etc.).

Instruments are sorted chronologically according to the approximate time of their introduction

et al. [11], Breschi and Catalini [12], Franceschini et al. [13] and many others. However, this type of analysis is a novelty in the LSDM field.

Our study focuses on the scientific publications and patents in the LSDM field and the citations that they obtained, respectively from other publications and patents. While the citations that a scientific publication obtains from other publications depict its impact/diffusion within scientific community [14], the citations that a patent obtains from other patents can be indicative of its technological importance or even (potential) market value and profitability [15]. Furthermore, this study makes it possible to identify the LSDM articles and patents of greater impact, the major scientific journals and conference proceedings and the major patent assignees.

The rest of the paper is structured in three sections. "Section 2" focuses on data collection and data cleaning, aimed at selecting a portfolio of documents as comprehensive as possible of the state of the art on LSDM. "Section 3" briefly describes the methodology of analysis of the selected portfolio and presents the analysis results in detail. Analysis can be split in three parts: (1) evaluation of the dominant technologies, (2) study of the evolution of LSDM systems in the last 20–30 years, from the double perspective of scientific publications and patents and (3) identification of the main scientific journals, conference proceedings and patent assignees in this field.

The final section summarizes the results of the study, highlighting the original contributions, implications and limitations.

2 Data collection

The objective of data collection is to identify a comprehensive set of scientific articles and patents in the LSDM literature.

Articles were collected through the Scopus database (Scopus [16]). We chose this database for two reasons: (1) in the field of Engineering Science, Scopus' coverage is superior to that of Web of Science [17], and (2) Scopus is much more accurate than Google Scholar database [18]. A limitation of Scopus is that it does not index books or book chapters but only articles from leading journals and conference proceedings, which, however, contain the vast majority of the relevant LSDM publications.

Patents are collected using the Questel-Orbit database, which integrates patent statistics from more than 95 national and international patent authorities (Questel [19]), e.g. EPO (European Patent Office), USPTO (United States Patent and Trademark Office), WIPO (World Intellectual Property Organization), JPO (Japan Patent Office), CPO (China Patent and Trademark Office), etc.

For both articles and patents, databases were queried on 8 March 2013, with the following string: «("large scale * metrology" OR "large scale * measur*" OR "large volume * metrology" OR "large volume * measur*") OR {("large scale" OR "large volume") AND ["laser tracker" OR "photogrammetr*" OR "CMM" OR "coordinate measur*" OR "structured light scan*"]}», searching into title, abstract or keywords of each document. Please note that "*" is a wildcard character, while "AND" and "OR" are basic Boolean operators.

The search string is deliberately general, so as to reduce so-called false negatives, i.e. documents that deal with LSDM but are ignored by databases because they do not meet the search query. The price to pay to reduce "false negatives" is identifying a large number of "false positives", i.e. documents that do not concern LSDM but meet the search query [20]. To reduce "false positives", the documents returned by databases were cleaned manually: After examining title, abstract and contents, we excluded those documents not concerning LSDM and the uncertain ones, e.g. some unclear articles/patents in Russian or Chinese language only.

Regarding articles, Scopus returned 555 articles, which were reduced to 180 after data cleaning. Selected articles are reported in Table 6, in Appendix. Regarding patents, Questel-Orbit returned 334 patents, which were reduced to 53 after data cleaning (reported in Table 7, in Appendix). For duplicated records, i.e. patents filed in multiple authorities, we considered the ones with the oldest "priority date".

One way to further reduce "false negatives" could be to expand the portfolio of cleaned documents, by including their "neighbours", i.e. those documents that cite or are cited by them, and then cleaning these additional documents manually. Of course, this operation would be significantly time-consuming.

During the manual cleaning activity, documents were also classified according to two criteria: (1) dominant technology and (2) typology of output. The dominant-technology classification is illustrated in Table 2. While not claiming to be exhaustive, it includes the main technologies of the vast majority of LSDM systems, in agreement with the literature review by Peggs et al. [5].

Documents concerning minor technologies (e.g. moiré patterns or capacitive probes, see respectively Art31 and Art143 in Table 6) or independent of a specific technology (e.g. documents about general measurement procedures or literature reviews) fall into the class h–N/A.

Table 3 illustrates the typology-of-output classification. As well as the previous classification, it adapts to both articles and patents. It is reasonable to expect that most of the patents will fall into the first three classes (A–Description of the measuring system, B–New hardware component(s) and C–New application/working procedure), while scientific articles will be distributed more uniformly among the seven classes.

3 Data analysis

3.1 Overall data analysis

Analyzing the two portfolios of articles and patents (reported in Tables 6 and 7), it is possible to identify the most popular technologies, both from the point of view of the total number of documents (P) and that of the total number of citations obtained (C). P is a proxy of the amount of research in the scientific literature, while C reflects its impact on the scientific community or industry.

For each article, we considered the citations obtained from other articles while, for each patent, those obtained from other patents, up to the moment of data collection (8 March 2013). In the following subsections, articles and patents will be analyzed separately.

Table 2 Dominant-technology classes for classifying documents (articles and patents)

Dominant technology	Description
a–Laser-interferometry/ADM	Documents about measuring systems based on the laser-interferometric and/or Absolute Distance Meter (ADM) technology, or similar ones.
b–Photogrammetry	Documents about measuring systems based on photogrammetric technology, in which one or more targets are localized using at least two cameras.
c–Ultrasound	Documents about measuring systems in which one or more targets are localized by using the distances estimated by the time-of-flight of ultrasonic signals from/to three or more “landmarks”, with known spatial position and orientation.
d–CMM	Documents about coordinate measuring machines (CMMs) for LSDM applications (e.g. gantry or horizontal-arm CMMs).
e–Theodolite/R-LAT	Documents about systems based on classic theodolites or rotary-laser automatic theodolites (R-LATs), such as the Nikon iGPS.
f–Structured-light scanning	Documents about measuring systems based on the projection of structured-light (e.g. encoded patterns) on the surface of the object to be measured, and analysis of the images taken by two or more cameras.
g–Hybrid	Documents about measuring systems equipped with components derived from multiple technologies, implementing multi-sensor data fusion techniques.
h–N/A	Not applicable: documents concerning minor technologies or independent of a specific technology (e.g. documents about generic measurement procedures or literature reviews).

Table 3 Typology-of-output classes for classifying documents (articles and patents)

Typology of output	Description
A–Description of the measuring system	Detailed description of a new LSDM system, its technical features, functionality, measurement procedure and (dis)advantages with respect to other systems.
B–New hardware component(s)	Development and characterization of new hardware components, which replace or complement those of an existing measuring system, improving its functionality and performance.
C–New application/working procedure	Description of novel measurement procedures or applications, aimed at expanding and improving the functionality and/or performance of an existing measuring system. These procedures/applications generally require additional external hardware equipment.
D–Development of system set-up/calibration	Illustration of a new procedure/algorithm aimed at enhancing the system set-up/calibration stage of an existing measuring system.
E–Optimization of measurement operations	Improvement of the efficiency/effectiveness of measurement operations and data management. This optimization is typically software-based and does not imply any change in the measuring system’s hardware or the introduction of external hardware.
F–Performance analysis	Analysis of the performance of an existent measuring system (e.g. evaluation of metrological characteristics, such as repeatability, accuracy, measurement uncertainty, sampling rate, etc.), based on empirical data or simulations. It may include performance verification according to standards and/or comparison with other measuring systems.
G–Literature review	Literature review of the LSDM measuring systems or those based on a specific technology.

3.1.1 Dominant-technology classification

From chart (1) in Fig. 1, we note that articles are quite evenly distributed among the dominant-technology classes. For example, the number of articles is not very different for classes a–Laser-interferometry/ADM, b–Photogrammetry and e–Theodolite/RLAT.

Regarding citations (see chart (2)), over half of the total citations are in the class h–N/A, being mainly captured by literature reviews, which are independent of a specific technology and tend to get more citations than standard research articles. Excluding the class h–N/A, citations are divided between the remaining technology classes in a fairly consistent way with articles.

Chart (3) illustrates the number of patents in the dominant-technology classes and shows a clear predominance of the class a–Laser-interferometry/ADM. Analyzing the patents in this class, we noticed that most of them concern laser-trackers. Inventions in the class b–Photogrammetry are relatively more cited than the others (see chart (4)). This is symptomatic of the great industrial interest for this technology, even in contexts outside of LSDM (e.g. videogame and home-entertainment). The class h–N/A includes many citations, most of which (i.e. 113) come from a single outstandingly cited patent (i.e. Pat3 in Table 7), which is independent of a specific technology.

3.1.2 Typology-of-output classification

As regards articles, they seem quite evenly distributed among classes (see chart (1) in Fig. 2), with the predominance of

