Autonomous Systems: A Bibliometric and Patent Analysis

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Abbreviations

DFKI	German Research Center for Artificial Intelligence
DII	Derwent Innovation Index
IOSB-INA	Fraunhofer Application Center Industrial Automation (IOSB-INA)
IPC	International Patent Classification
NPL	Non-Patent Literature
OFFIS	Oldenburger Institut für Informatik
R&D	Research and Development
SWOT	strengths-weaknesses-opportunities-threats
UK	United Kingdom
US	United States of America
WoS	Web of Science

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Chapter 0: Executive Summary

This report examines Germany's research and patent position in four autonomous systems: smart homes, smart factories, autonomous vehicles (non-hostile environments), and autonomous vehicles in hostile environments. Bibliometric analysis of scholarly papers indexed in the Web of Science and patent analysis of documents in Patstat and Derwent Innovation Index (representing patents from more than 40 patent authorities worldwide) are conducted for all records published in the 2002 to 2017 (May) time period.

Autonomous systems comprise a good-sized collection of publications and patents. There are nearly 5,900 smart home publications, more than 3,700 smart factory publications, more than 29,000 autonomous vehicles publications (non-hostile environments), and more than 9,500 publications concerning autonomous vehicles in hostile environments. These same figures for patents: more than 5,400 smart home patents, 5,100 smart factory patents, 6,000 autonomous vehicle patents, and 1,800 patents concerning autonomous vehicles in hostile environments. Much of the growth of autonomous systems publications and patents in these four areas has occurred in the last five years, which suggests that there are still opportunities for policy action to affect the competitive positioning of Germany in this emerging technology.

Although it is not the leader in overall counts or citations, Germany falls among the top countries in smart home research publications, comprising nearly 6% of these research papers. German research is distinctively prominent in certain smart home subareas – localization and computer vision. Germany is part of a group of countries studying how to better support assisted living applications in the home. China and the South Korea have the largest number of smart home patents, with patents from German organizations accounting for less than 1% of total patent output. Nevertheless, Germany is among the top smart home patenting countries, several of its globally recognized companies have patents in the area, and German patents is particularly strong in the scientific content of its patents and patent family filings.

Germany is the top smart factory research paper producing country in the 2011 to 2017 period, with 17% of all research publications having at least one German-based author. Germany is a leading producer of research publications across the technology catalogue, with particular prominence in sensor fusion, representation, and localization. Germany has diverse types of organizations involved in smart factory research including universities, research institutes and an employers' federation. Germany accounts for 7% of smart factory patents. Among the major smart factory patenting countries, German patents are most similar to Chinese patents in terms of their distribution across International Patent Classification (IPC) technology categories. However, German patents are more tightly based in non-patent literature and more likely to be taken in multiple countries. The most active German patenting firms in smart factory patents are similar to organizations prevalent in smart factory publications in that they are diverse, ranging from industrial manufacturing companies, semiconductor companies, and automobile manufacturing companies.

Germany is the third largest producer of autonomous vehicle research publications after the US and China. Seven percent of autonomous vehicle publications over the 2002-2017 period had a German-affiliated author. Most of the research comes from universities. German research is particularly strong in representation technologies. German patents account for 9% of total patent output in the autonomous vehicle area. Although the US and Japan have larger numbers of autonomous vehicles patents overall and larger numbers of highly cited patents, German automakers are well represented among the top autonomous vehicle patent filing organizations. German patents have more science linkages and larger family sizes than most of the comparator countries indicating the global value of German patents in this autonomous system. Indeed, German patents are prevalent among international patent cooperation treaty (PCT) applications.

German authors generated nearly 5% of research publications having to do with autonomous vehicles in hostile environments, and this share doubled from the first to the second decade of the 2000s. Although Germany is not the dominant producer of scholarly works involving autonomous vehicles in hostile environments, German research is particularly strong in representation technologies in this system. German publications in this autonomous system have a larger share of co-authored papers with one of the other study countries than in any of the other autonomous system. Most of the research in this domain comes from universities located throughout the country as well as from a cluster of organizations in the Bremen area. Germany produced 7% of the total patents related to autonomous vehicle in hostile environments, albeit with a growth similar to that of research publications. German patent ownership in this domain is somewhat concentrated among a few large firms. Atlas Elektronik, Bosch, Daimler, Siemens and Audi account for 45% of the patents in this domain. The German patent portfolio is much more internationalized and yet more distinctive in terms of technological emphasis than the patent portfolios of other major comparator countries.

These results suggest that Germany has great strengths in autonomous systems, particularly in the smart factory and autonomous vehicles domains. German research publications are particularly strong in hard technological areas such as representation, localization, computer vision, and sensor vision. The diversity of research organizations and patenting sectors is another strength of Germany’s. German patents also benefit from being more science-based and international than those from other comparator nations. On the other hand, Germany has less research publication and patent output in the smart home and autonomous vehicles in hostile environment system domains. Germany is less likely to show strength in data analytic and machine learning areas.

An analysis of the US regulatory environment in the four autonomous systems indicates that it is an emerging area of policy activity at the national and state levels. A diversity of public and private stakeholders is involved. Cross-cutting themes of this activity include privacy, security, safety, licensing, standards, insurance, liability, support for R&D through multiple mechanisms (prize competitions as well as traditional research grants) and funding agencies, and international engagement.

Chapter 1. Introduction

1.1. Definitions and Markets

Autonomous systems have attracted much interest based on the potential of these technologies to enhance the quality of home life and transportation, improve manufacturing productivity, and ensure the safety of those involved in hostile or hazardous environments. Autonomous systems are defined by acatech as "digital technology…enabled by sensors, machine learning, and robotics."[1] Acatech focuses on four autonomous system application areas that will be particularly important in the coming decade:

- *Smart homes* that can offer greater energy efficiency, security, and independent living abilities
- *Smart factories* that can provide greater automation and adaptive production in accordance with Industrie 4.0
- *Autonomous vehicles* that can accommodate different transportation schedules and needs in an environmental and climate friendly manner
- Autonomous vehicles in *hostile environments* that can ensure safer work in nuclear plants, battlefields and maritime warfare, oil exploration, and natural and man-made disasters.

The global markets for these applications are estimated to be quite large: US$6 billion for autonomous cars and US$41 billion for smart homes.[2] A proxy for smart factors, the application of the Internet of Things to discrete manufacturing, is estimated at US$40 billion by 2020.[3] The global market for unmanned underwater vehicles is estimated at US$4 billion by 2020.[4] Although the basis for these estimates is not always identified, the estimates do suggest that autonomous system applications have and will continue to have a market presence.

Although some applications of autonomous systems are mature and others combine mature technologies such as sensors and capacitors, many of the most transformative applications continue to be involved with research and development. Germany has the potential to be an R&D leader in these autonomous systems through companies such as Siemens, Kuka, Devolo, Thermokon Sensortechnik, eq-3 AG, German automakers, and others. Germany also has a diversity research institutes active in the domain including robotics research centers at Technical University of Munich and other German universities, Max Planck Institutes (e.g., Biological Cybernetics), the German Research Center for Artificial Intelligence, and the Oldenburger OFFIS - Institut für Informatik. It is useful to examine the research and innovation system associated with the four targeted autonomous domains through bibliometric and patent analysis to understand Germany's position in these systems as an early indicator of the country's possible future presence once these applications fully enter the market.

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[1] Acatech, FACHFORUM AUTONOME SYSTEME CHANCEN UND RISIKEN FÜR WIRTSCHAFT, WISSENSCHAFT UND GESELLSCHAFT, p. 26.

[2] Statistica (2017). Forecast market size for the global smart home market from 2016 to 2022 (in billion U.S. dollars), https://www.statista.com/statistics/682204/global-smart-home-market-size/ (retrieved August 3, 2017); Statistica (2017). Projected size of the global autonomous vehicle market in 2025, by type (in billions U.S. dollars), https://www.statista.com/statistics/428692/projected-size-of-global-autonomous-vehicle-market-by-vehicle-type/ (retrieved August 3, 2017).

[3] Statistica (2017). Spending on Internet of Things worldwide by vertical in 2015 and 2020 (in billion U.S. dollars). https://www.statista.com/statistics/666864/iot-spending-by-vertical-worldwide/ (retrieved August 3, 2017).

[4] Accuray Research (2016). The Global Unmanned Underwater Vehicles (UUV) Market is poised to grow at a CAGR of around 12.2% over the next decade to reach on year field.approximately $7.25 billion by 2025. https://www.researchandmarkets.com/research/hxt6g4/global_unmanned (retrieved August 3, 2017).

1.2. Data Sources

This report examines research and innovation system around the four important autonomous system application areas. The project uses bibliometric and patent analysis methods to understand the trajectory and characteristics of these four areas. The project begins with a domain definition of autonomous systems. Because there is no existing industry class, set of journals, or patent classes that fully cover autonomous systems in the four domains of interest, this study used a literature review, discussion with experts, and progressive keyword-based search screening approach to identify the most relevant keywords to use to extract relevant publications from the Web of Science (WoS) Core Collection (which indexes papers from more than 12,000 publications including journal articles, conference proceedings, and books and book chapters) and relevant patents from Derwent Innovations Index (DII) which indexes patent documents from more than 40 worldwide patent-issuing authorities for each of the four autonomous systems over the 2002-2017 period. The patent authorities include the European Patent Office, national patent authorities, and Patent Cooperation Treaty applications. This mix of national, regional, and international patent data is provided to capture and enable the analysis of comparator country patentees such as in China which tend to patent in their national authority, as well as patentees in countries such as Germany and to some extent the US, which patent outside their national patent office. The report could have focused on Patent Cooperation Treaty applications or patents involving the European Patent Office, US Patent Office, and Japan Patent Office (the Trilateral Patent Offices), but that approach would have not enabled a full analysis of patents from China. The report addresses this issue by presenting indicators of patent family size, which represents patents filed internationally in more than one national patent authority, as well as overall counts of patents.

It is notable that DII uses patent publication year, rather than application priority year. This use of patent publication year is most comparable to scientific paper publication year and also is most comparable across countries' law changes and patent authorities' changes in procedures.[5] Seventy to 80% of DII records (depending on the autonomous system) were matched to PatStat records to obtain data on the use of non-patent literature in citations of prior art. The metadata from WoS and DII was extracted in May of 2017, so 2017 and to some extent (because of indexing time lags) 2016 counts represent only partial year information. PatStat is only available twice a year; the Fall 2016 version was used for this analysis.

1.3. Search Strategy

A document that details the search strategy to facilitate replicability of this study can be found in the Appendix. Two important points about the search strategy are noted. The first point is that the search strategy splits autonomous vehicles records into those relating to non-hostile and hostile environments. Publications and patents associated with terms such as hazard or disaster or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea or military or battlefield split off from the autonomous vehicle search into a separate file of records relating to hostile environments. The second point is that one of the main domain definition principles is how to address the distinction between autonomy and automation. These systems cannot be "autonomous" without greater automation. One of the principles of our search strategy was to focus on "autonomy," in contrast to other terms like "automatic" that can well refer to remote human operator controlled systems. Our search strategy uses terms such as "smart" or "intelligence" which are indicators of autonomy. Although some applications that are primarily driven by automatic technologies such as smart energy systems may be included, we tested and explicitly did not include the term "automated" in our search strategy for the reason that automated/automatic can refer to remote human operator controlled systems.

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[5] https://images.webofknowledge.com/WOK50B6/help/DII/h_fieldtags.html provides for more information about the patent publication year field used in Derwent Innovation Index.

1.4. Country Comparison

Data clean-up to group variations of the same name and analysis was performed using VantagePoint software (https://thevantagepoint.com). The analysis compares Germany's research position in terms of publications to its patent position. In addition, country comparisons are made between Germany and the US, South Korea, Japan, China, and India over the entire dataset. The study does not isolate these six countries, but rather shows them in context with other countries with similar publication and patent output, with the exception of Indian patents because there are relatively few of them. In the case of publications, *country* refers to author-affiliated organization location. In the case of patents, there is no country field in DII. Thus, *country* refers to coding of assignee organization names into their country; sometimes the name will include the country but, where this information is missing, the organization is assigned to the headquarters location. The analysis uses full counting in which the publication count is fully allocated to all authors rather than fractional counting in which the publication count is proportionally allocated to all authors. Full counting is used to isolate and fully capture Germany's position in publications and patents, but it does mean that country counts cannot be added to generate a total because co-authorships would be counted twice.

1.5. Analysis

In the case of publications, country comparisons are also made within six autonomous system research subareas provided by acatech from its Technology Catalogue: data analysis (converting unprocessed data into information more useful for decision making), representation ("of knowledge, environment, context, semantics, behavior models"), localization (which enables feature matching of a place), machine learning (an artificial intelligence capability to perform without specifically being programmed), sensor fusion (a program that integrates information from multiple sensors), and computer vision (processing information from images or videos). These subareas resonated well with the text in titles and abstracts of scholarly publications; these subareas are broken into author-affiliated country percentages but should not be summed to a total because publications may encompass two or more subareas and (because of co-authorships) two or more countries. They did not work well in isolating patents because of the application orientation of patents, so we were not able to perform this analysis on the patent documents. We did perform a patent topic similarity analysis that uses International Patent Classifications (IPCs) to understand common or different topical emphases (refer to the next paragraph).

Analyses are performed at the level of the country, organization, author, and publication/patent. Organizations displayed in the report have the most publications or patents above a natural break in the distribution. We performed several network analyses at the country level to understand cross-national relationships. For these network analyses, we used (1) VantagePoint's cluster mapping tool to show co-authorship relationships and (2) its matrix viewer function to plot force-directed node-edge graphs of cosine similarities between countries from a matrix to show countries working on similar topics as proxied by author-supplied keywords. The matrix viewer function allows strength of edge relationships to vary through path erasing to the point at which clusters of network relationships are best revealed. We used this same approach to perform a similarity analysis based on IPCs to understand the extent to which different countries are working on the same or different IPC-defined topics.

The report presents an analysis based on citations in publications, by examining highly cited papers at or above the top 10% threshold. This same analysis was applied to patent citations, percent of citations to non-patent literature, and number of patent families. However, the top 5% threshold was used because the patent distributions were flatter. The report presents the share of non-patent literature (NPL) citations above this 5% threshold, where NPL refers to the number of citations to scholarly literature and other non-patent sources (e.g., conference proceedings, databases, statistical manuals, other sources) divided by the total number of citations. This measure is sometimes taken as an indicator of the scientific basis of a patent. An additional patent measure presented is the number of patent families, where a patent family is a patent that is taken in multiple countries/patent authorities. Patents with multiple families are considered to be of greater value because of their wider geographic scope and larger fees paid to protect these patents in multiple authorities.

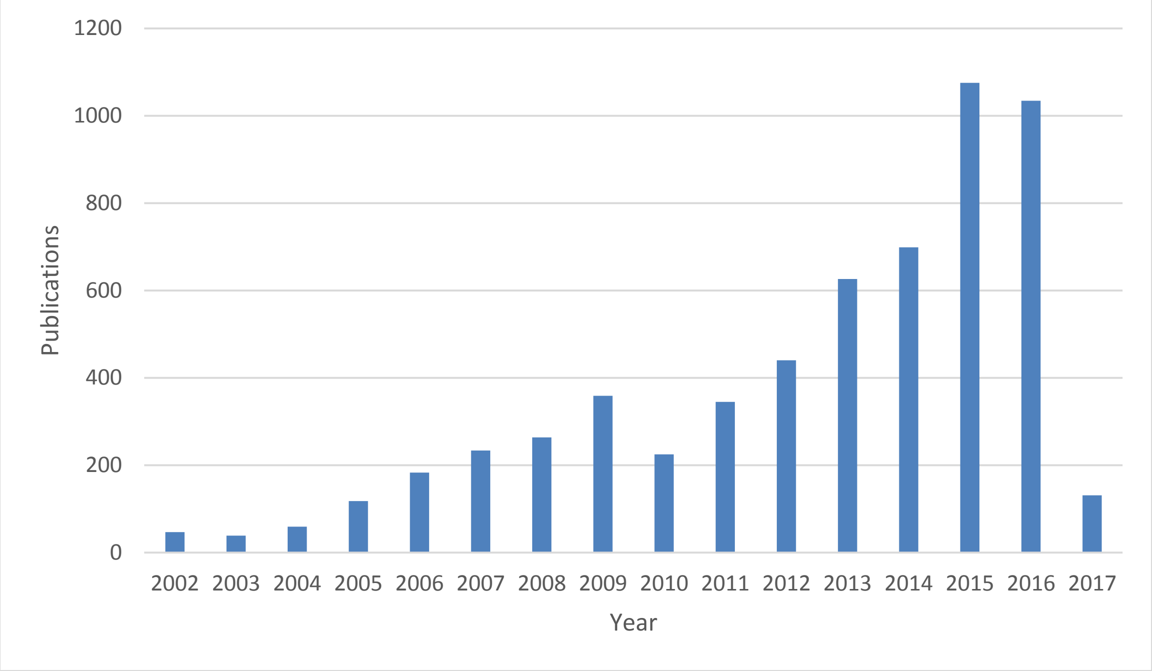
The results are integrated into a strengths-weaknesses-opportunities-threats (SWOT) structure to help inform R&D policy and strategy. In addition, autonomous system laws and regulations at the US national and state levels are shared to help inform Germany's regulatory framework.

Chapter 2. Smart Homes

2.1. Smart Home Publications

Nearly 5,900 smart home research publications were indexed in WoS. The number of publications nearly tripled from the earlier 2002-2010 period to 2011-2017, with a 50% growth alone occurring from 2014 to 2015 (Figure 2.1).

Figure 2.1. Number of Smart Home Publications by Publication Year: 2002-2017 (May)



Source: Smart Homes publications, 2002–2017 (May), (N = 5878 Web of Science records). See text for search strategy.

Germany has the seventh largest number of publications over the 2002-2017 time period. German authors accounted for nearly 6% of all smart home publications in the 2011-2017 period, up from 4.6% in the 2002-2010 period (Table 2.1). Germany is comparatively stronger in localization and computer vision technologies associated with smart homes. German-based authors account for 9% of the smart home publications in these two areas (Table 2.2). China has the largest share of research publications in the data analysis area (16%), followed by the US at 15%; China and the US along with the UK and France are strongest in the representation area; China and Italy are most prominent in the localization area; the US is dominant in the machine learning area (with 27% of the publications in this area); France is strongest in the sensor fusion area; and the US is strongest in the computer vision area.

Table 2.1. Top Countries by Number of Smart Home Publications

Countries	# Publications	Share (%)	# in 2002-2010	# in 2011-2017
China	912	15.5%	138	774
USA	701	11.9%	183	518
South Korea	570	9.7%	220	350
UK	387	6.6%	101	286
Taiwan	335	5.7%	78	257
Germany	326	5.5%	70	256
France	290	4.9%	85	205
India	268	4.6%	7	261
Italy	268	4.6%	34	234
Canada	252	4.3%	51	201
Spain	237	4.0%	60	177
Japan	212	3.6%	35	177

Source: Refer to Figure 2.1. Country share is based on the count of publications with an author affiliated with an organization in the country divided by the total number of records in Figure 2.1.

Table2.2. Countries by Smart Home Research Subarea

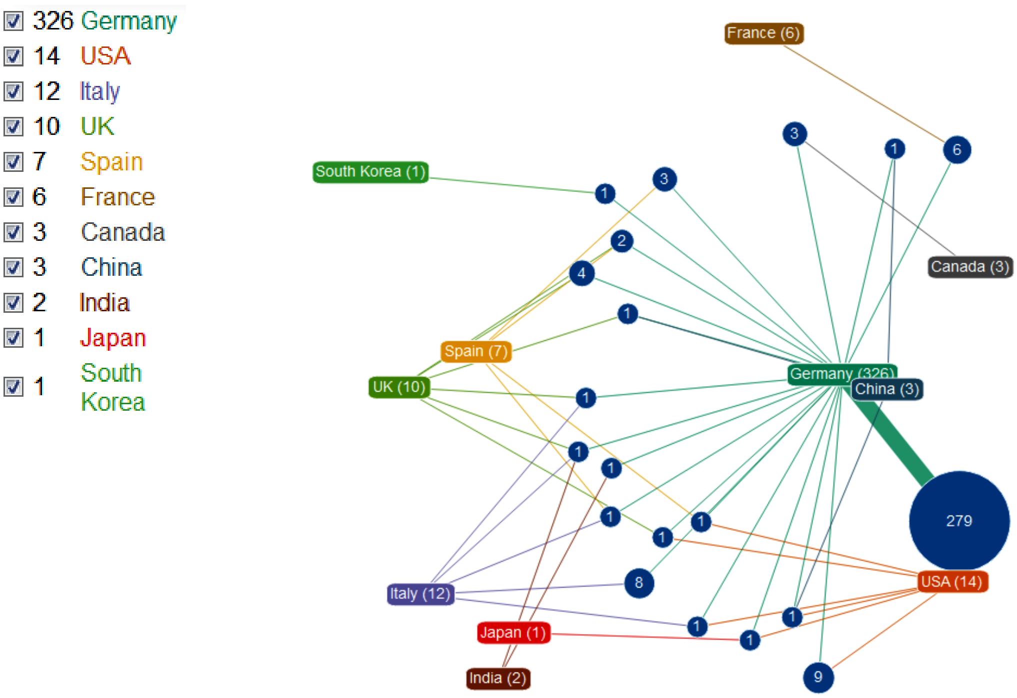
Country	Smart Home Research Subarea					
	data analysis	representation	localization	machine learning	sensor fusion	computer vision
China	16.0%	11.7%	14.2%	8.0%	10.7%	9.0%
USA	14.7%	11.7%	11.8%	25.9%	9.3%	17.9%
South Korea	8.4%	6.6%	10.2%	10.7%	0.0%	7.5%
UK	9.7%	10.9%	1.6%	11.6%	10.7%	14.9%
Taiwan	4.9%	2.2%	3.9%	3.6%	13.3%	6.0%
Germany	4.9%	5.1%	8.7%	4.5%	4.0%	9.0%
France	4.3%	11.7%	8.7%	1.8%	18.7%	3.0%
India	4.9%	0.7%	5.5%	4.5%	4.0%	3.0%
Italy	4.9%	4.4%	14.2%	3.6%	9.3%	1.5%
Canada	5.0%	2.9%	8.7%	5.4%	0.0%	1.5%
Spain	3.0%	8.0%	2.4%	5.4%	10.7%	7.5%
Japan	2.1%	1.5%	2.4%	2.7%	1.3%	1.5%
Number of Publications	536	137	127	112	75	67

Source: Refer to Figure 2.1. Percentages are based on the number of records associated with each subarea divided into the number with an author affiliated with an organization in the country. Percentages cannot be summed to a total because a publication may involve multiple subareas and author-affiliated countries.