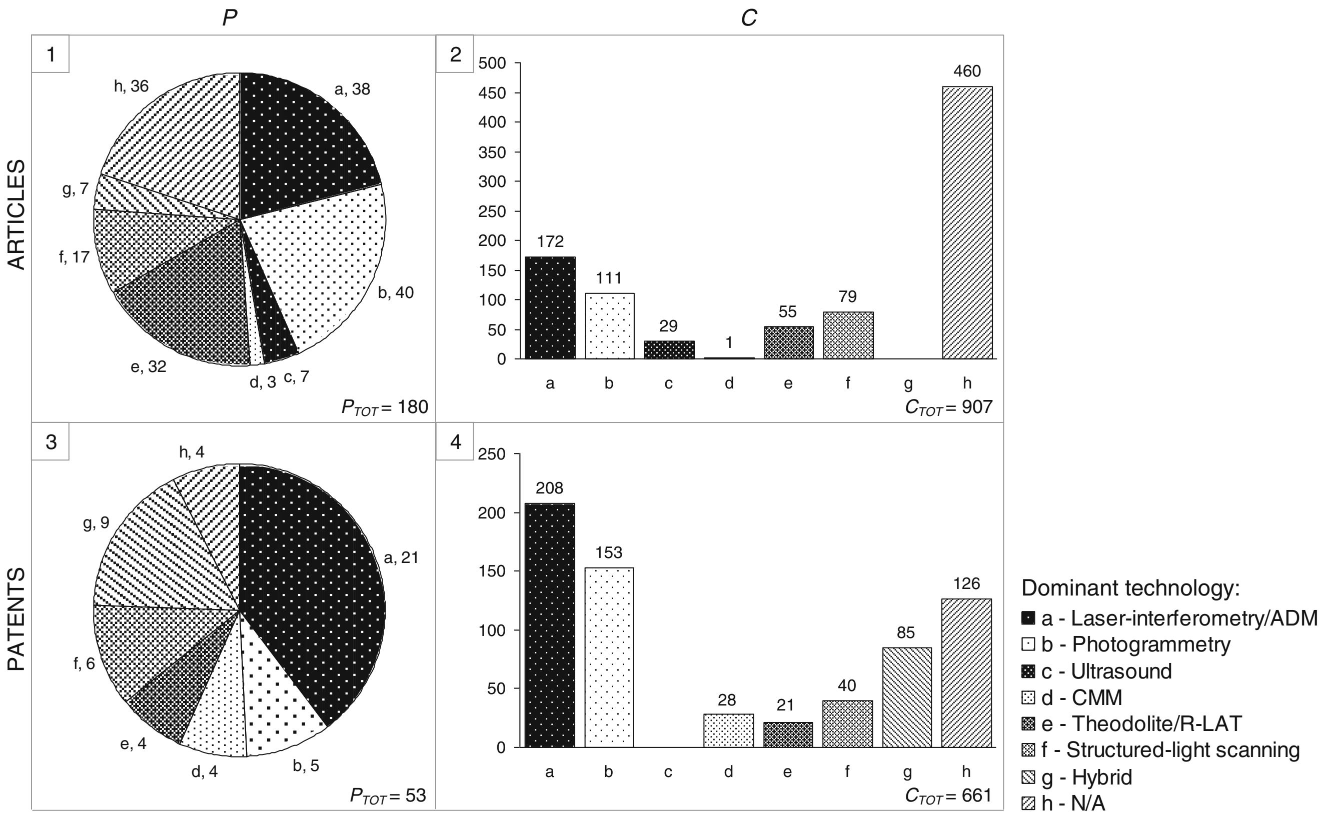

Fig. 1 Charts concerning the distributions of the number of documents (P) and that of the corresponding citations (C), on the basis of the dominant-technology classification. Charts are constructed both for articles (charts (1) and (2)) and patents (charts (3) and (4)). For each chart, it is reported the number of documents/citations in each class

documents concerning classes C–New application/working procedure and F–Performance analysis. There is a relatively low fraction of articles in the classes A–Description of the measuring system and B–New hardware component(s), which concern the construction of new hardware equipment. Not surprisingly, nearly half of the total citations fall in the class G–Literature review (see chart (2)). Excluding this class, the distribution of citations among the remaining classes is quite in line with that of the articles (see chart (1)).

Regarding patents, the first three classes (A–Description of the measuring system, B–New hardware component(s) and C–New application/working procedure) predominate, both from the viewpoint of P and C (see charts (3) and (4)).

The typical industrial sectors in which LSDM systems are used can be identified by examining in more detail the documents in the class C–New application/working procedure. Almost all the patents examined concern the assembly phase of aircrafts. As for articles, nearly half of the applications concern the aircraft industry; other active sectors are those related to the assembly phase of ship hulls and railway equipments, measurement and control of telescope components, part alignment and measurement in specific manufacturing processes (e.g. forming, welding, etc.).

3.1.3 "Technology-typology" maps

The maps in Fig. 3 aggregate the results of the dominant-technology and typology-of-output classifications. Consistently with the results presented in "Sections 3.1.1 and 3.1.2", it can be noticed that, as regards the patents, the densest part of the maps is the upper left-hand side. On the other hand, maps related to articles look more uniform.

3.2 Temporal evolution

3.2.1 Evolution according to the dominant-technology classification

The four diagrams in Fig. 4 depict the temporal collocation of documents and their citations, according to the dominant-technology classification. The reference year for patents is that of the oldest priority date, which is generally close to the date of the invention [21]. Time classes include 3 years; the only exception is represented by the broader first class (i.e. from 1978 to 1992), because of the relatively low number of documents issued in this period.

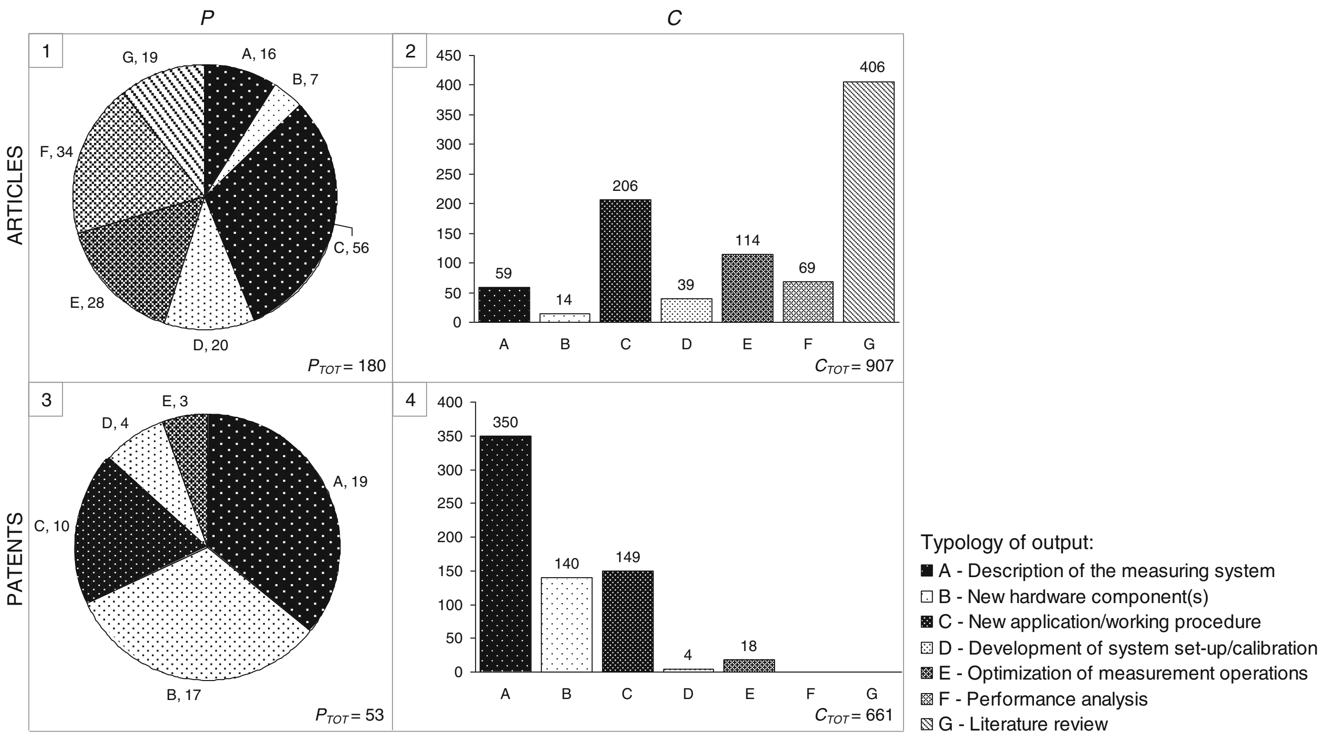

Fig. 2 Charts concerning the distributions of the number of documents (P) and that of the corresponding citations (C), on the basis of the typology-of-output classification. Charts are constructed both for articles (charts (1) and (2)) and patents (charts (3) and (4)). For each chart, it is reported the number of documents/citations in each class

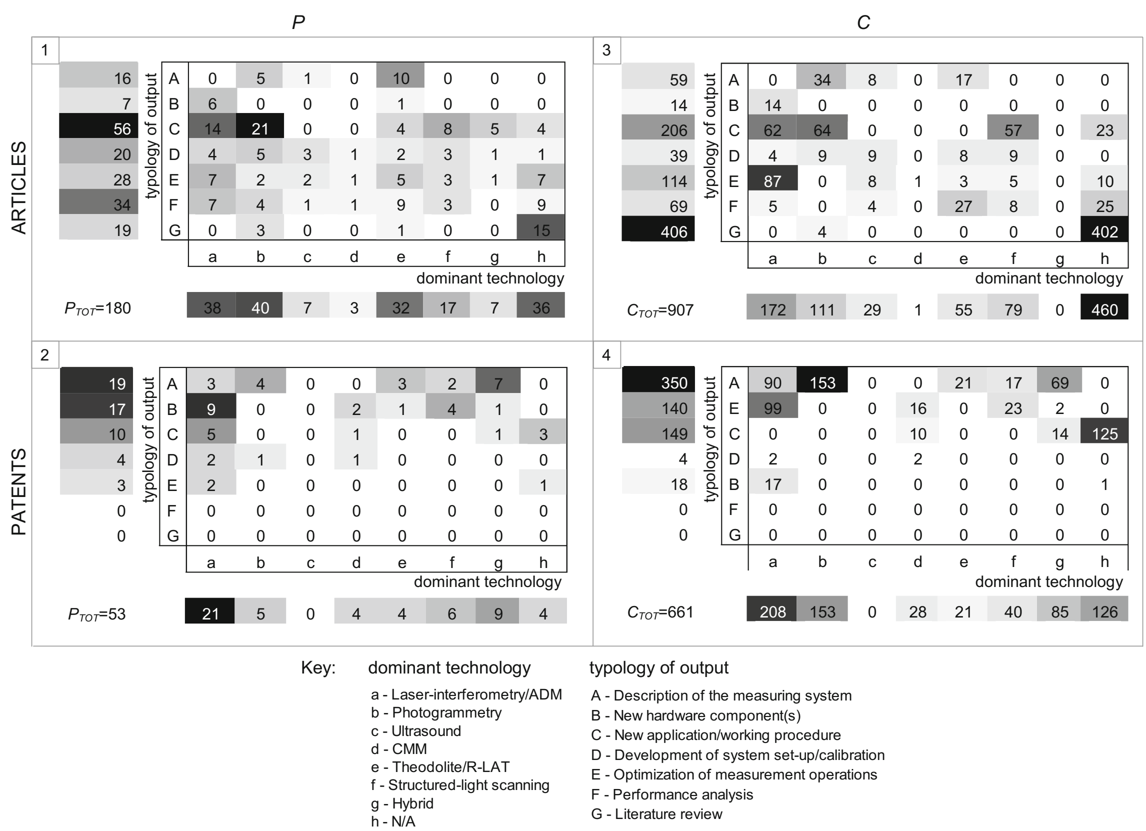

Fig. 3 Maps concerning the partition of documents (P) and citations obtained (C) on the basis of dominant-technology (*horizontal axis*) and typology-of-output (*vertical axis*) classes—both for articles (maps (1) and (3)) and patents (maps (2) and (4)). To ease readability of each map, the grey level of cells is proportional to their numeric value, which represents the number of documents/citations

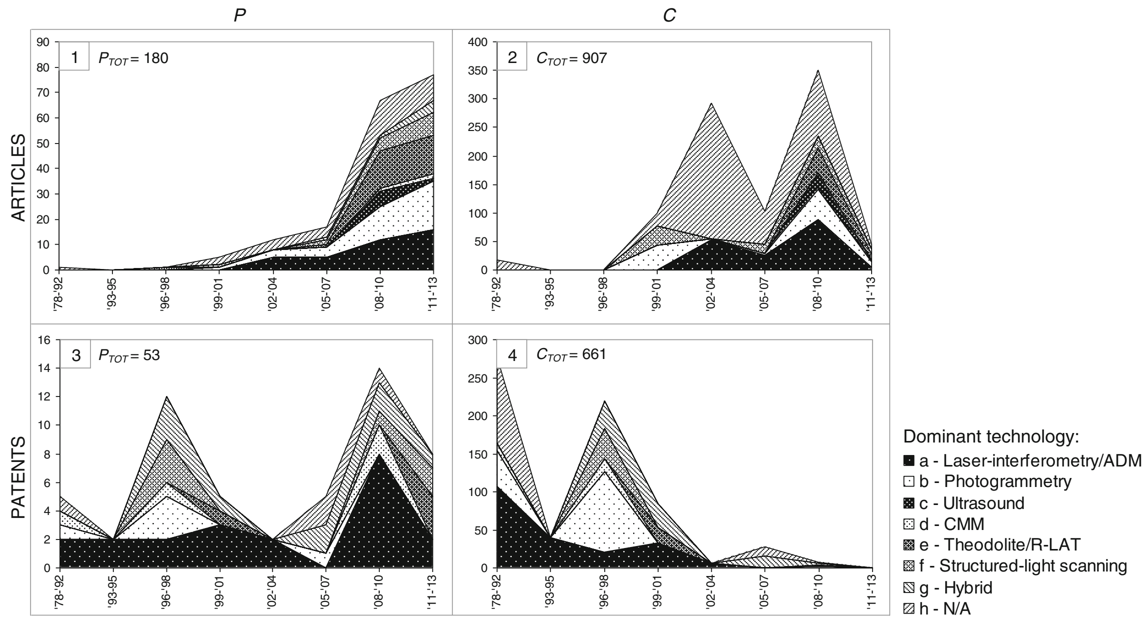

Fig. 4 Temporal distribution of the number of documents (*P*) and the corresponding citations (*C*) on the basis of the dominant-technology classification. Charts are constructed both for articles (charts (1) and (2)) and patents (charts (3) and (4))

Chart (1), relating to the number of articles, shows that there is almost no article before 1996 (apart from Art1 in 1978, see Table 6 in Appendix). Then, there is a gradual rise until 2008; this year signals a sort of explosion in terms of productivity. Consistently with Fig. 1(1), it can be noticed that the article distribution over the dominant-technology classes is relatively even. Of course, the 2008 explosion in the number of articles is partly affected by the general growth of the whole scientific literature in recent years [22]. Nevertheless, this growth is so strong that it seems fairly symptomatic of a real increase of the scientific community's interest towards LSDM research.

Chart (2) in Fig. 4 shows the number of citations obtained up to the moment of data collection (C), by articles issued in different years. We note that the pattern reflects that of the curves in chart (1), except for two features:

- The huge number of citations received by some articles in the class h–N/A and issued in 2002–2004 (see the first local peak in chart (2)). Curiously, most of the citations (i.e. 229) come from three highly cited literature reviews (i.e. Art8, Art11 and Art18, in Table 6), which are independent of a specific technology;
- The fact that the most recent articles (issued in 2011–2013) obtained a few citations, due to the still not complete maturation period of the citation impact [23].

Charts (3) and (4) are similar to the previous ones but referring to patents. Chart (3) shows that a significant amount of patents were issued in the last 15 years of twentieth century, and they are mainly related to the class a–Laser interferometry/ADM. In the first 4–5 years of the twenty-first century, there is a slight decrease in patent production, followed by a powerful growth. This sort of "rebound" effect seems to be in synergy with the impressive growth of scientific articles in the last decade. Also, the numerous patents issued in the end of twentieth century, and the subsequent market entry of new patented technologies may have somehow stimulated the recent growth of scientific articles.

Chart (4), relating to the citations obtained by patents, is quite consistent with chart (3), just before 2005. Instead, the recent growth phase (from 2005 onwards) is almost absent. This behaviour is not surprising: Regarding patents, the maturation time of citation impact is generally much longer than for scientific articles [24].

3.2.2 Evolution according to the typology-of-output classification

The four diagrams in Fig. 5 are similar to those in Fig. 4, but they are about the typology-of-output classification. Consistently with the results presented in "Section 3.1.2", we note that:

- Articles are quite uniformly distributed among the classes, over the years;
- Patents are almost exclusively related to the first three classes (A–Description of the measuring system, B–New hardware component(s) and C–New application/working procedure). We note that, in the last 10 years, there has been a growth of patents in class B and C, to the detriment of those in class A.

A possible interpretation is that innovative LSDM systems were developed about 15–20 years ago, but, due to the engineering-design-process time [25], they began to enter the market and to be studied at academic level in the last

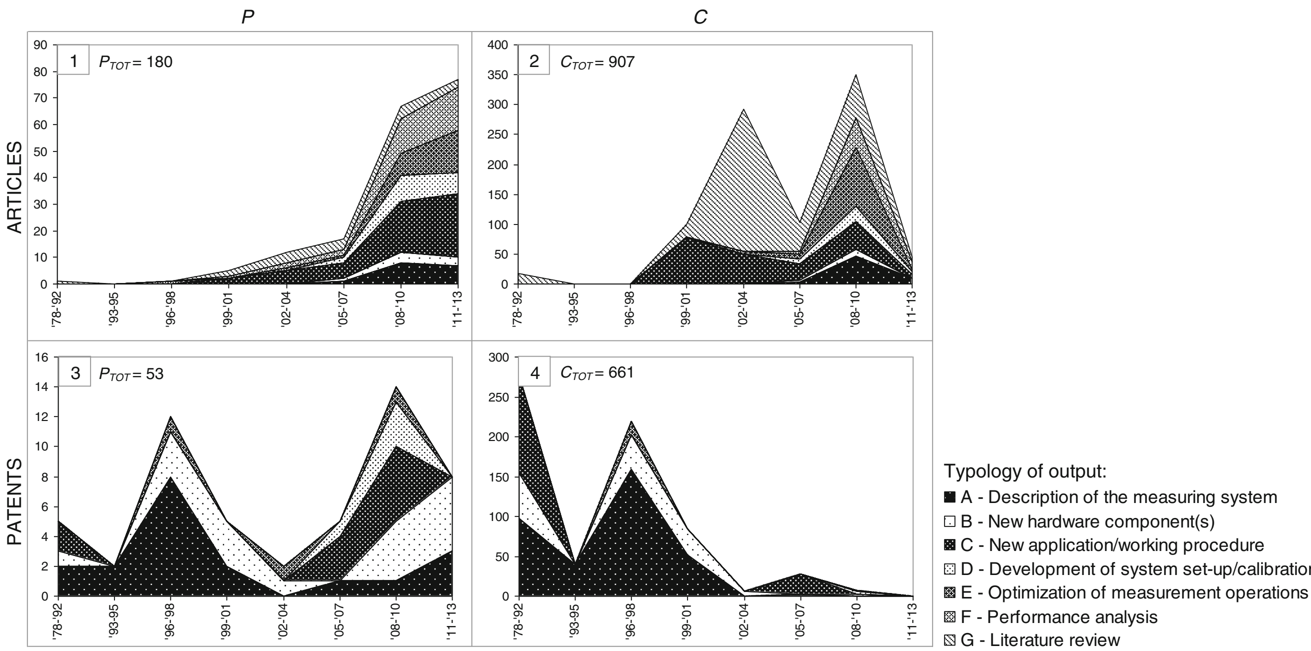

Fig. 5 Temporal distribution of the number of documents (*P*) and the corresponding citations (*C*) on the basis of the typology-of-output classification. Charts are constructed both for articles (charts (1) and (2)) and patents (charts (3) and (4))

10–12 years only. In this recent period, there has been an explosion of new scientific articles and patents aimed at improving and refining these systems.

3.2.3 Trying to predict the near future of LSDM research

After studying the past evolution of the LSDM research, a question may arise: How will it evolve? Answering is not easy because the documents that we examined inevitably reflect the past. This applies to articles and especially patents, since their pending-period (i.e. time lapse between filing date and issue date) is very rarely shorter than 3 years. Also, extrapolating future trends can be hasty because LSDM is a relatively young and unpredictable discipline.

Nevertheless, we will try to outline possible future scenarios, taking into account the results of this study but also the current level of diffusion of LSDM equipments within industrial environments.

The analysis of the documents showed that the major technological innovations stem from a first "wave" of patents, issued in the last decade of twentieth century. Around 10 years later, many of these patented technologies were turned into real measuring systems, which started to be used in industrial contexts and analyzed in scientific articles.