The network of collaborators with German authors indicates that 17% of German authors' publications involve collaborators from the five comparison countries plus the other contextual countries with similar publication outputs (Figure 2.2). German co-authors most commonly collaborate with authors from the

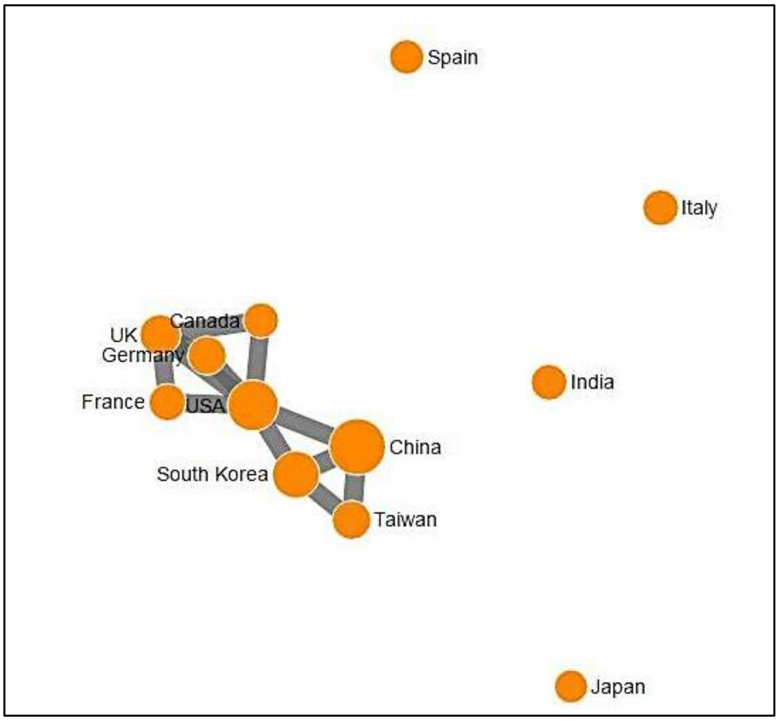
US, Italy, and the UK while there is only one smart home article with Japanese or South Korean co-authors. Most of these co-authorships are bilateral, involving a German author and a co-author from another country, but a few have multiple authors from different countries. For example, nine of the 14 US-Germany co-authored papers are solely between these two countries, with the rest involving Germany, the US, and a third country such as the UK. The extent to which researchers in different countries work on similar topics can be examined by performing a co-occurrence analysis based on cosine similarities among author-supplied keywords. A group of eight countries – including Germany, China, the US, and South Korea—are working on similar smart home topics, while four countries including India and Japan work on different topics (Figure 2.3). German smart home authors distinctively work on assisted living and related topics.

Figure 2.2. German Co-author Affiliations by Selected Countries

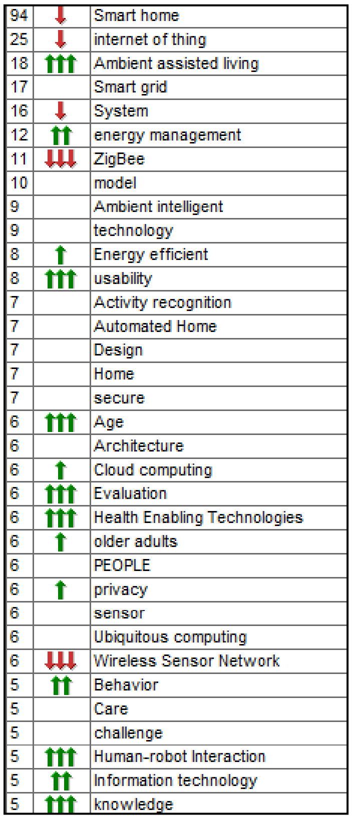


Source: Refer to Figure 2.1.

Figure 2.3. Smart Home Country Co-occurrence based on Cosine Keyword Similarity
Arrows next to German article keywords represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).



Top German Article Keywords



94	↓	Smart home
25	↓	internet of thing
18	↑↑↑	Ambient assisted living
17		Smart grid
16	↓	System
12	↑↑	energy management
11	↓↓↓	ZigBee
10		model
9		Ambient intelligent
9		technology
8	↑	Energy efficient
8	↑↑↑	usability
7		Activity recognition
7		Automated Home
7		Design
7		Home
7		secure
6	↑↑↑	Age
6		Architecture
6	↑	Cloud computing
6	↑↑↑	Evaluation
6	↑↑↑	Health Enabling Technologies
6	↑	older adults
6		PEOPLE
6	↑	privacy
6		sensor
6		Ubiquitous computing
6	↓↓↓	Wireless Sensor Network
5	↑↑	Behavior
5		Care
5		challenge
5	↑↑↑	Human-robot Interaction
5	↑↑	Information technology
5	↑↑↑	knowledge

The top organizations with 50 or more smart home publications based on author affiliation are University of Ulster (UK), Massey University (Australia), Washington State University (US), and Kyung Hee University (South Korea). The top German organizations with 10 or more smart home publications are Rhein Westfal TH Aachen University, Technical University of Munich, Technical University of Carolo Wilhelmina Braunschweig, Technical University of Dresden, University of Bremen, Technical University of Berlin, and Technical University of Darmstadt. Table 2.4 lists the top German authors by number of publications in the smart home area, alongside their organizational affiliations. Universities dominate the list, although there are two research institutes – the German Research Center for Artificial Intelligence (DFKI) and the OFFIS – Institut für Informatik.

Table 2.3. Top Organizations by Number of Smart Home Publications

Top Global Organizations	# Publications		Top German Organizations	# Publications
Univ Ulster	76		Rhein Westfal TH Aachen	19
Massey Univ	56		Tech Univ Berlin	19
Washington State Univ	54		Tech Univ Munich	16
Kyung Hee Univ	51		Tech Univ Carolo Wilhelmina Braunschweig	13
Natl Taiwan Univ	49		Tech Univ Dresden	13
Natl Cheng Kung Univ	48		Univ Bremen	13
Elect & Telecommun Res Inst (South Korea)	47		Tech Univ Darmstadt	12
Korea Adv Inst Sci & Technol	44		Siemens AG	8
Beijing Univ Posts & Telecommun	40		Univ Rostock	8
Chinese Acad Sci	39		Hannover Med Sch	6
			Karlsruhe Inst Technol	6
			OFFIS Inst Informat Technol	6

Source: Refer to Figure 2.1.

Table 2.4. Top German Affiliated Authors by Number of Smart Home Publications

Top German Affiliated Authors	Organization	# Publications
Moeller, Sebastian	Tech Univ Berlin	10
Marschollek, Michael	Hannover Med Sch	10
Haux, Reinhold	Tech Univ Carolo Wilhelmina Braunschweig	9
Wolf, Klaus-Hendrik	Tech Univ Carolo Wilhelmina Braunschweig	8
Frey, Jochen	German Res Ctr Artificial Intelligence	6
Kuehnel, Christine	Tech Univ Berlin	6
Hein, Andreas	OFFIS Inst Informat Technol	5
Kays, Ruediger	TU Dortmund Univ	5
Retkowitz, Daniel	Rhein Westfal TH Aachen	5
Ziefle, Martina	Rhein Westfal TH Aachen	5
Gietzelt, Matthias	Tech Univ Carolo Wilhelmina Braunschweig	5
Song, Bianying	Tech Univ Carolo Wilhelmina Braunschweig	5
Schmeck, Hartmut	Karlsruhe Inst Technol	4

Source: Refer to Figure 2.1.

The top 10% of highly cited smart home publications received 60 or more citations. Germany is at this average, with 5% of German publications attracting 60 or more citations. China, Japan, and India have relatively fewer highly cited smart home publications, while the UK and, to a lesser extent, the US have more than one would expect based on publication output size (Table 2.5). There are eleven smart home publications that received 150 or more citations (Table 2.6). The most highly cited work is an Australian-authored paper about the Internet of Things, which received 875 citations. Other topics of these highly cited papers include activity recognition through home sensors, middleware, a review of smart home developments, sensor-facilitated rehabilitation, a smart house pilot, energy and smart grid applications, smart home technologies for seniors, and data management.

Table 2.5. Top 10% of Highly Cited Smart Home Publications by Country

Countries	**Top 10% of Highly Cited Publications (60+ times cited)***	
	# Publications in Top 10%	% of Publications in Top 10% (618 publications)
China	55	8.9%
USA	135	21.8%
South Korea	65	10.5%
UK	83	13.4%
Taiwan	34	5.5%
Germany	31	5.0%
France	48	7.8%
India	4	0.6%
Italy	30	4.9%
Canada	39	6.3%
Spain	36	5.8%
Japan	11	1.8%

*The top 10% of highly cited publications is across the full distribution of highly cited publications in this system (618 publications); this subset of highly cited publications is then broken down by country to determine which country affiliations account for the greatest share of highly cited publications.

Table 2.6. List of Most Highly Cited Smart Home Publications (with 150 or more citations)

Title	Source	Countries	Times Cited
Internet of Things (IoT): A vision, architectural elements, and future directions	FUTURE GENERATION COMPUTER SYSTEMS-THE INTERNATIONAL JOURNAL OF ESCIENCE	Australia	875
Activity recognition in the home using simple and ubiquitous sensors	PERVASIVE COMPUTING, PROCEEDINGS	USA	337
A service-oriented middleware for building context-aware services	JOURNAL OF NETWORK AND COMPUTER APPLICATIONS	Singapore	319
A review of smart homes - Present state and future challenges	COMPUTER METHODS AND PROGRAMS IN BIOMEDICINE	France	250
A review of wearable sensors and systems with application in rehabilitation	JOURNAL OF NEUROENGINEERING AND REHABILITATION	USA	239
The Gator Tech Smart House: A programmable pervasive space	COMPUTER	USA	238
Coordinated Scheduling of Residential Distributed Energy Resources to Optimize Smart Home Energy Services	IEEE TRANSACTIONS ON SMART GRID	Australia	231
A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges	IEEE COMMUNICATIONS SURVEYS AND TUTORIALS	USA	199
Older adults' attitudes towards and perceptions of 'smart home' technologies: a pilot study	MEDICAL INFORMATICS AND THE INTERNET IN MEDICINE	USA	163
Design and Implementation of Smart Home Energy Management Systems based on ZigBee	IEEE TRANSACTIONS ON CONSUMER ELECTRONICS	South Korea	158
From databases to dataspaces: A new abstraction for information management	SIGMOD RECORD	USA	151

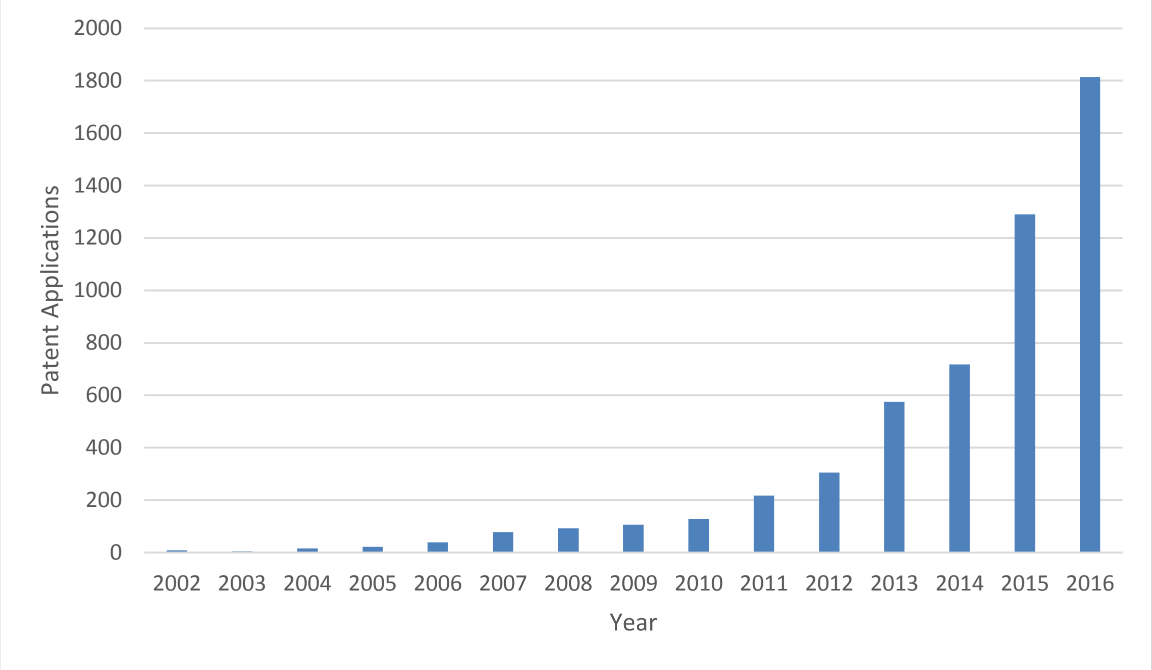
Source: Refer to Figure 2.1.

In sum, Germany falls among the top countries in smart home publications, although it is not the leader in overall counts or citations. German research is distinctively prominent in certain smart home subareas – localization and computer vision. Moreover, Germany is part of a group of countries studying how to better support assisted living applications in the home.

2.2. Smart Home Patents

More than 5,400 patents related to smart home technologies were obtained from DII. The number of patents increased by more than 10 fold from the 2002-2010 period to 2011-2016 period, with an 80% annual growth alone occurring from 2014 to 2015 (Figure 2.4). Germany has produced 27 smart home patents and ranks sixth in terms of number of smart home patents in the 2002 to 2016 time period. German patents account for 0.5% of the entire smart home patent applications. Germany’s ranking has increased from seventh in the 2002-2010 period to sixth in the 2011-2016 period (Table 2.7).

Figure 2.4. Number of Smart Home Patents by Patent Publication Year: 2002-2016



Source: Smart Homes patents, 2002–2016, (N = 5,415 Derwent Innovation Index). See text for search strategy.

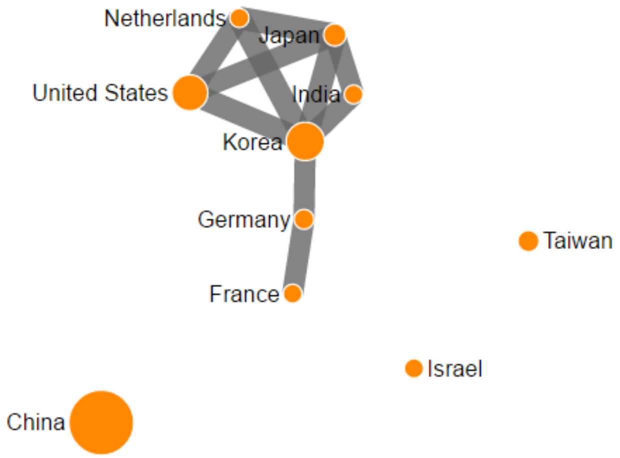
Table 2.7. Top Countries by Number of Smart Home Patents

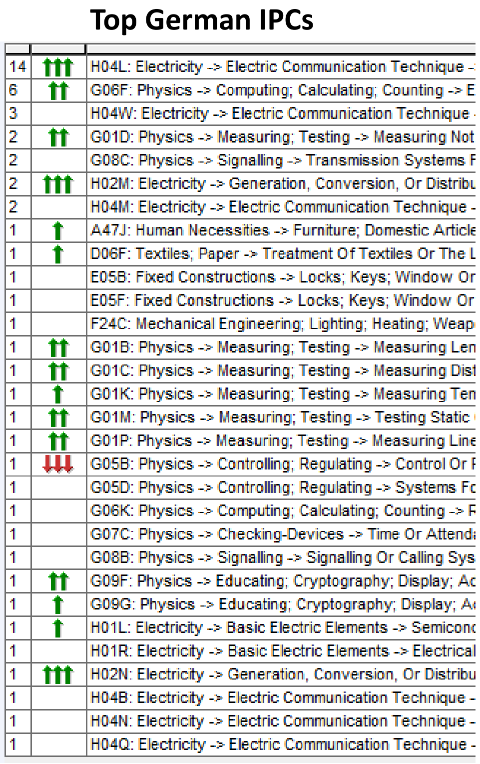
Countries	# Patents	Share (%)	# in 2002-2010	# in 2011-2016
China	3138	58.0%	110	3028
South Korea	671	12.4%	173	498
United States	545	10.1%	59	486
Japan	66	1.2%	24	42
Germany	27	0.5%	8	19
India	17	0.3%	1	16

Source: Refer to Figure 2.4. Country share is based on the count of patents assigned to organizations in the country divided by the total number of patents in Figure 2.1. Note individual assignees are not included.

German smart home patents are similar to French and South Korean patents in terms of their patents' IPCs (Figure 2.5). German patents were also similar to the US, Japan, and India via South Korean patents. The top German patent subclasses were Electricity – Transmission of Digital Information (H04L), Physics – Electric Digital Data Processing (G06F), Wireless Communication Networks (H04W), and Systems for Regulating Electric or Magnetic Variables (G05F). China is somewhat isolated from other countries based on the IPC-categorized topics of its patents. German patents are mostly associated with electric communication techniques and computing, which are foundational technologies in smart home patents.

Figure 2.5. Smart Home Country Co-occurrence based on Cosine IPC Similarity
Arrows next to German patent IPCs represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).




Top German IPCs

14	↑↑↑	H04L: Electricity -> Electric Communication Technique -
6	↑↑	G06F: Physics -> Computing; Calculating; Counting -> E
3		H04W: Electricity -> Electric Communication Technique
2	↑↑	G01D: Physics -> Measuring; Testing -> Measuring Not
2		G08C: Physics -> Signalling -> Transmission Systems F
2	↑↑↑	H02M: Electricity -> Generation, Conversion, Or Distribu
2		H04M: Electricity -> Electric Communication Technique -
1	↑	A47J: Human Necessities -> Furniture; Domestic Article
1	↑	D06F: Textiles; Paper -> Treatment Of Textiles Or The L
1		E05B: Fixed Constructions -> Locks; Keys; Window Or
1		E05F: Fixed Constructions -> Locks; Keys; Window Or
1		F24C: Mechanical Engineering; Lighting; Heating; Weap
1	↑↑	G01B: Physics -> Measuring; Testing -> Measuring Len
1	↑↑	G01C: Physics -> Measuring; Testing -> Measuring Dist
1	↑	G01K: Physics -> Measuring; Testing -> Measuring Ten
1	↑↑	G01M: Physics -> Measuring; Testing -> Testing Static
1	↑↑	G01P: Physics -> Measuring; Testing -> Measuring Line
1	↓↓↓	G05B: Physics -> Controlling; Regulating -> Control Or
1		G05D: Physics -> Controlling; Regulating -> Systems F
1		G06K: Physics -> Computing; Calculating; Counting -> F
1		G07C: Physics -> Checking-Devices -> Time Or Attend
1		G08B: Physics -> Signalling -> Signalling Or Calling Sys
1	↑↑	G09F: Physics -> Educating; Cryptography; Display; Ac
1	↑	G09G: Physics -> Educating; Cryptography; Display; A
1	↑	H01L: Electricity -> Basic Electric Elements -> Semicon
1		H01R: Electricity -> Basic Electric Elements -> Electrical
1	↑↑↑	H02N: Electricity -> Generation, Conversion, Or Distribu
1		H04B: Electricity -> Electric Communication Technique -
1		H04N: Electricity -> Electric Communication Technique -
1		H04Q: Electricity -> Electric Communication Technique -

Source: Refer to Figure 2.4.

The top organizational assignees with 40 or more smart home patents are mostly from East Asia. They include Samsung (South Korea), Google (USA), Chengdu Kechuangcheng Technology (China), Chengdu Hongyi Tiancheng Technology (China), LG (South Korea), Sichuan Changhong Electric (China) and Electronic & Telecom Research Institute (South Korea) (Table 2.2). The top German organizations with 2 or more smart home patents are Bosch, Siemens, Aizo (DigitalSTORM), Deutsche Telekom and Philips Intellectual Property GMBH (Table 2.8, Table 2.9).

Table 2.8. Top Global Organizations by Number of Smart Home Patents

Name	Country	# Patents
Samsung Electronics CO LTD	South Korea	297
Google INC	USA	188
Chengdu Kechuangcheng Technology CO LTD	China	65
Chengdu Hongyi Tiancheng Technology CO	China	51
LG Electronics INC	South Korea	50
Sichuan Changhong Electric CO LTD	China	47
Electronics & Telecommunication Research Institute	South Korea	40

Source: Refer to Figure 2.4.

Table 2.9. Top Five German Organizations by Number of Smart Home Patents

Name	# Patents
Bosch GMBH	7
Siemens AG	6
Aizo Group AG	2
Deutsche Telekom AG	2
Philips Intellectual Property GMBH	2

Source: Refer to Figure 2.4.

The top 5% highly cited smart home patents received five or more citations. Roughly 1% of the German patents received five or more citations, which is lower than the China, US, South Korea and Japan (Table 2.10). Out of entire smart home patent sample, five patents have received 40 or more citations. They are mostly assigned to the US organizations. For example, the most cited patent belongs to IBM's patent on smart home entertainment networks, which received 109 citations (Figure 2.11).

Table 2.10. Top 5% of Highly Cited Smart Home Patents by Country (5 + citations)

Countries	Top 5% of Highly Cited Patents (5+ times cited) (218 Patents)*	
	# Patents in Top 5%	% of Patents in Top 5%
China	86	39.4%
United States	44	20.2%
South Korea	27	12.4%
Israel	6	2.8%
Japan	5	2.3%
Germany	2	0.9%
India	1	0.5%

*The top 5% of highly cited patents is across the full distribution of highly cited patents in this system (218 patents); this subset of highly cited patents is then broken down by country to determine which country affiliations account for the greatest share of highly cited patents. Samples are restricted to 4,268 patents with citation information available from PatStat database.

Table 2.11. List of Highly Cited Smart Home Patents (40 + citations)

Patent Number	Title	Assignees	Country	Times Cited
US 2004054789	Operation method of smart home entertainment network	IBM	USA	109
US 6714534	Lifeline connection method for integrated residence gateway and node connected to hybrid fiber communication line adapter	AT&T CORP	USA	70
US 8539567	Method for authenticating e.g. client device to communicate with cloud-based remote server	Nest Labs INC (Google)	USA	47
WO 2006106393	Access Management in a Wireless Local Area Network	Nokia	Finland	46
US 2004192270	Hotlist system and method for communication devices	Motorola INC	USA	40

Source: Refer to Figure 2.1.

The number non-patent literature (NPL) citations may provide an indicator of the "science intensity" of patented inventions. The "Share of NPL" in the last column of Table 2.12 indicates the share of NPL from total citations (NPL + Patent Citations) of a given country. Despite China having the largest number of smart home patent publications, counts of backward citations of patents of Chinese organizations, including both NPLs and patent citations, are smaller than those of the US. Although Germany has fewer patents than the US, China, South Korea, and Japan, the share of NPL in German patents is higher, which indicates that German patents are more "science intensive" than patents in other countries.

Table 2.12. List of Countries by Number and Share of Non-Patent Literature (NPL)

Country	NPLs	Patent Citations	Total Citations	Share of NPL
United States	264	2557	2821	9.4%
China	137	1796	1933	7.1%
South Korea	47	1178	1225	3.8%
Germany	34	82	116	29.3%
Japan	11	146	157	7.0%
India	0	18	18	0.0%

Source: Refer to Figure 2.4. Samples are restricted to 4,268 patents with citation information available from PatStat database.

A patent family represents the same invention being filed in multiple patent authorities, and a count of these countries reflects the value of the patent because filing patents in multiple countries requires significant financial resources. South Korea has the largest number of patents filed in four or more patent authorities (Figure 2.13). This is not surprising given that South Korea is an export-oriented economy. On the other hand, out of 321 top 5% patent families, 7 patents were taken by German organizations in four or more patent authorities.