This confirms that it is unlikely that disruptive innovations are introduced to the outside world in the form of scientific articles. Given the obvious strategic and commercial implications, it is customary to protect the most promising innovations with patents or even to keep them secret until they are ready to be transformed into well-established products [26].

The second "wave" of patents, i.e. those deposited roughly in the last 10–12 years, and the simultaneous explosion of scientific articles suggest that the current trend is to gradually improve and refine the available technologies. More precisely, some of the possible research directions are:

1. Development of new hardware components, which enhance the functionality of existing measuring systems (e.g. innovative photogrammetric cameras, 6-DOF probes, etc.).
2. Optimization of measurement procedures, such as enhancing and speeding up the setup/calibration stage of existing measuring systems.
3. Development of new standards aimed at assessing the functionality and performance of existing measuring systems and allowing their verification and comparison. Nowadays, standards on LSDM equipment are very few; for instance, the relatively recent ASME B89.4.19 for laser trackers [27], the German guideline VDI/VDE 2634 for photogrammetry [28] and the relatively well-established ISO 10360 series standards for CMMs [29]. For most of the other systems, standards are absent (e.g. there still is no standard for the emerging R-LAT systems).
4. Development of measurement techniques based on the combined used of LSDM systems of different nature. This requirement originates from a practical reason: In industrial contexts, complex measurements often require the

Table 4 List of the sources (journals and conference proceedings) that contain at least four LSDM articles

	Abbr.	Source title	*P*	*C*	*CPP*
(a) Articles	Src1	*CIRP Annals-Manufacturing Technology*	14	377	26.9
	Src2	*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*	5	56	11.2
	Src3	*International Journal of Computer Integrated Manufacturing*	4	35	8.8
	Src4	*Optics and Lasers in Engineering*	4	29	7.3
	Src5	*Guangxue Xuebao/Acta Optica Sinica*	10	71	7.1
	Src6	*Guangdianzi Jiguang/Journal of Optoelectronics Laser*	6	19	3.2
	Src7	*Precision Engineering*	7	22	3.1
	Src8	*Measurement Science and Technology*	6	14	2.3
	Src9	*International Journal of Advanced Manufacturing Technology*	8	10	1.3
	Src10	*Hongwai yu Jiguang Gongcheng/ Infrared and Laser Engineering*	5	6	1.2
	Src11	*Guangxue Jingmi Gongcheng/ Optics and Precision Engineering*	4	2	0.5
	Src12	*Proceedings of SPIE-The International Society for Optical Engineering*	15	5	0.3
	Src13	*Applied Mechanics and Materials*	4	0	0.0

For each source, its abbreviation ("Abbr."), total number of documents (*P*), total number of citations accumulated up to the moment of data collection (*C*) and average citations per document (*CPP*) are reported. Sources are sorted according to their *CPP* values

Table 5 List of the assignees of at least two LSDM patents

	Abbr.	Assignee	*P*	*C*	*CPP*
(b) PATENTS	Ass1	Motion Games	3	106	35.3
	Ass2	MIT	2	36	18.0
	Ass3	Lawrence Livermore National Security	2	26	13.0
	Ass4	Faro	3	34	11.3
	Ass5	Boeing	4	29	7.3
	Ass6	Nikon	5	21	4.2
	Ass7	Zhejiang University	4	0	0.0

For each assignee, its abbreviation ("Abbr."), total number of documents (*P*), total number of citations accumulated up to the moment of data collection (*C*) and average citations per document (*CPP*) are reported. Assignees are sorted according to their *CPP* values

combined use of multiple measuring systems. As a result, common (hardware and software) platforms that enable sharing and integration of information are essential. In the recent scientific literature, there are several researches aimed at achieving them (e.g. development of systems based on hybrid technologies), although our impression is that this is just the beginning.

3.3 Study of the major scientific journals and patent assignees

Table 4 contains the list of the main sources (journals and conference proceedings) of the articles examined. For each source, it is reported the abbreviation, the total number of articles on LSDM (*P*), the total number of citations they have obtained up to the moment of data collection (*C*) and the average number of citations per paper (CPP). The map in Fig. 6a displays the bibliometric positioning of the sources, according to their *P* and *C* values. Of course, the most influential sources in this field are those that tend to be positioned in the upper-right corner. The dominant source is Src1 (CIRP Annals–Manufacturing Technology), which contains articles presented in a traditional world-class conference

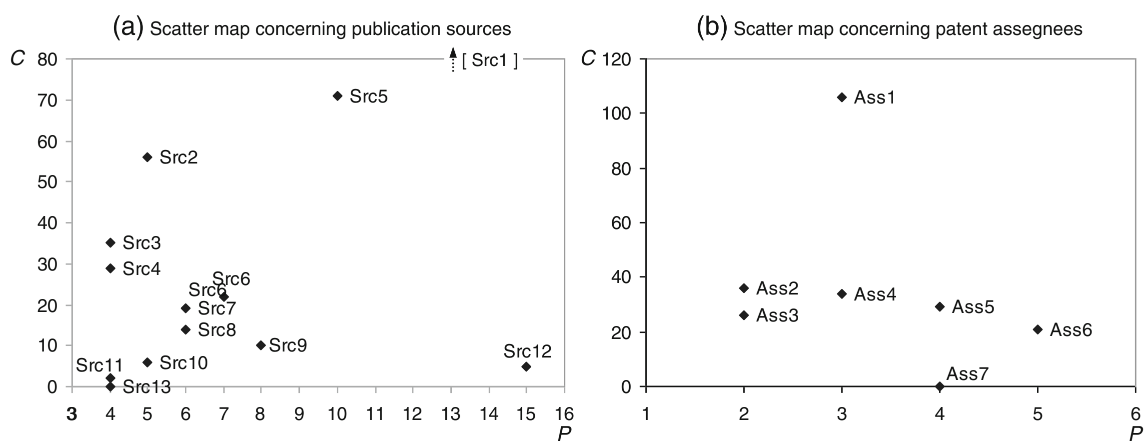

Fig. 6 Scatter maps representing the bibliometric positioning of the sources/assignees reported in Tables 4 and 5, according to their *P* and *C* values. The corresponding *CPP* values are reported in brackets. Abbreviations of sources and assignees are shown in Tables 4 and 5, respectively. Given the high number of citations (377), Src1 falls above the quadrant of map (**a**)

in the field of manufacturing [30]. The vast number of citations is partly due to the fact that 7 out of the 14 articles published by this source are literature reviews with a relatively large diffusion. Src12 is the source with the largest number of articles (i.e. 15), but their citation impact is dramatically low (just five total Citations).

The same analysis can be extended to patents, just replacing article sources with patent assignees. Table 5 shows the list of the assignees of at least two patents. For each assignee, it is also reported the total number of patents (P), the total number of citations they have obtained (C), and the average number of citations per patent (CPP). The map in Fig. 6b displays the bibliometric positioning of the patent assignees, according to their P and C values. Curiously, the most cited patents are those by Ass1 (i.e. Pat13, Pat14 and Pat15, in Table 7), relating to videogame and home-entertainment applications based on photogrammetry or structured-light scanning. We also notice that the list includes important companies in the field of metrology (e.g. Faro and Nikon) and aerospace (Boeing). Finally, it can be seen that some important universities (e.g. MIT and Zhejang University) are assignees of a portion of the patents.

4 Conclusions

The recent evolution of LSDM systems is evidenced by the gradual growth of scientific articles and patents, particularly in the last 10–15 years.

Our study isolated a platform of documents that can be of interest to the reader who approaches LSDM. The combined analysis of scientific articles and patents showed a sort of dualism, summarized in the following points:

- As expected, almost all patents deal with new measurement systems, hardware components and working procedures. As for the articles, apart from literature reviews, the main contributions concern working procedures, performance analysis, development of the system setup/calibration stage and optimization of measurement operations, for existing measuring systems.
- Regarding the temporal collocation, a substantial portion of patents were issued in the last 15 years of twentieth century. On the other hand, most of the articles were issued after 2004. It appears clear that articles followed the evolution of patents, probably after the new (patented) technologies became available on the market.
- Referring to the dominant-technology classification, it is observed that scientific articles are distributed quite uniformly among the major available technologies. On the contrary, patents are polarized primarily on the laser-interferometry technology, followed by other more affordable ones, but with lower accuracy, i.e. photogrammetry and structured-light scanning. Probably, the future evolution of these emerging technologies will make them more competitive… time will tell! Another impression we experienced is that academic research is probably more focused on developing affordable measurement systems, while the most expensive and accurate ones are mainly designed and refined by companies who have the resources for developing, engineering and marketing them.

A limitation of this work is the data collection procedure, which, although being meticulous and transparent, is not free from the risk of omitting a portion of LSDM documents (i.e. relevant documents that are not indexed by the databases in use or do not meet the search query). This risk is even larger for patents, since their language is sometimes captious and can complicate the searching by keywords [31]. Future research could be aimed at extending the portfolio of documents potentially related to LSDM, by analyzing those that cite or are cited by other ones.