Table 2.13. Top 5% of Patent Families by Country (4+ Patent Families)

Countries	Top 5% of Patent Families by Country (4+ Families) (321 Patents)*	
	# Patents in Top 5%	% of Patents in Top 5%
South Korea	131	40.8%
United States	93	29.0%
China	36	11.2%
Japan	22	6.9%
Germany	7	2.2%
India	1	0.3%

*The top 5% of patent families is across the full distribution of patents in this system (321 patents); this subset of patents with multiple families is then broken down by country to determine which country affiliations account for the greatest share of the top 5% family patents. Samples are restricted to 4,268 patents with citation information available from PatStat database.

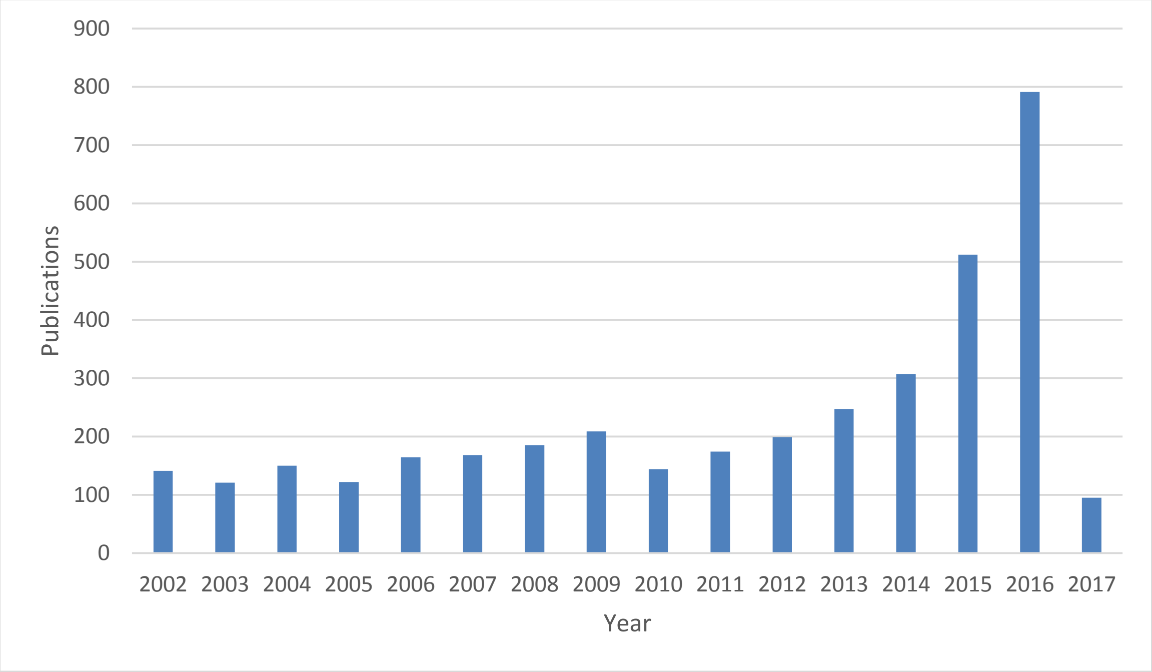
The distributions of patents across countries are extremely skewed with China accounting for nearly 60% of the entire smart home patents. Although China and the US have the largest number of smart home patents, Germany is among the top smart home patenting countries. Several of its globally recognized companies have patents in the area, and it is particularly strong in the scientific content of its patents and patent family filings.

Chapter 3. Smart Factory

3.1. Smart Factory Publications

More than 3,700 smart factory publications were indexed in WoS from 2002 to 2017. There was a 66% increase in publications in the 2011 to 2017 period compared with the previous 2002-2010 period (Figure 3.1). An uptick in publications was particularly evident from 2014 to 2015, which underwent a 66% increase in publications and again from 2015 to 2016, which underwent a 54% increase.

Figure 3.1. Number of Smart Factory Publications by Publication Year: 2002-2017 (May)



Source: Smart Factory publications, 2002–2017 (May), (N = 3,729 Web of Science records). See text for search strategy.

Germany is the top research paper producing country in the 2011 to 2017 period, with 17% of all papers having at least one German-based author (Table 3.1). This top position of Germany likely reflects the release of Industrie 4.0. German-based authors have strength across all six research subareas (Table 3.2) but particular strength in sensor fusion (accounting for 30% of smart factory publications in this area), representation (accounting for one-quarter of the publications), and localization (accounting for 24% of smart factory publications in this area). The US is stronger in data analysis and machine learning.

Table 3.1. Top Countries by Number of Smart Factory Publications

Countries	# Publications	Share (%)	# in 2002-2010	# in 2011-2017
China	654	17.2%	195	459
Germany	627	16.5%	120	507
USA	613	16.1%	255	358
Japan	212	5.6%	110	102
Italy	182	4.8%	74	108
UK	181	4.8%	68	113
Taiwan	172	4.5%	67	105
South Korea	144	3.8%	64	80
Spain	132	3.5%	43	89
France	116	3.1%	40	76
India	83	2.2%	40	43

Source: Refer to Figure 3.1. Country share is based on the count of publications with an author affiliated with an organization in the country divided by the total number of records in Figure 3.1. Percentages cannot be summed to a total because a publication may involve multiple subareas and author-affiliated countries.

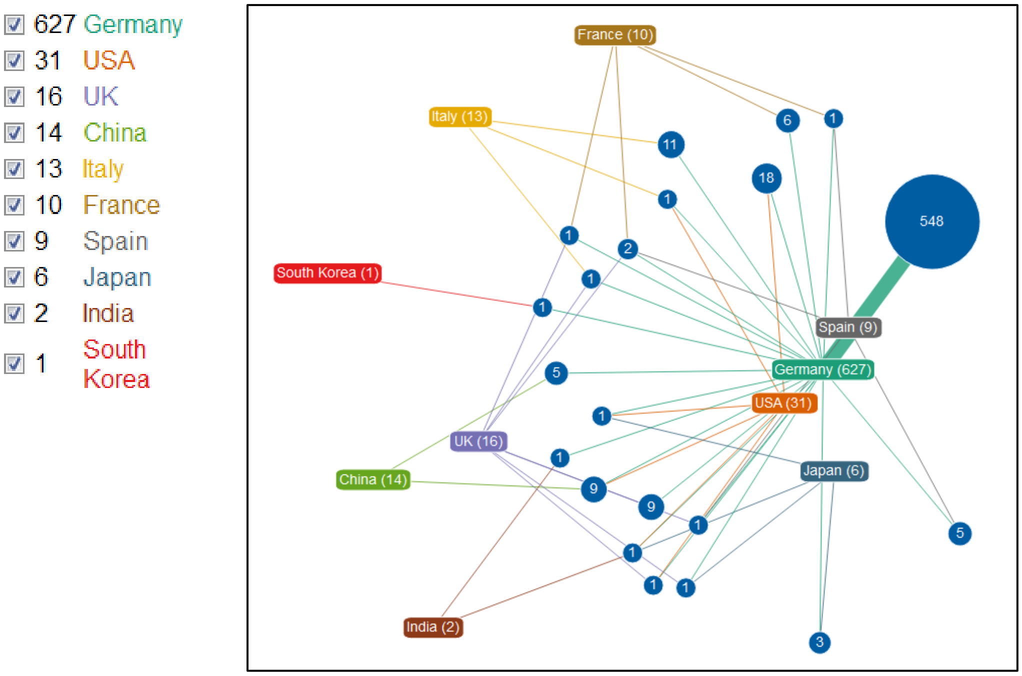
Table 3.2. Countries by Smart Factory Research Subarea

Country	Smart Factory Research Subarea					
	data analysis	representation	computer vision	machine learning	localization	sensor fusion
China	19.9%	11.2%	17.9%	17.4%	18.2%	11.8%
Germany	14.4%	25.0%	19.6%	13.0%	24.2%	29.4%
USA	21.9%	19.8%	19.6%	28.3%	18.2%	17.6%
Japan	4.1%	5.2%	5.4%	6.5%	9.1%	0.0%
Italy	3.8%	6.0%	1.8%	2.2%	3.0%	5.9%
UK	8.2%	2.6%	7.1%	10.9%	3.0%	0.0%
Taiwan	8.6%	4.3%	3.6%	4.3%	3.0%	5.9%
South Korea	4.5%	1.7%	3.6%	2.2%	3.0%	5.9%
Spain	3.1%	10.3%	5.4%	4.3%	0.0%	0.0%
France	0.3%	1.7%	0.0%	4.3%	9.1%	0.0%
India	3.4%	1.7%	3.6%	2.2%	3.0%	0.0%
Number of Publications	292	116	56	46	33	17

Source: Refer to Figure 3.1. Percentages are based on the number of records associated with each subarea divided into the number with an author affiliated with an organization in the country.

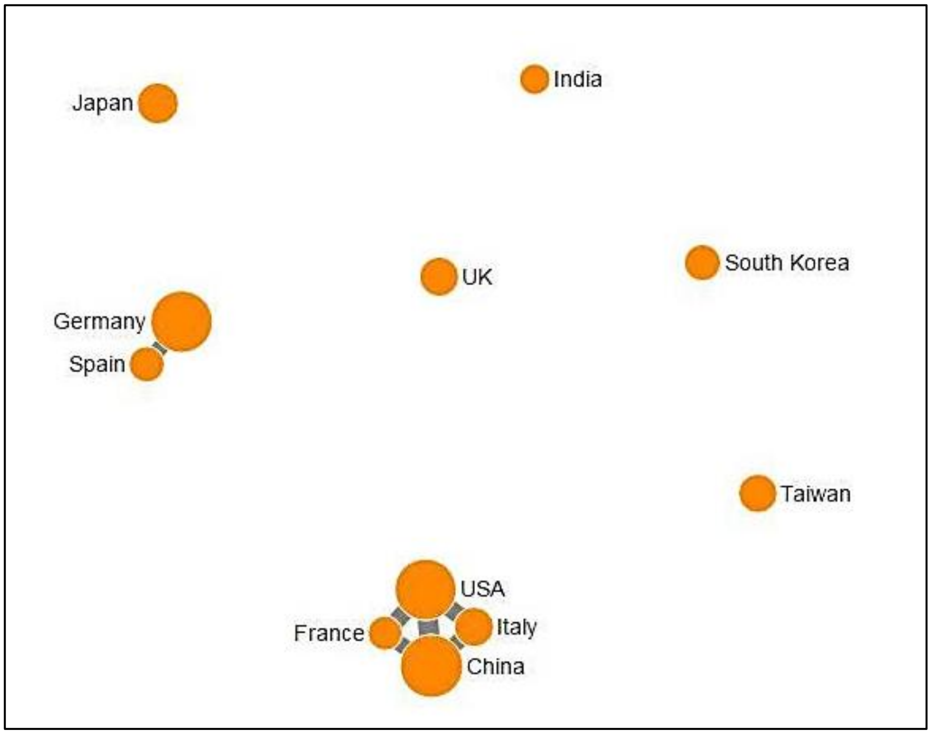
Thirteen percent of German authors' research publications involve collaborators from the five comparison countries plus the other contextual countries with similar publication outputs (Figure 3.2). German co-authors most commonly collaborate with authors from the US, UK, China, and Italy, but there is only one smart factory article with a South Korean co-author and only two with a co-author from India. The smart factory area has more multi-country papers than was evidenced in smart home research. For example, only 18 of the 31 German-US co-authored papers solely involve authors from these two countries; the other papers involve co-authors from at least three countries, including nine also involving Chinese co-authors. The network plot of keyword similarities shows that Germany and Spain are working on similar smart factory topics, while another group of four countries—China, the US, Italy and France—are working a different set of common topics (Figure 3.3). German smart factory authors distinctively work on digital factory, human-machine interaction, learning, and augmented reality topics.

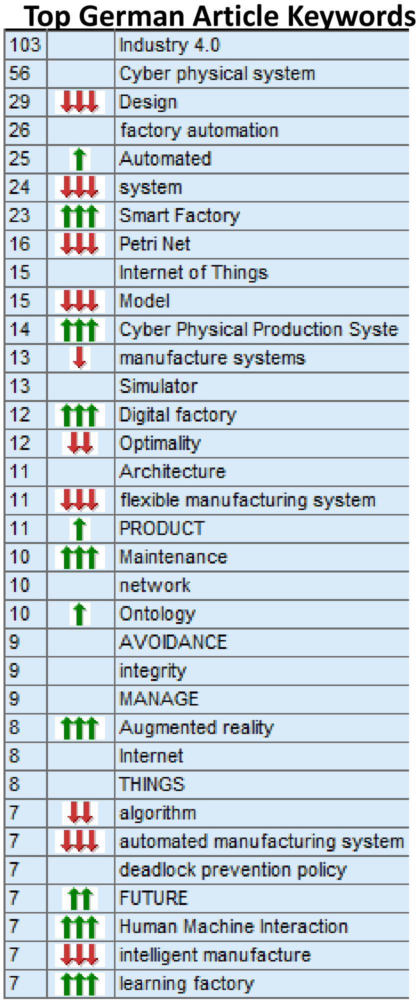
Figure 3.2. German Co-author Affiliations by Selected Countries



Source: Refer to Figure 3.1.

Figure 3.3. Smart Factory Country Co-occurrence based on Cosine Keyword Similarity
Arrows next to German article keywords represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).




Top German Article Keywords

103		Industry 4.0
56		Cyber physical system
29	↓↓↓	Design
26		factory automation
25	↑	Automated
24	↓↓↓	system
23	↑↑↑	Smart Factory
16	↓↓↓	Petri Net
15		Internet of Things
15	↓↓↓	Model
14	↑↑↑	Cyber Physical Production Syste
13	↓	manufacture systems
13		Simulator
12	↑↑↑	Digital factory
12	↓↓	Optimality
11		Architecture
11	↓↓↓	flexible manufacturing system
11	↑	PRODUCT
10	↑↑↑	Maintenance
10		network
10	↑	Ontology
9		AVOIDANCE
9		integrity
9		MANAGE
8	↑↑↑	Augmented reality
8		Internet
8		THINGS
7	↓↓	algorithm
7	↓↓↓	automated manufacturing system
7		deadlock prevention policy
7	↑↑	FUTURE
7	↑↑↑	Human Machine Interaction
7	↓↓↓	intelligent manufacture
7	↑↑↑	learning factory

The top organizations with 40 or more smart factory publications based on author affiliation are Xidian University (China), New Jersey Institute of Technology (US), Tongji Univ (China), Guangdong University of Technology (China), Tech University of Munich (Germany), and Rhein Westfal TH Aachen (Germany). In addition, University of Stuttgart-affiliated authors produced 37 smart factory publications. Table 3.4 lists the top German authors by number of publications in the smart factory area, alongside their organizational affiliations. Although many are universities, also involved are research institutes– the German Research Center for Artificial Intelligence (DFKI), the Application Center Industrial Automation IOSB-INA, and an employers' federation—Employers Federation Südwestmetall.

Table 3.3. Top Organizational Affiliations by Number of Smart Factory Publications

Top Global Organizations	# Publications		Top German Organizations	# Publications
Xidian Univ	110		Tech Univ Munich	43
New Jersey Inst Technol	92		Rhein Westfal TH Aachen	42
Tongji Univ	52		Univ Stuttgart	37
Guangdong Univ Technol	43		Siemens AG	16
Tech Univ Munich	43		Tech Univ Darmstadt	16
Rhein Westfal TH Aachen	42		Tech Univ Berlin	16
Chinese Acad Sci	39		Univ Halle Wittenberg	15
Natl Tsing Hua Univ	38		Tech Univ Dresden	14
Univ Stuttgart	37		Univ Bremen	13
Tampere Univ Technol	35		Univ Erlangen Nurnberg	12
			Univ Magdeburg	12

Source: Refer to Figure 3.1.

Table 3.4. Top German Affiliated Authors by Number of Smart Factory Publications

Top German Affiliated Authors	Organization	# Publications
Vogel-Heuser, Birgit	Tech Univ Munich	15
Franke, Joerg	Univ Erlangen Nurnberg	9
Diedrich, Christian	Univ Magdeburg	8
Jasperneite, Juergen	Fraunhofer Applicat Ctr Ind Automat IOSB INA	8
Jeschke, Sabina	Rhein Westfal TH Aachen	8
Dick, Peer-Michael	Head Office, Südwestmetall, Stuttgart	7
Thoben, Klaus-Dieter	Univ Bremen	7
Reinhart, Gunther	Tech Univ Munich	7
Schuh, Guenther	Univ Aachen	7
Anderl, Reiner	Tech Univ Darmstadt	6
Brecher, Christian	Univ Aachen	6
Gorecky, Dominic	German Res Ctr Artificial Intelligence DFKI	6
Lueder, Arndt	Univ Magdeburg	6
Potente, Till	Rhein Westfal TH Aachen	6
Trsek, Henning	Ostwestfalen Lippe Univ Appl Sci	6
Weyrich, Michael	Univ Stuttgart	6

Source: Refer to Figure 3.1.

The top 10% of highly cited smart factory publications received 10 or more citations. In part because Germany has so much output in this area, it has a smaller share of total output with 10 or more citations (Table 3.5). Japan also has a smaller share of highly cited papers, whereas India's share of highly cited papers is more than twice its output share, albeit from a much smaller base of works than Germany has. There are 11 smart factory publications that received 150 or more citations (Table 3.6). These publications cover topics such as control methodologies, industrial wireless sensor networks, cloud manufacturing, agent-based systems in smart manufacturing, agile manufacturing control architectures, and inductive power transfer.

Table 3.5. Top 10% of Highly Cited Smart Factory Publications by Country

Countries	Top 10% of Highly Cited Publications (10+ times cited)*	
	# Publications in Top 10%	% of Publications in Top 10% (394 Publications)
China	108	27.4%
Germany	37	9.4%
USA	118	29.9%
Japan	9	2.3%
Italy	24	6.1%
UK	30	7.6%
Taiwan	27	6.9%
South Korea	16	4.1%
Spain	15	3.8%
France	22	5.6%
India	18	4.6%

*The top 10% of highly cited publications is across the full distribution of highly cited publications in this system (394 publications); this subset of highly cited publications is then broken down by country to determine which country affiliations account for the greatest share of highly cited publications.

Table 3.6. List of Most Highly Cited Smart Home Publications (with 150 or more citations)

Title	Source	Countries	Times Cited
Control methodologies in networked control systems	CONTROL ENGINEERING PRACTICE	USA	540
Industrial Wireless Sensor Networks: Challenges, Design Principles, and Technical Approaches	IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS	Turkey, South Africa	469
From cloud computing to cloud manufacturing	ROBOTICS AND COMPUTER-INTEGRATED MANUFACTURING	New Zealand	343
Agent-based distributed manufacturing control: A state-of-the-art survey	ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE	Portugal	220
Applications of agent-based systems in intelligent manufacturing: An updated review	ADVANCED ENGINEERING INFORMATICS	Canada	205
Deadlock control methods in automated manufacturing systems	IEEE TRANSACTIONS ON SYSTEMS MAN AND CYBERNETICS PART A-SYSTEMS AND HUMANS	China, USA, Italy	201
Deadlock Resolution in Automated Manufacturing Systems A Novel Petri Net Approach Introduction	DEADLOCK RESOLUTION IN AUTOMATED MANUFACTURING SYSTEMS: A NOVEL PETRI NET APPROACH	China, USA, Italy	183
ADACOR: A holonic architecture for agile and adaptive manufacturing control	COMPUTERS IN INDUSTRY	Portugal	176
Auto ID systems and intelligent manufacturing control	ENGINEERING APPLICATIONS OF ARTIFICIAL INTELLIGENCE	USA, UK	172
Inductive Power Transfer	PROCEEDINGS OF THE IEEE	New Zealand	164
Modern Trends in Inductive Power Transfer for Transportation Applications	IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS	New Zealand	152

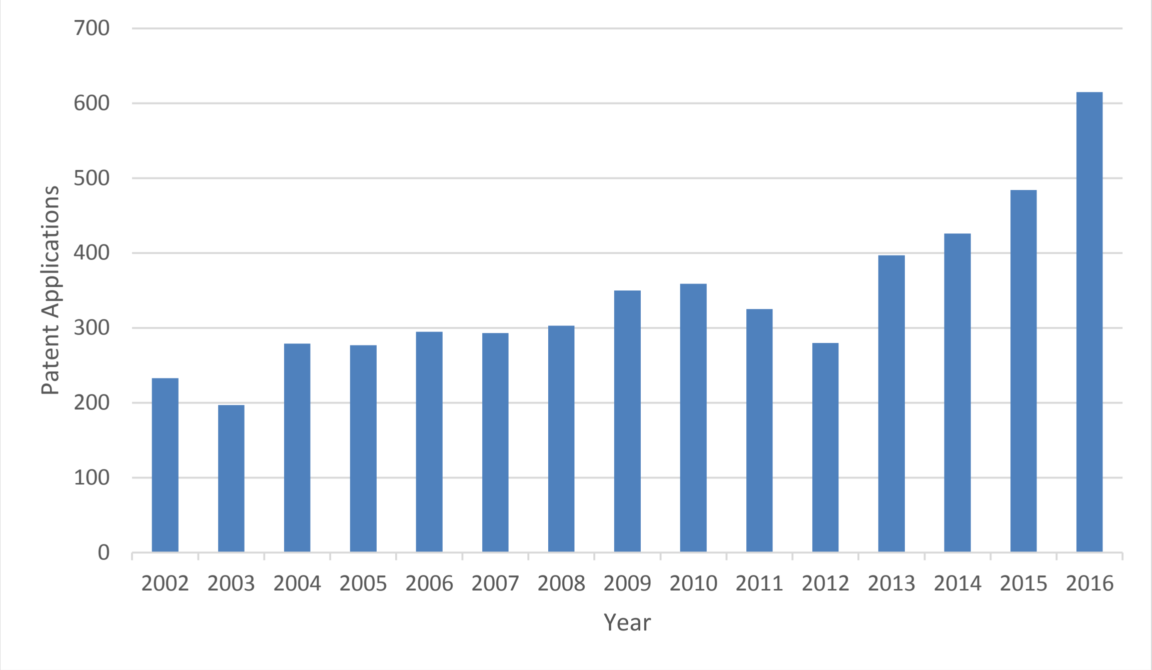
Source: Refer to Figure 3.1.

In sum, Germany is the leader in smart factory research output. It is a leading producer of publications across the technology catalogue, with particular prominence in sensor fusion, representation, and localization. Germany has diverse types of organizations involved in this research including universities, research institutes and an employers' federation.

3.2. Smart Factory Patents

There were more than 5,100 smart factory patents in DII from 2002 to 2016. A modest increase in patents occurred from the earlier 2002-2010 period to 2011-2016 period (Figure 3.4). Germany produced 352 smart factory patents over the 2002 to 2016 study period, or 7% of the total number of patents in this domain. Germany's patent share is below that of Japan, China, the US, and South Korea. China had the greatest growth in number of smart factory patents and surpassed Japan to become the largest patenting country in this autonomous system in the latter time period (Table 3.7).

Figure 3.4. Number of Smart Factory Patents by Patent Publication Year: 2002-2016



Source: Smart Factory patents, 2002–2016, (N = 5,113 Derwent Innovation Index). See text for search strategy.