Appendix

Table 6 List of the papers selected for the analysis

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art1	Puttock	1978	Large-scale metrology	*CIRP Annals-Manufacturing Technology*	h	G	17
Art2	Ding and Coleman	1996	Adjustment of precision metrology networks in three dimension	*Survey Review*	e	E	0
Art3	Li et al.	2000	Phase-measuring profilometry in large scale measurement	*Guangxue Xuebao/Acta Optica Sinica*	f	C	34

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art4	Clarke et al.	2001	Performance verification for large volume metrology systems	*Laser Metrology and Machine Performance V*	h	F	1
Art5	Li et al.	2001	Large-scale three-dimensional object measurement: A practical coordinate mapping and image data-patching method	*Applied Optics*	b	C	43
Art6	Peters et al.	2001	Contribution of CIRP to the development of metrology and surface quality evaluation during the last fifty years	*CIRP Annals-Manufacturing Technology*	h	G	17
Art7	Swyt	2001	Length and dimensional measurements at NIST	*Journal of Research of the National Institute of Standards and Technology*	h	G	5
Art8	Estler et al.	2002	Large-scale metrology—an update	*CIRP Annals-Manufacturing Technology*	h	G	61
Art9	Saadat and Cretin	2002	Dimensional variations during Airbus wing assembly	*Assembly Automation*	a	C	8
Art10	Saadat and Cretin	2002	Measurement systems for large aerospace components	*Sensor Review*	h	G	9
Art11	Schwenke et al.	2002	Optical methods for dimensional metrology in production engineering	*CIRP Annals-Manufacturing Technology*	h	G	63
Art12	Brown et al.	2003	Recent work at NML to establish traceability for survey electronic distance measurement (EDM)	*Proceedings of SPIE-The International Society for Optical Engineering*	a	F	0
Art13	Jones et al.	2003	Laser Induced Fluorescence for Photogrammetric Measurement of Transparent or Reflective Aerospace Structures	*Proceedings of the International Instrumentation Symposium*	b	C	1
Art14	Kruth et al.	2003	Behaviour and accuracy specification - Study on an LED-CMOS camera 3D measuring system	*Laser Metrology and Machine Performance VI*	b	F	0
Art15	Maropoulos	2003	Digital enterprise technology - Defining perspectives and research priorities	*International Journal of Computer Integrated Manufacturing*	a	C	31
Art16	Maropoulos et al.	2003	A novel digital enterprise technology framework for the distributed development and validation of complex products	*CIRP Annals-Manufacturing Technology*	a	C	9
Art17	Zhang et al.	2003	A study on the optimal design of laser-based multi-lateration systems	*CIRP Annals-Manufacturing Technology*	a	E	5
Art18	Weckenmann et al.	2004	Probing systems in dimensional metrology	*CIRP Annals-Manufacturing Technology*	h	G	105
Art19	Yang and Cheng	2004	Application of photogrammetric technique to astronomical telescope measurement and control	*Proceedings of SPIE-The International Society for Optical Engineering*	b	C	0
Art20	Aguilar et al.	2005	Development of a stereo vision system for non-contact railway concrete sleepers measurement based in holographic optical elements	*Measurement: Journal of the International Measurement Confederation*	f	C	8
Art21	Balsamo et al.	2005	A portable stereovision system for cultural heritage monitoring	*CIRP Annals-Manufacturing Technology*	b	A	3

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art22	Canning et al.	2005	Uncertainty of spatial coordinate measurements using trilateration	*Transactions of the North American Manufacturing Research Institute of SME*	h	F	1
Art23	Jeffery	2005	Right first time	*Engineering*	e	G	0
Art24	Parker	2005	Multidirectional retroreflector assembly with a common virtual reflection point using four-mirror retroreflectors	*Precision Engineering*	a	B	3
Art25	Schwenke and Wendt	2005	Technologies for co-ordinate metrology	*VDI Berichte*	h	G	0
Art26	Shih and Lo	2005	Photogrammetry technique for 3-D model extraction - Processing of a wind tunnel test video data	*Conference Proceedings of the Society for Experimental Mechanics Series*	b	C	0
Art27	Zhang et al.	2005	Modelling and optimization of novel laser multilateration schemes for high-precision applications	*Measurement Science and Technology*	a	E	7
Art28	Cheok and Lytle	2006	Performance evaluation of 3D imaging systems	*Standardization News*	b	G	0
Art29	Maropoulos et al.	2006	Integration of measurement planning with aggregate product modelling for spacecraft design and assembly	*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*	h	C	8
Art30	Ouyang et al.	2006	Research of measuring accuracy of laser tracker system	*Proceedings of SPIE-The International Society for Optical Engineering*	a	F	4
Art31	Tournier et al.	2006	Estimation and control of a quadrotor vehicle using monocular vision and moiré patterns	*AIAA Guidance, Navigation, and Control Conference 2006*	g	C	0
Art32	Wang et al.	2006	High precision large scale metrology using a chirped laser pulse	*Proceedings of SPIE-The International Society for Optical Engineering*	a	C	0
Art33	Maropoulos et al.	2007	Key digital enterprise technology methods for large volume metrology and assembly integration	*International Journal of Production Research*	a	C	12
Art34	Parian et al.	2007	Network and system design for a photogrammetric measurement of large space structures using projected light spots targeting approach	*European Space Agency*	b	D	0
Art35	Savio et al.	2007	Metrology of freeform shaped parts	*CIRP Annals-Manufacturing Technology*	h	G	49
Art36	Zhou et al.	2007	Calibrating double sensors laser vision measurement system	*Guangdianzi Jiguang/Journal of Optoelectronics Laser*	f	D	8
Art37	Maisano et al.	2008	Indoor GPS: System functionality and initial performance evaluation	*International Journal of Manufacturing Research*	e	F	21
Art38	Maropoulos et al.	2008	Large volume metrology process models: A framework for integrating measurement with assembly planning	*CIRP Annals-Manufacturing Technology*	h	C	8
Art39	Muralikrishnan et al.	2008	Performance evaluation of laser trackers	*PerMIS 2008*	a	F	0
Art40	Wu et al.	2008	A novel calibration method for large-scale stereo vision sensor based on one-dimensional target	*Proceedings of SPIE-The International Society for Optical Engineering*	b	D	0

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art41	Ye et al.	2008	Status and development of large-scale coordinate measurement research	*Jiliang Xuebao/Acta Metrologica Sinica*	h	G	7
Art42	Zhang et al.	2008	Development of measurement system for accuracy control in subsection manufacture	*Key Engineering Materials*	a	C	0
Art43	Zhang et al.	2008	Large-scale space angle measurement	*CIRP Annals-Manufacturing Technology*	f	C	2
Art44	Zhang et al.	2008	A method of precision evaluation for field large-scale measurement	*Guangxue Xuebao/Acta Optica Sinica*	h	E	6
Art45	Zhang et al.	2008	Quantity traceability in large-scale measurement in situ	*Journal of Tianjin University Science and Technology*	h	E	2
Art46	Zhang et al.	2008	Evaluation of uncertainty in large-scale fusion metrology	*Proceedings of SPIE-The International Society for Optical Engineering*	h	F	0
Art47	Coddington et al.	2009	Rapid and precise absolute distance measurements at long range	*Nature Photonics*	a	E	74
Art48	Cuypers et al.	2009	Optical measurement techniques for mobile and large-scale dimensional metrology	*Optics and Lasers in Engineering*	b	A	28
Art49	Franceschini et al.	2009	Mobile Spatial coordinate Measuring System (MScMS) - Introduction to the system	*International Journal of Production Research*	c	A	8
Art50	Franceschini et al.	2009	The problem of distributed wireless sensors positioning in the mobile spatial coordinate measuring system (MSCMS)	*ESDA 2008*	c	D	0
Art51	Franceschini et al.	2009	On-line diagnostics in the Mobile Spatial coordinate Measuring System (MScMS)	*Precision Engineering*	c	E	7
Art52	Franceschini et al.	2009	Mobile spatial coordinate measuring system (MScMS) and CMMs: A structured comparison	*International Journal of Advanced Manufacturing Technology*	h	F	4
Art53	Galetto et al.	2009	An innovative indoor coordinate measuring system for large-scale metrology based on a distributed IR sensor network	*MSEC2009*	b	A	2
Art54	Liu et al.	2009	Improved scheme and mathematical model for measuring the time-of-flight in pulse laser ranging	*Guangdianzi Jiguang/Journal of Optoelectronics Laser*	a	C	1
Art55	Lv et al.	2009	Data fusion algorithm for high accuracy coordinate transformation	*Proceedings of SPIE-The International Society for Optical Engineering*	a	E	1
Art56	Maisano et al.	2009	A comparison of two distributed large-volume measurement systems: The mobile spatial co-ordinate measuring system and the indoor global positioning system	*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*	h	F	14
Art57	Mao et al.	2009	Analysis on optical coordinate measurement based on phase target	*Guangxue Xuebao/Acta Optica Sinica*	b	D	9
Art58	Martin and Chetwynd	2009	Angle calibration of robotic total stations and laser trackers	*IMEKO 2009*	h	D	0
Art59	Neuschaefer-Rube et al.	2009	Test procedures and artefacts for optical coordinate metrology	*Proceedings of SPIE-The International Society for Optical Engineering*	a	D	0
Art60	Peggs et al.	2009	Recent developments in large-scale dimensional metrology	*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*	h	G	24

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art61	Pollinger et al.	2009	Diode-laser-based high-precision absolute distance interferometer of 20m range	*Applied Optics*	a	B	11
Art62	Qu et al.	2009	Application study on laser ranging in large-scale measurement	*Chinese Journal of Scientific Instrument*	a	C	1
Art63	Ren et al.	2009	Study on portable optical 3D coordinate measuring system	*Proceedings of SPIE-The International Society for Optical Engineering*	b	A	0
Art64	Swann et al.	2009	Absolute ranging using frequency combs	*CLEO/QELS 2009*	a	B	0
Art65	Tang et al.	2009	Three-dimensional shape measurement of aspheric mirror based on fringe reflection	*Guangxue Xuebao/Acta Optica Sinica*	f	C	5
Art66	Wang et al.	2009	Three-dimensional measurement of object in water by tracking phase value	*Guangxue Xuebao/Acta Optica Sinica*	f	C	2
Art67	Weckenmann et al.	2009	Multisensor data fusion in dimensional metrology	*CIRP Annals-Manufacturing Technology*	h	G	37
Art68	Zhou and Cheng	2009	Study on wide-range device for high precision measurement	*Bandaoti Guangdian/Semiconductor Optoelectronics*	a	B	0
Art69	Zhu et al.	2009	Principle and implementation method of three-dimensional precision positioning in large field working space	*Guangxue Xuebao/Acta Optica Sinica*	b	C	10
Art70	Cai et al.	2010	An algorithm for computing extrinsic camera parameters for far-range photogrammetry based on essential matrix	*Proceedings of SPIE-The International Society for Optical Engineering*	b	D	0
Art71	Domboski et al.	2010	Design of a multi-function vector bar	*DETC2009*	e	B	0
Art72	Ferri et al.	2010	Sources of variability in the set-up of an indoor GPS	*International Journal of Computer Integrated Manufacturing*	e	D	3
Art73	Forbes A.	2010	CMM uncertainty and conformance assessment	*ENBIS-IMEKO TC21 2010*	d	F	0
Art74	Franceschini et al.	2010	An unmanned aerial vehicle-based system for large scale metrology applications	*International Journal of Production Research*	b	C	1
Art75	Franceschini et al.	2010	Ultrasound transducers for large-scale metrology: A performance analysis for their use by the MScMS	*IEEE Transactions on Instrumentation and Measurement*	c	F	4
Art76	Galetto and Pralio	2010	Optimal sensor positioning for large scale metrology applications	*Precision Engineering*	c	D	7
Art77	Galetto et al.	2010	Indoor environmental mapping by means of autonomous guided agents	*ESDA2010*	b	C	1
Art78	Galetto et al.	2010	A wireless sensor network-based approach to large-scale dimensional metrology	*International Journal of Computer Integrated Manufacturing*	b	C	1
Art79	Galetto et al.	2010	The Mobile Spatial coordinate Measuring System II (MScMS-II): System description and preliminary assessment of the measurement uncertainty	*ENBIS-IMEKO TC21 2012*	b	F	0
Art80	Geng et al.	2010	Analysis of angle measurement uncertainty for wMPS	*Proceedings of SPIE-The International Society for Optical Engineering*	e	F	0