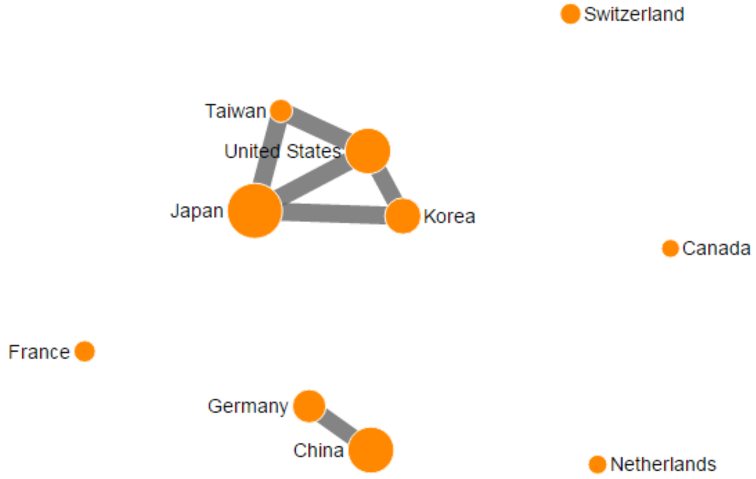
Table 3.7. Top Countries by Number of Smart Factory Patents

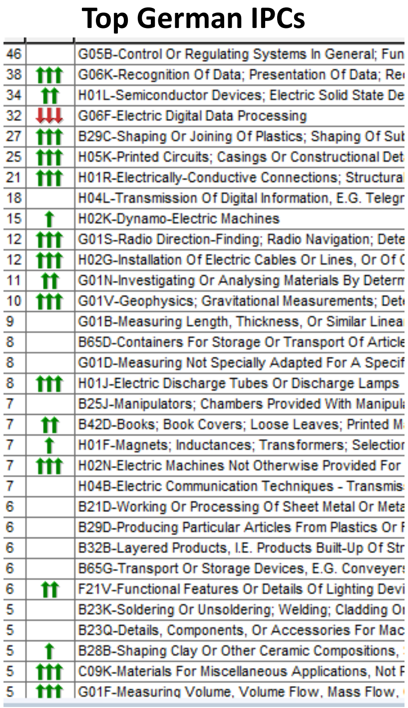
Countries	# Patents	Share (%)	# in 2002-2010	# in 2011-2016
Japan	1467	28.7%	1077	390
China	913	17.9%	121	792
United States	890	17.4%	490	400
South Korea	456	8.9%	219	237
Germany	352	6.9%	174	178
India	8	0.2%	1	7

Source: Refer to Figure 3.4. Country share is based on the count of patents assigned to organizations in the country divided by the total number of patents in Figure 3.4. Note individual assignees are not included.

An examination of IPC patent similarities shows that there were two clusters of countries (Figure 3.5). The first was a cluster of German and Chinese patents, suggesting that these two countries have the greatest concordance in their patent classes (Figure 3.2). The most common IPC subclasses among German patents were Control or Regulation System (G05B), Recognition of Data (G06K), Semiconductor Devices (H01L), and Electric Digital Data Processing (G05F) technologies, although Electric Digital Data Processing IPC category appears less among German patents than among patents in other countries. The second was a cluster of Japanese, US, South Korean and Taiwanese patents.

Figure 3.5. Smart Factory Country Co-occurrence based on Cosine IPC Similarity
Arrows next to German patent IPCs represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).




Top German IPCs

46		G05B-Control Or Regulating Systems In General; Fun
38	↑↑↑	G06K-Recognition Of Data; Presentation Of Data; Re
34	↑↑	H01L-Semiconductor Devices; Electric Solid State De
32	↓↓↓	G06F-Electric Digital Data Processing
27	↑↑↑	B29C-Shaping Or Joining Of Plastics; Shaping Of Su
25	↑↑↑	H05K-Printed Circuits; Casings Or Constructional Det
21	↑↑↑	H01R-Electrically-Conductive Connections; Structura
18		H04L-Transmission Of Digital Information, E.G. Telegr
15	↑	H02K-Dynamo-Electric Machines
12	↑↑↑	G01S-Radio Direction-Finding; Radio Navigation; Dete
12	↑↑↑	H02G-Installation Of Electric Cables Or Lines, Or Of
11	↑↑	G01N-Investigating Or Analysing Materials By Determ
10	↑↑↑	G01V-Geophysics; Gravitational Measurements; Det
9		G01B-Measuring Length, Thickness, Or Similar Linea
8		B65D-Containers For Storage Or Transport Of Article
8		G01D-Measuring Not Specially Adapted For A Specif
8	↑↑↑	H01J-Electric Discharge Tubes Or Discharge Lamps
7		B25J-Manipulators; Chambers Provided With Manipul
7	↑↑	B42D-Books; Book Covers; Loose Leaves; Printed M
7	↑	H01F-Magnets; Inductances; Transformers; Selectio
7	↑↑↑	H02N-Electric Machines Not Otherwise Provided For
7		H04B-Electric Communication Techniques - Transmis
6		B21D-Working Or Processing Of Sheet Metal Or Meta
6		B29D-Producing Particular Articles From Plastics Or
6		B32B-Layered Products, I.E. Products Built-Up Of Str
6		B65G-Transport Or Storage Devices, E.G. Conveyer
6	↑↑	F21V-Functional Features Or Details Of Lighting Devi
5		B23K-Soldering Or Unsoldering; Welding; Cladding O
5		B23Q-Details, Components, Or Accessories For Mac
5	↑	B28B-Shaping Clay Or Other Ceramic Compositions,
5	↑↑↑	C09K-Materials For Miscellaneous Applications, Not
5	↑↑↑	G01F-Measuring Volume, Volume Flow, Mass Flow,

Source: Refer to Figure 3.4

The top organizations with 50 or more smart factory patents based on assignees are mostly from Japan. They include Omron (Japan), Mitsubishi Electric (Japan), Rockwell Automation Technologies (US), Yaskawa Electric (Japan), Sharp (Japan) and Matsushita (Japan) (Table 3.8). The top German organizations with 10 or more smart factory patents represent industrial automation, semiconductor, and automotive industries: Siemens, Sick, Bosch, Infineon Technologies, and Daimler (Table 3.9).

Table 3.8. Top Global Organizations by Number of Smart Factory Patents

Name	Country	# Patents
Omron KK	Japan	154
Mitsubishi Electric CORP	Japan	147
Rockwell Automation Technologies INC	USA	96
Yasakawa Electric CORP	Japan	88
Sharp KK	Japan	58
Matsushita Denki Sangyo KK	Japan	53

Source: Refer to Figure 3.4.

Table 3.9. Top Five German Organizations by Number of Smart Factory Patents

Name	# Patents
Siemens AG	35
Sick AG	18
Bosch GMBH	13
Infineon Technologies AG	13
Daimler AG	10

Source: Refer to Figure 3.4.

The top 5% highly cited smart factory patents received 10 or more citations. Out of 188 top 5% cited patents, 7 patents were from Germany (around 4%), which is lower than those of the US and Japan but higher than those of China, South Korea and India (Table 3.10). Among the highly cited patents, five patents have received 70 or more citations, which were all assigned to US organizations) (Table 3.11).

Table 3.10. Top 5% of Highly Cited Smart Factory Patents by Country (10 + citations)

Countries	Top 5% of Highly Cited Patents (10+ times cited) (188 patents)*	
	# Patents in Top 5%	% of Patents in Top 5%
United States	101	53.7%
Japan	37	19.7%
Germany	7	3.7%
Korea	6	3.2%
China	3	1.6%
India	0	0.0%

*The top 5% of highly cited patents is across the full distribution of patents in this system (188 patents); this subset of highly cited patents is then broken down by country to determine which country affiliations account for the greatest share of highly cited patents. Samples are restricted to 3,535 patents with citation information available from PatStat database.

Table 3.11. List of Highly Cited Smart Factory Patents (100 +citations)

Patent Publication Number	Title	Assignees	Country	Times Cited
US 6402028	Integrated production of smart cards	Visa International Service Association	USA	145
US 6624388	Distributed welding system for vehicle assembly	The Lincoln Electric Company	USA	127
US 2004002943	System management framework for configuration management of personal digital assistant and mobile telephone	Individuals	USA	111
US 6847856	Computer implemented method for determining physical juxtaposition between components for automated manufacturing system	Lucent Technologies Inc	USA	100

Source: Refer to Figure 3.4.

Out of the 1,428 prior art sources that German smart factory patents have cited, 145 citations or 10% were to NPL (Table 3.12). This share is higher than Japan, China, and South Korea but lower than the US. This share is much higher than Germany's 7% smart factory total patent output share. German patents' use of NPL is second only to the US, which indicates strong science-based elements of German smart factory patents.

Table 3.12. List of Countries by Number and Share of Non-Patent Literature (NPL)

Country	NPL	Patent Citations	Total Citations	Share of NPL
United States	867	5435	6302	13.8%
Germany	145	1283	1428	10.2%
Japan	73	1942	2015	3.6%
China	49	568	617	7.9%
South Korea	14	511	525	2.7%
India	8	8	16	50.0%

Source: Refer to Figure 3.4. Samples are restricted to 3,535 patents with citation information available from PatStat database.

In terms of patent families, 18% of the top 5% patent families, or 62 patents, were assigned to German organizations (Table 3.13). This number falls behind the US (134 patents) and Japan (105 patents). Despite the growth of smart factory patents in China, only two of its patents were applied to more than four patent authorities, which indicates that China's smart factory patent portfolio is primarily for domestic purposes.

Table 3.13. Top 5% of Patent Families by Country (5+ Patent Families)

Countries	Top 5% of Patent Families by Country (5+ Families) (392 Patents)*	
	# Patents in Top 5%	% of Patents in Top 5%
United States	134	34.2%
Japan	105	26.8%
Germany	62	15.8%
Korea	18	4.6%
China	2	0.5%
India	1	0.3%

*The top 5% of patent families is across the full distribution of patents in this system (392 patents); this subset of patents with multiple families is then broken down by country to determine which country affiliations account for the greatest share of the top 5% family patents. Samples are restricted to 3,535 patents with citation information available from PatStat database.

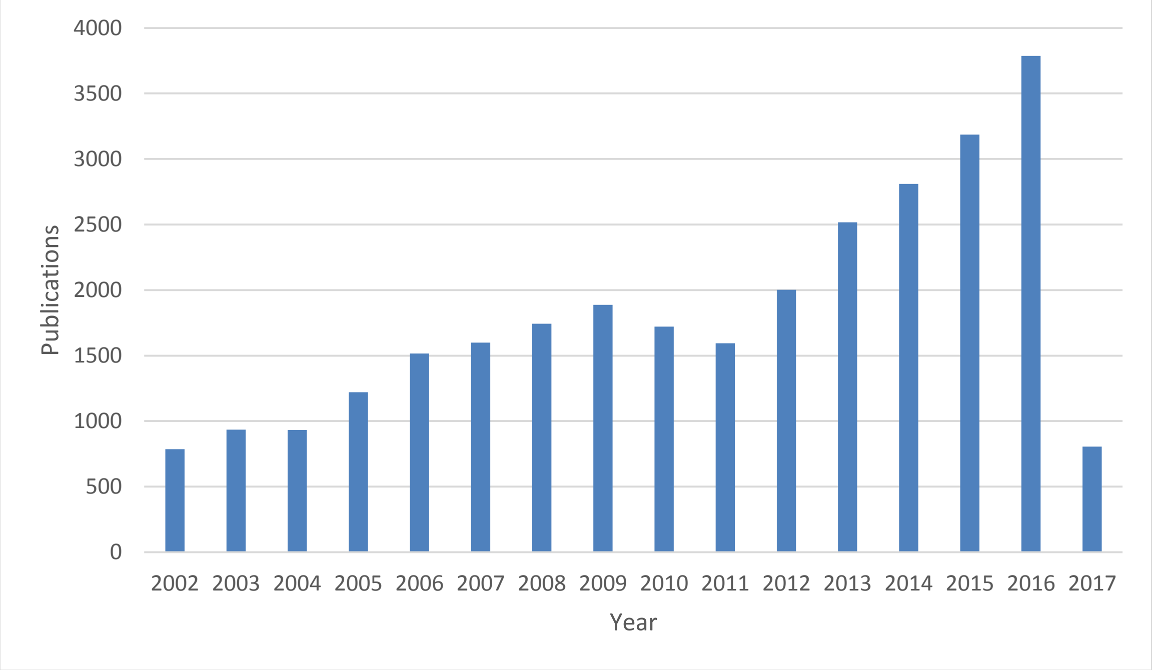
Overall, Germany is among the top smart factory patent players although its share has not kept pace with the growth of Chinese patents. Among the major smart factory patenting countries, German patents are most similar to Chinese patents in terms of their distribution across IPC technology categories. However, German patents are more tightly based in NPL and more likely to be taken in multiple countries. The most active German patenting firms in smart factory technologies are diverse, ranging from industrial manufacturing companies, semiconductor companies, and automobile manufacturing companies.