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art81	Jamshidi et al.	2010	Manufacturing and assembly automation by integrated metrology systems for aircraft wing fabrication	*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*	h	C	6
Art82	Koelman	2010	Application of a photogrammetry-based system to measure and re-engineer ship hulls and ship parts: An industrial practices-based report	*CAD Computer Aided Design*	b	C	2
Art83	Liu et al.	2010	Mobile large scale 3D coordinate measuring system based on network of rotating laser automatic theodolites	*Proceedings of SPIE-The International Society for Optical Engineering*	e	A	0
Art84	Liu et al.	2010	Position and orientation measurement for large-size workpiece based on binocular vision	*Proceedings of SPIE-The International Society for Optical Engineering*	e	C	0
Art85	Liu et al.	2010	A large scale 3D positioning method based on a network of rotating laser automatic theodolites	*ICIA 2010*	e	E	2
Art86	Martin D.	2010	Instrument calibration at the european synchrotron radiation facility	*ENBIS-IMEKO TC21 2011*	g	C	0
Art87	Mastrogiacomo and Maisano	2010	Network localization procedures for experimental evaluation of mobile spatial coordinate measuring system (MScMS)	*International Journal of Advanced Manufacturing Technology*	c	D	2
Art88	Muelaner et al.	2010	Estimation of uncertainty in three-dimensional coordinate measurement by comparison with calibrated points	*Measurement Science and Technology*	e	F	3
Art89	Muelaner et al.	2010	Large-volume metrology instrument selection and measurability analysis	*Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*	h	G	4
Art90	Predmore	2010	Bundle adjustment of multi-position measurements using the Mahalanobis distance	*Precision Engineering*	h	F	4
Art91	Schmitt et al.	2010	Performance evaluation of iGPS for industrial applications	*IPIN 2010*	e	F	0
Art92	Schneider	2010	Requirements for positioning and navigation in underground constructions	*IPIN 2010*	h	G	0
Art93	Schwendemann et al.	2010	Indoor navigation of machines and measuring devices with iGPS	*IPIN 2010*	e	C	0
Art94	Wang et al.	2010	3-D shape measurement for isolated objects based on color-encoded fringe projection	*Guangdianzi Jiguang/Journal of Optoelectronics Laser*	f	E	5
Art95	Wanli and Zhankui	2010	New method for large-scale dimensional metrology using laser tracker system	*Advanced Materials Research*	a	C	0
Art96	Wendt et al.	2010	Mobile multi-lateration measuring system for high accurate and traceable 3D measurements of large objects	*ISMQC 2010*	a	C	0
Art97	Xie et al.	2010	Underwater line structured-light self-scan three-dimension measuring technology	*Chinese Journal of Lasers*	f	C	6

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art98	Yang et al.	2010	Novel method for spatial angle measurement based on rotating planar laser beams	*Chinese Journal of Mechanical Engineering*	e	A	5
Art99	Yang et al.	2010	Large-scale coordinates measurement method based on intersection of optical planes	*Hongwai yu Jiguang Gongcheng/ Infrared and Laser Engineering*	e	A	4
Art100	Yang et al.	2010	Error analysis of workspace measurement positioning system based on optical scanning	*Guangdianzi Jiguang/Journal of Optoelectronics Laser*	e	E	1
Art101	Yang et al.	2010	Evaluating the accuracy of large scale vision measurement by fitting point	*Journal of Huazhong University of Science and Technology*	b	F	0
Art102	Zhang et al.	2010	In-situ optical measurement of separation angles between bifacial lines in large scale space	*Proceedings of SPIE-The International Society for Optical Engineering*	e	A	0
Art103	Zhang et al.	2010	The design of double-theodolite 3D coordinate measurement system	*Chinese Journal of Sensors and Actuators*	e	D	5
Art104	Duanmu et al.	2011	3D coordinate measurement system based on optoelectronic scanning	*Hongwai yu Jiguang Gongcheng/ Infrared and Laser Engineering*	e	A	1
Art105	Galetto et al.	2011	MScMS-II: An innovative IR-based indoor coordinate measuring system for large-scale metrology applications	*International Journal of Advanced Manufacturing Technology*	b	A	1
Art106	Gao et al.	2011	Precision measurement technology of 3D surfaces	*Hongwai yu Jiguang Gongcheng/ Infrared and Laser Engineering*	a	F	0
Art107	Geng et al.	2011	Key techniques on rotating laser plane coordinate measuring system	*Hongwai yu Jiguang Gongcheng/ Infrared and Laser Engineering*	e	A	1
Art108	Geng et al.	2011	Research on angle measurement uncertainty of wMPS	*Guangdian Gongcheng/Opto-Electronic Engineering*	e	F	1
Art109	Gonzalez-Jorge et al.	2011	Standard artifact for the geometric verification of terrestrial laser scanning systems	*Optics and Laser Technology*	f	F	6
Art110	Hughes et al.	2011	Laser tracker error determination using a network measurement	*Measurement Science and Technology*	a	D	3
Art111	Lao et al.	2011	Optimization of calibration method for scanning planar laser coordinate measurement system	*Guangxue Jingmi Gongcheng/Optics and Precision Engineering*	f	D	1
Art112	Liu et al.	2011	3D auto-inspection for large thin-wall object	*Guangxue Xuebao/Acta Optica Sinica*	b	C	1
Art113	Maropoulos et al.	2011	Early design verification of complex assembly variability using a Hybrid-Model Based and Physical Testing-Methodology	*CIRP Annals-Manufacturing Technology*	h	E	1
Art114	Mbarek et al.	2011	Positioning System for the Aircraft Structural Assembly	*SAE International Journal of Aerospace*	a	C	0
Art115	Often et al.	2011	Multiple-camera instrumentation of a single point incremental forming process pilot for shape and 3D displacement measurements: Methodology and results	*Proceedings of the Society for Experimental Mechanics*	b	C	3

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art116	Orteu et al.	2011	Multiple-Camera Instrumentation of a Single Point Incremental Forming Process Pilot for Shape and 3D Displacement Measurements: Methodology and Results	*Experimental Mechanics*	b	C	0
Art117	Peng et al.	2011	Phase-aided three-dimensional imaging and metrology	*Guangxue Xuebao/Acta Optica Sinica*	b	G	4
Art118	Ruther et al.	2011	Kinect: On using a gaming RGBD camera in micro-metrology applications	*IEEE CVPRW 2011*	f	D	0
Art119	Shi et al.	2011	Half century of coordinate metrology technology - Evolution and trends	*Journal of Beijing University of Technology*	h	G	4
Art120	Sun et al.	2011	A calibration method for stereo vision sensor with large FOV based on 1D targets	*Optics and Lasers in Engineering*	b	C	1
Art121	Von Enzberg et al.	2011	A physical simulation approach for active photogrammetric 3D measurement systems	*IEEE Instrumentation and Measurement Technology Conference*	b	F	0
Art122	Wang et al.	2011	High accuracy mobile robot positioning using external large volume metrology instruments	*International Journal of Computer Integrated Manufacturing*	e	C	0
Art123	Wang et al.	2011	Experimental comparison of dynamic tracking performance of iGPS and laser tracker	*International Journal of Advanced Manufacturing Technology*	e	F	2
Art124	Wang et al.	2011	Impact of attitude deviations on laser point cloud of airborne LiDAR	*Chinese Journal of Scientific Instrument*	f	F	1
Art125	Zhang et al.	2011	Laser automatic theodolite measurement system based on vision guidance	*Guangdianzi Jiguang/Journal of Optoelectronics Laser*	e	A	4
Art126	Zhong et al.	2011	Calibration algorithm of structure parameters in combined large-scale 3D metrology system	*Journal of Tianjin University Science and Technology*	g	D	0
Art127	Ziegler and Franke	2011	A cost-effective stereo camera system for online pose control of patient handling robots	*ICARA 2011*	b	C	0
Art128	Bian et al.	2012	3D coordinate measurement based on inverse photogrammetry and fringe analysis	*Optik*	g	C	0
Art129	Boerez et al.	2012	Analysis and filtering of the effect of tides on the hydrostatic levelling systems at CERN	*Survey Review*	h	F	0
Art130	Brinksmeier et al.	2012	Diamond Micro Chiseling of large-scale retroreflective arrays	*Precision Engineering*	a	B	0
Art131	Cao et al.	2012	Application of Gerchberg iterative algorithm in three-dimensional shape measurement	*Guangxue Jishu/Optical Technique*	f	E	0
Art132	Cuesta et al.	2012	Feasibility evaluation of Photogrammetry versus Coordinate Measuring Arms for the assembly of welded structures	*Advanced Materials Research*	b	C	0
Art133	Du et al.	2012	Precision analysis of iGPS measurement field and its application	*Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica*	e	F	0

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art134	Duanmu et al.	2012	Study on tracking algorithm for wMPS based on least square-Kalman filter	*Chinese Journal of Sensors and Actuators*	e	E	0
Art135	Flynn	2012	Synthesizing Metrology Technologies to Reduce Engineering Time for Large CNC Machine Compensation	*SAE International Journal of Materials and Manufacturing*	d	D	0
Art136	Forbes	2012	Weighting observations from multi-sensor coordinate measuring systems	*Measurement Science and Technology*	a	E	0
Art137	Gomez-Acedo et al.	2012	A method for thermal characterization and modeling of large gantry-type machine tools	*International Journal of Advanced Manufacturing Technology*	d	E	1
Art138	Gonzalez-Jorge et al.	2012	Photogrammetry and laser scanner technology applied to length measurements in car testing laboratories	*Measurement: Journal of the International Measurement Confederation*	h	F	1
Art139	He et al.	2012	High-precision automatic measurement of two-dimensional geometric features based on machine vision	*Journal of Southeast University*	b	C	0
Art140	Hu et al.	2012	Measurement of large-scale space angle formed by non-uniplanar lines	*Guangxue Jingmi Gongcheng/Optics and Precision Engineering*	f	C	0
Art141	Hu et al.	2012	A novel color fringe projection method for 3D measurement of colorful objects	*Guangxue Xuebao/Acta Optica Sinica*	f	C	0
Art142	Kampke et al.	2012	Navigation in landmark networks	*Springer Tracts in Advanced Robotics*	h	E	0
Art143	Lee et al.	2012	Precision measurement of carriage slide motion error of a drum roll lathe	*Precision Engineering*	h	C	1
Art144	Li et al.	2012	Laser coarse-fine coupling scanning method by steering double prisms	*Applied Optics*	e	A	2
Art145	Lin et al.	2012	Field evaluation of laser tracker angle measurement error	*Chinese Journal of Scientific Instrument*	a	F	0
Art146	Liu et al.	2012	Automatic registration of range images combined with the system calibration and global ICP	*Proceedings of SPIE - The International Society for Optical Engineering*	b	C	0
Art147	Liu et al.	2012	Photogrammetric techniques for aerospace applications	*Progress in Aerospace Sciences*	b	G	0
Art148	Muelaner et al.	2012	Verification of the indoor GPS system, by comparison with calibrated coordinates and by angular reference	*Journal of Intelligent Manufacturing*	e	F	0
Art149	Nasr et al.	2012	ASME B89.4.19 standard for laser tracker verification - Experiences and optimisations	*International Journal of Metrology and Quality Engineering*	a	F	0
Art150	Ni and Zheng	2012	Optimal configuration method for large-scale measurement systems based on form error uncertainty	*Jiliang Xuebao/Acta Metrologica Sinica*	h	E	1
Art151	Pollinger et al.	2012	The upgraded PTB 600 m baseline: A high-accuracy reference for the calibration and the development of long distance measurement devices	*Measurement Science and Technology*	a	D	0

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
Art152	Pollinger et al.	2012	Effective humidity in length measurements: Comparison of three approaches	*Measurement Science and Technology*	a	F	1
Art153	Samper et al.	2012	A stereo-vision system to automate the manufacture of a semitrailer chassis	*International Journal of Advanced Manufacturing Technology*	b	C	0
Art154	Sanchez-Lasheras et al.	2012	Study of the technical feasibility of photogrammetry and coordinated measuring arms for the inspection of welded structures	*AIP 2012*	b	C	0
Art155	Santolaria et al.	2012	Laser tracker-based kinematic parameter calibration of industrial robots by improved CPA method and active retroreflector	*International Journal of Advanced Manufacturing Technology*	a	C	0
Art156	Shi et al.	2012	High-speed measurement algorithm for the position of holes in a large plane	*Optics and Lasers in Engineering*	b	C	0
Art157	Stiros	2012	Levelling in antiquity: Instrumentation, techniques and accuracies	*Survey Review*	h	F	0
Art158	Wendt et al.	2012	Measuring large 3D structures using four portable tracking laser interferometers	*Measurement: Journal of the International Measurement Confederation*	a	C	0
Art159	Wu et al.	2012	On-line three-dimensional inspection based on orthogonal two-frequency grating projection	*Chinese Journal of Lasers*	f	E	0
Art160	Xiong et al.	2012	Workspace measuring and positioning system based on rotating laser planes	*Mechanika*	e	A	0
Art161	Xiong et al.	2012	Verification of horizontal angular survey performance for workspace measuring and positioning system	*Guangdianzi Jiguang/Journal of Optoelectronics Laser*	e	F	0
Art162	Yang et al.	2012	Distributed optical sensor network with self-monitoring mechanism for accurate indoor location and coordinate measurement	*Applied Mechanics and Materials*	e	A	0
Art163	Yang et al.	2012	Orientation method for workspace measurement positioning system based on scale bar	*Journal of Tianjin University Science and Technology*	b	E	0
Art164	Yang et al.	2012	Correction method for orientation parameters of workspace measurement positioning system	*Hongwai yu Jiguang Gongcheng/Infrared and Laser Engineering*	e	E	0
Art165	Yu and Pan	2012	Camera internal-parameters calibration based on the construction of initial measurement network	*Guangxue Xuebao/Acta Optica Sinica*	b	D	0
Art166	Zatarain et al.	2012	Raw part characterisation and automated alignment by means of a photogrammetric approach	*CIRP Annals-Manufacturing Technology*	b	C	0
Art167	Zhang and Qu	2012	Fusion estimation of point sets from multiple stations of spherical coordinate instruments utilizing	*Measurement Science Review*	a	C	0

Table 6 (continued)

Ref. no.	Author(s)	Year	Title	Source title	Techn.	Typ.	Cites
			uncertainty estimation based on Monte Carlo				
Art168	Zhang et al.	2012	Design and implementation of software system for large-scale coordinate measurement based on the laser tracker	*Applied Mechanics and Materials*	a	E	0
Art169	Zhou et al.	2012	Dynamic length measuring system for large scale workpieces	*Guangxue Jingmi Gongcheng/Optics and Precision Engineering*	g	C	0
Art170	Zhou et al.	2012	Application of bundle adjustment to accuracy evaluation of laser tracker	*Guangxue Jingmi Gongcheng/Optics and Precision Engineering*	a	D	1
Art171	Zhu and Zheng	2012	Multiple-objective optimization algorithm based on key assembly characteristics to posture best fit for large component assembly	*Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica*	h	E	0
Art172	Galetto and Mastrogiacomo	2013	Corrective algorithms for measurement improvement in MScMS-II (mobile spatial coordinate measurement system)	*Precision Engineering*	b	E	0
Art173	Gholami et al.	2013	An artificial neural network approach to the problem of wireless sensors network localization	*Robotics and Computer-Integrated Manufacturing*	c	E	1
Art174	Jiawen et al.	2013	An analysis model for structural optimization of polygon ranging-based space coordinate measurement network	*Applied Mechanics and Materials*	h	E	0
Art175	Liu et al.	2013	3D measurement and quality evaluation for complex aircraft assemblies	*Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica*	g	C	0
Art176	Ma et al.	2013	Non-diffracting beam based probe technology for measuring coordinates of hidden parts	*Optics and Lasers in Engineering*	a	B	0
Art177	Norman et al.	2013	Validation of iGPS as an external measurement system for cooperative robot positioning	*International Journal of Advanced Manufacturing Technology*	e	C	0
Art178	Senin et al.	2013	Point set augmentation through fitting for enhanced ICP registration of point clouds in multisensor coordinate metrology	*Robotics and Computer-Integrated Manufacturing*	g	E	0
Art179	Wang et al.	2013	Flash sliver prevents laser penetrating organic materials	*Applied Mechanics and Materials*	a	E	0
Art180	Wang et al.	2013	Evaluate error sources and uncertainty in large scale measurement systems	*Robotics and Computer-Integrated Manufacturing*	f	F	1

Articles are sorted by issue year ("Year") and author name ("Author(s)"). Sources are journals or conference proceedings indexed by the Scopus database. For each article, also reported are the dominant-technology class ("Techn.") and the typology-of-output class ("Typ."), according to the classifications in Tables 2 and 3

Table 7 List of the patents selected for the analysis

Ref. no.	Publ. no.	Year	Title	Assignee(s)	Techn.	Typ.	Cites
Pat1	JP60233581	1984	Frequency modulated laser radar	Digital Optronics et al.	a	E	57
Pat2	DE3640287	1986	Method of producing a common system of coordinates in the case of multi-armed coordinate measuring instruments	Zeiss	d	C	10
Pat3	EP-290809	1987	Integrated assembly system	Northrop Grumman	h	C	113
Pat4	US4714339	1987	Three- and five-axes laser tracking systems	US Department of Commerce	a	A	50
Pat5	NO9103994	1991	Method and system for point by point measurement of spatial coordinates	Metronor	b	A	47
Pat6	GB9400066	1994	Optical coordinate measuring system for large objects	Creo Products	a	A	19
Pat7	WO9723787	1995	Optical coordinate measuring machine	Kodak and Research Corpus Technologies	a	A	21
Pat8	DE19621195	1996	Method and device for determining the direction in which an object is located	Leica	a	E	4
Pat9	US20040105100	1996	Apparatus and methods for surface contour measurements	MIT	g	A	17
Pat10	US20040260422	1996	Software for improving the accuracy of machines	Boeing	a	B	17
Pat11	US20060012802	1996	Apparatus and methods for surface contour measurement	MIT	g	A	19
Pat12	US5822877	1996	Multi-probe system for dimensional metrology	Chase Manhattan Bank and Hexagon	d	E	16
Pat13	US20060202953	1997	Novel man machine interfaces and applications	Motion Games	b	A	19
Pat14	US20080122786	1997	Advanced video gaming methods for education and play using camera based inputs	Motion Games	b	A	23
Pat15	US20120040755	1997	Interactive video based games using objects sensed by TV cameras	Motion Games	b	A	64
Pat16	US5644141	1997	Apparatus and method for high-speed characterization of surfaces	Commerce Bank Pennsylvania et al.	f	A	14
Pat17	US6017125	1997	Bar coded retroreflective target	Lawrence Livermore and US Dept. of Energy	f	E	23
Pat18	US6618132	1997	Miniature laser tracker	Lawrence Livermore	f	A	3
Pat19	RU2139497	1998	Device measuring distance to various points on surface of objects	Benditskij et al.	g	A	0
Pat20	US20120327390	1999	Methods for using a locator camera in a laser tracker	Faro	a	E	0
Pat21	WO200362744	1999	Laser-based coordinate measuring device and laser-based method for measuring coordinates	Faro	a	E	32
Pat22	WO200237133	2000	Position measurement system and method using cone math calibration	Arc Second, Nikon	e	A	21
Pat23	CN1375682	2001	Trackless large-part measuring device and method	Sichuan University	a	E	0
Pat24	US20020145563	2001	Body motion tracking system	Tera Research	g	A	31
Pat25	TW200513632	2003	Compensation of laser tracker measuring	Tsay Yuh-Feng	a	B	0
Pat26	US20050157410	2004	Multidirectional retroflector	Associated Universities	a	E	6
Pat27	CA2569798	2005	Full-field three-dimensional measurement method	University of Ottawa and University of Waterloo	g	C	14
Pat28	WO200725362	2005	Imaging system and method	Neptec	g	A	2
Pat29	CN1971206	2006	Calibration method for binocular vision sensor based on one-dimension target	Beihang university	b	D	0
Pat30	US20090112348	2007	System, method, and computer program product for computing jack locations to align parts for assembly	Boeing	h	C	4
Pat31	US20110270571	2007	System for assembling aircraft	Boeing	h	C	8
Pat32	NL1037087	2008	Interferometer Calibration System and Method	Agilent Technologies	a	D	0
Pat33	US20090125265	2008	Method for Calibrating a Laser-Based Spherical Coordinate Measurement System by a Mechanical Harmonic Oscillator	Parker D.H.	a	D	2
Pat34	US7924441	2008	Fast and high-precision 3D tracking and position measurement with MEMS micromirrors	Mirrorcle Technologies	f	E	0
Pat35	WO2009115130	2008	Position estimation enhancement for a global navigation satellite system receiver	Telespazio	h	B	1
Pat36	US20100176270	2009	Volumetric error compensation system with laser tracker and active target	Automated Precision	d	D	2

Table 7 (continued)

Ref. no.	Publ. no.	Year	Title	Assignee(s)	Techn.	Typ.	Cites
Pat37	CN101850850	2010	Layout method of central airframe digital assembly of big plane	Zhejiang University	a	C	0
Pat38	CN101915563	2010	Measurement method of aircraft rudder deflection angle	Xi An Aircraft Design & Research Institute of AVIC	a	C	0
Pat39	CN102001451	2010	Airplane component attitude adjusting and butting system based on four numeric control positioners, attitude adjusting platform and mobile bracket and corresponding method	Boeing	a	C	0
Pat40	CN102059549	2010	Airplane engine attitude regulation installation system based on four numerical control positioners and use method thereof	Zhejiang University	a	C	0
Pat41	US20120037705	2010	System and method for object metrology	Honeywell	g	A	0
Pat42	US20120038994	2010	Universal sphere mount	Hubbs W.O.	a	E	0
Pat43	US20120059624	2010	Method and apparatus for dynamic 6DOF measurement	Madhavan Viswanathan	a	C	0
Pat44	US8375594	2010	Pneumatic counterbalance for optical head gantry	Bruker Nano	d	E	0
Pat45	WO201185283	2010	Method and apparatus for synchronizing measurements taken by multiple metrology devices	Faro	g	E	2
Pat46	CN102322815	2011	High-precision and high-volume measurement device and method based on three-dimensional laser scanning	Zhejiang Measurement Science Research Institute	f	E	0
Pat47	CN102374847	2011	Work space six degree-of-freedom posture dynamic measurement equipment and method	Tianjin University	e	A	0
Pat48	CN202133430U	2011	Three-dimensional laser scan-based large volume measurement equipment with high precision	Zhejiang Measurement Science Research Institute	f	E	0
Pat49	US20120186059	2011	Target for large-scale metrology system	Nikon	a	E	0
Pat50	US20120286147	2011	Wide-angle laser signal sensor	Southwest Research Institute	a	E	0
Pat51	US20130003042	2011	Stroboscopic light source for a transmitter of a large scale metrology system	Nikon	e	E	0
Pat52	WO2012110635	2011	System for measuring the position and movement of an object	Nikon	g	A	0
Pat53	US20120050726	2012	Large-scale metrology apparatus and method	Nikon	e	A	0

Patents are sorted by priority year (“Year”) and by publication number (“Publ. No.”). To avoid duplications, in the case of patents filed in multiple patent authorities, we refer to the one with the oldest priority date. For each patent, it is also reported the dominant-technology class (“Techn.”) and the typology-of-work class (“Typ.”), according to the classifications in Tables 2 and 3

References

1. Puttock MJ (1978) Large-scale metrology. Ann CIRP 21(1):351–356
2. Franceschini F, Galetto M, Maisano D, Mastrogiacomo L (2009) On-line diagnostics in the mobile spatial coordinate measuring system (MScMS). Precis Eng 33(4):408–417
3. Franceschini F, Galetto M, Maisano D, Mastrogiacomo L, Pralio B (2011) Distributed large-scale dimensional metrology. Springer, London
4. Estler WT, Edmundson KL, Peggs GN, Parker DH (2002) Large-scale metrology—an update. CIRP Ann Manuf Technol 51(2):587–609
5. Peggs GN, Maropoulos PG, Hughes EB, Forbes AB, Robson S, Ziebart M, Muralikrishnan B (2009) Recent developments in large-scale dimensional metrology. Proc Inst Mech Eng B J Eng Manuf 223(6):571–595
6. Muelaner JE, Cai B, Maropoulos PG (2010) Large-volume metrology instrument selection and measurability analysis. Proc Inst Mech Eng B J Eng Manuf 224(6):853–868
7. Jun S, Lee J (2012) Emerging technology forecasting using new patent information analysis. Int J Softw Eng Appl 6(3):107–116
8. Glänzel W, Meyer M (2003) Patents cited in the scientific literature: an exploratory study of 'reverse' citation relations. Scientometrics 58(2):415–428
9. Seeber F (2007) Patent searches as a complement to literature searches in the life sciences—a 'how-to' tutorial. Nat Protoc 2(10):2418–2428
10. Van Looy B, Callaert J, Debackere K (2006) Publication and patent behavior of academic researchers: conflicting, reinforcing or merely co-existing? Res Policy 35(4):596–608
11. Czarnitzki D, Glänzel W, Hussinger K (2007) Patent and publication activities of German professors: an empirical assessment of their co-activity. Res Eval 16(4):311–319
12. Breschi S, Catalini C (2010) Tracing the links between science and technology: an exploratory analysis of scientists' and inventors' networks. Res Policy 39(1):14–26
13. Franceschini F, Maisano D, Turina E (2012) European research in the field of production technology and manufacturing systems: an exploratory analysis through publications and patents. Int J Adv Manuf Technol 62(1–4):329–350
14. De Bellis N (2009) Bibliometrics and citation analysis: from the Science Citation Index to Cybermetrics. Lanham Scarecrow Press, MD, USA

15. Cheng YH, Kuan FY, Chuang SC (2010) Profitability decided by patent quality? An empirical study of the U.S. semiconductor industry. Scientometrics 82(1):175–183
16. Scopus – Elsevier (2013) www.info.scopus.com [8 March 2013]
17. Bar-Ilan J (2010) Citations to the 'introduction to informetrics' indexed by WOS, Scopus and Google Scholar. Scientometrics 82(3):495–506
18. Jacsó P (2008) Testing the calculation of a realistic h-index in Google Scholar, Scopus, and Web of Science for F. W. Lancaster. Libr Trends 56(4):784–815
19. Questel – Orbit (2013) www.questel.com/prodsandservices/orbit.htm [8 March 2013]
20. Yu, J., Chong, Z., Lu, H., Zhou, A. (2004) False positive or false negative: Mining frequent itemsets from high speed transactional data streams. Proceedings of the Thirtieth international conference on Very large data bases (VLDB '04), 30: 204–215
21. Hinze, S., Schmoch, U. (2004) Opening the black box, In: Moed, H.F., Glänzel, W., Schmoch U. (eds.), Handbook of quantitative science and technology studies, 215–236 Kluwer Academic Publishers, Dordrecht, The Netherlands
22. Larsen PO, von Ins M (2010) The rate of growth in scientific publication and the decline in coverage provided by Science Citation Index. Scientometrics 84(3):575–603
23. Rogers E (2013) Diffusion of innovations, 5th edn. Free Press, NY
24. Guan JC, Gao X (2009) Exploring the h-index at patent level. J Am Soc Inf Sci Technol 60(1):35–40
25. Hara T, Arai T, Shimomura Y, Sakao T (2007) Service/product engineering: a new discipline for value production, in 19th International Conference on Production Research (ICPR-19), 29 July to 2 August 2007. Valparaiso, Chile
26. Mohan-Ram, V. (2001) Patent first, publish later: how not to ruin your chances of winning a patent. Science Career, 26 October 2001, http://sciencecareers.sciencemag.org [8 March 2013]
27. ASME B89.4.19-2006 (2006). Performance evaluation of laser-based spherical coordinate measurement systems, http://www.asme.org [8 March 2013]
28. VDI/VDE 2634–1 (2002) Optical 3-D measuring systems and imaging systems with point-by-point probing. Beuth Verlag, Berlin
29. ISO 10360–2 (2001) Geometrical product specifications (GPS)—acceptance and reverification tests for coordinate measuring machines (CMM), Part 2: CMMs used for measuring size. International Organization for Standardization, Geneva
30. CIRP (2013) Organization website: http://www.cirp.net. [8 March 2013]
31. Foglia P (2007) Patentability search strategies and the reformed IPC: a patent office perspective. World Patent Inf 29(1):33–53