Chapter 4. Autonomous Vehicles

Chapter 4.1. Autonomous Vehicles Publications

Autonomous vehicles is the largest of the four autonomous systems, comprising more than 29,000 research publications in the WoS over the study period. The number of publications in the 2011-2017 time period was 35% higher than in the 2002-2010 time period. The greatest rise in publications is from 2012 to 2013, in which more than 500 autonomous vehicles publications were issued, a 26% increase over the previous year (Figure 4.1).

Figure 4.1. Number of Autonomous Vehicle Publications by Publication Year: 2002-2017 (May)



Source: Autonomous vehicle publications, 2002–2017 (May), (N = 29,045 Web of Science records). See text for search strategy.

Table 4.1. Top Countries by Number of Autonomous Vehicle Publications

Countries	# Publications	Share (%)	# in 2002-2010	# in 2011-2017
USA	5648	19.4%	2803	2845
China	4760	16.4%	3209	1551
Germany	2022	7.0%	1163	859
Japan	1919	6.6%	899	1020
South Korea	1794	6.2%	1020	774
Spain	1448	5.0%	777	671
France	1358	4.7%	802	556
Canada	1121	3.9%	623	498
Italy	1117	3.8%	654	463
UK	1109	3.8%	686	423
Australia	927	3.2%	527	400
Taiwan	720	2.5%	425	295
India	677	2.3%	525	152

Source: Refer to Figure 4.1. Country share is based on the count of publications with an author affiliated with an organization in the country divided by the total number of records in Figure 4.1.

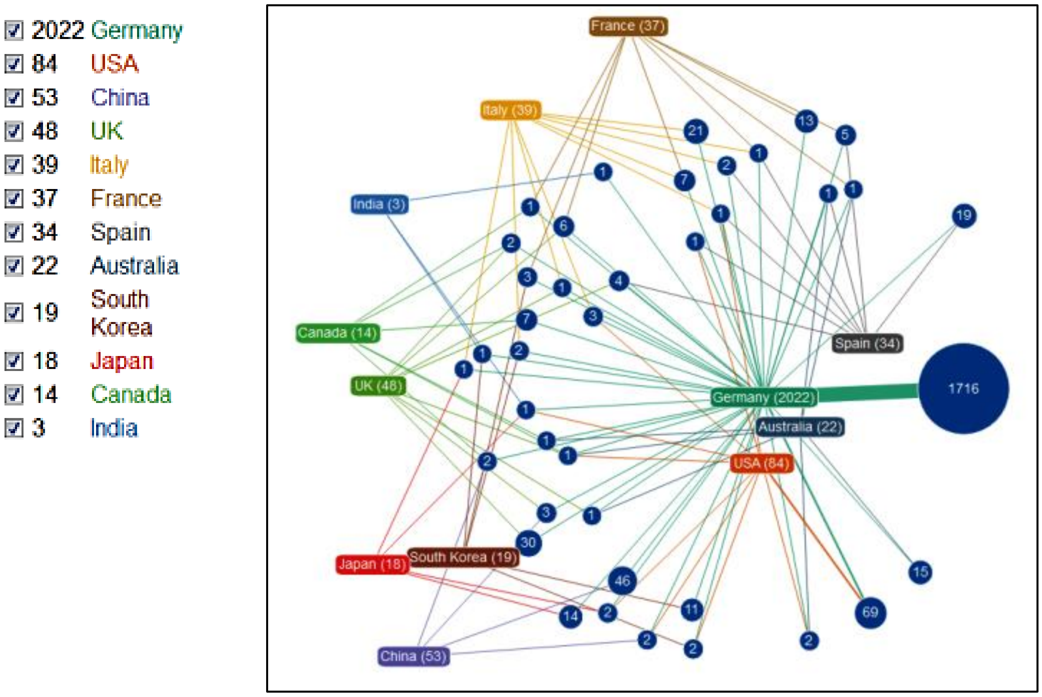
Table 4.2. Countries by Autonomous Vehicle Research Subarea

Country	Autonomous Vehicle Research Subarea					
	localization	data analysis	representation	sensor fusion	computer vision	machine learning
USA	15.3%	22.9%	18.8%	15.9%	23.0%	22.1%
China	15.7%	14.3%	7.5%	19.1%	10.2%	12.9%
Germany	8.8%	9.3%	12.7%	8.4%	5.0%	9.2%
Japan	8.5%	3.1%	4.7%	4.0%	4.3%	4.6%
South Korea	9.9%	5.7%	3.5%	8.9%	4.5%	5.0%
Spain	6.4%	6.3%	7.7%	4.2%	10.9%	7.9%
France	4.7%	4.4%	7.0%	5.0%	2.8%	2.9%
Canada	3.8%	3.3%	3.1%	3.5%	2.9%	4.2%
Italy	4.6%	5.2%	4.5%	5.0%	5.4%	4.6%
UK	3.1%	5.0%	5.8%	3.1%	2.8%	5.8%
Australia	3.0%	3.6%	4.5%	3.8%	4.8%	3.8%
Taiwan	2.9%	1.0%	1.0%	3.0%	3.1%	0.4%
India	1.4%	2.1%	1.5%	1.7%	3.5%	5.4%
Number of Publications	4,346	1,199	1,051	947	578	240

Source: Refer to Figure 4.1. Percentages are based on the number of records associated with each subarea divided into the number with an author affiliated with an organization in the country. Percentages cannot be summed to a total because a publication may involve multiple subareas and author-affiliated countries.

Germany is the third largest producer of autonomous vehicle research publications over the full study period, after the US and China; Japan and South Korea rank fourth and fifth (Table 4.1). It is interesting that four of the top five autonomous vehicle research producing countries are also leading automobile exporters (China manufactures automobiles primarily for its domestic market). Seven percent of autonomous vehicle publications over the 2002-2017 period had a German-affiliated author. German-affiliated research papers grew at the overall average of 35% from the 2002-2010 to the 2011-2017 periods. China had the greatest gains in autonomous vehicle research papers, more than doubling between the earlier and later time periods. Germany is relatively stronger in representation technologies concerning autonomous vehicles, with German authors accounting for 13% of the autonomous vehicles publications in this area (Table 4.2). China is most prominent in sensor fusion autonomous vehicle publications, while the US is stronger in computer vision, data analysis, and machine learning autonomous vehicle papers.

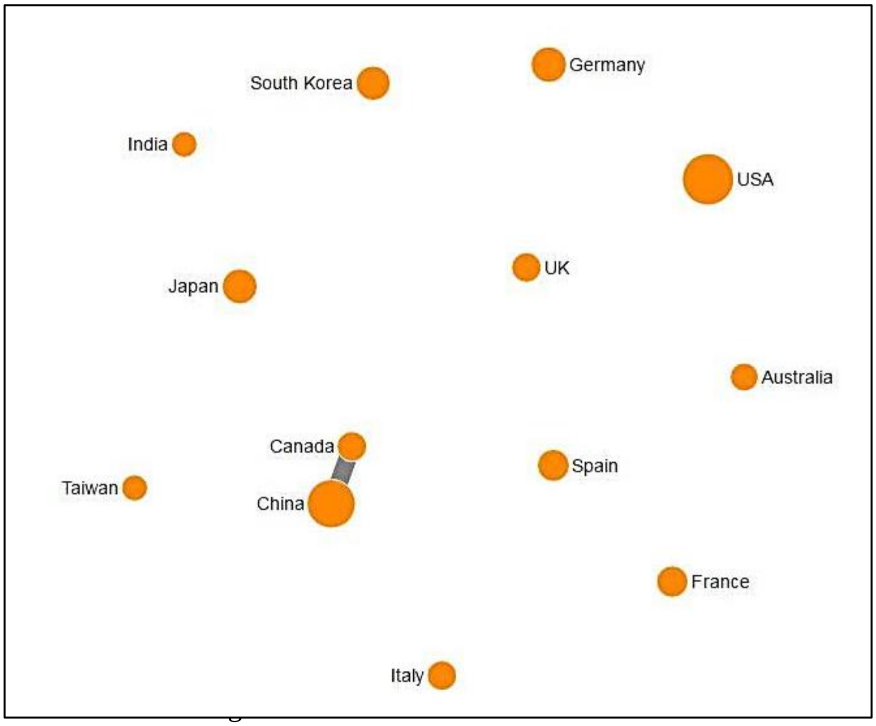
Figure 4.2. German Co-author Affiliations by Selected Countries



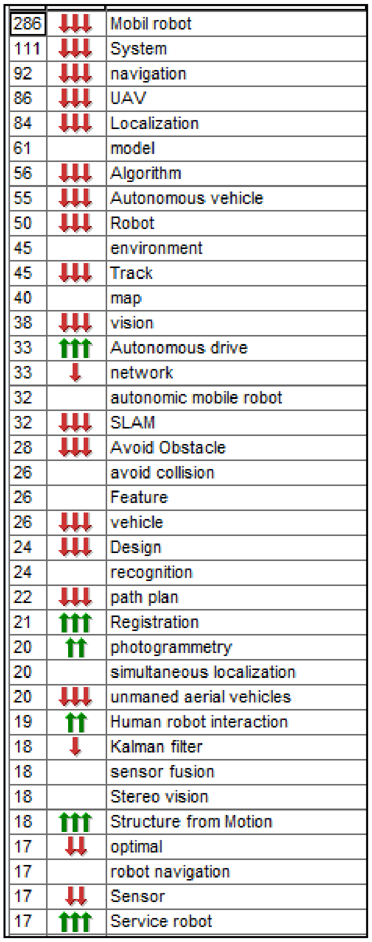
Source: Refer to Figure 4.1

Fifteen percent of German authors' research publications involve collaborators from the five comparison countries plus the other contextual countries with similar publication outputs (Figure 4.2). German co-authors most commonly collaborate with authors from the US, China, and the UK; there are only three with a co-author from India. Fifteen of the 84 German-US co-authored papers have a co-author from another country; the rest are bilateral papers between authors from the two countries. Likewise, seven of the 53 Chinese-authored papers have authors from Germany plus at least one other country. The same is true for seven of the 19 German-South Korean authored papers and four of the 18 German-Japanese autonomous system papers. The network plot of keyword similarities shows that most countries are working on autonomous vehicle research topics that are idiosyncratic to the research interests prominent in the country. The exception is China and Canada, which are working on similar autonomous vehicle topics (Figure 4.3). German autonomous vehicle authors distinctively work on autonomous drive, registration, photogrammetry, human-robotic interaction, structure from motion, and service robotics topics.

Figure 4.3. Autonomous Vehicle Country Co-occurrence based on Cosine Keyword Similarity
Arrows next to German article keywords represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).



Top German Article Keywords



286	↓↓↓	Mobil robot
111	↓↓↓	System
92	↓↓↓	navigation
86	↓↓↓	UAV
84	↓↓↓	Localization
61		model
56	↓↓↓	Algorithm
55	↓↓↓	Autonomous vehicle
50	↓↓↓	Robot
45		environment
45	↓↓↓	Track
40		map
38	↓↓↓	vision
33	↑↑↑	Autonomous drive
33	↓	network
32		autonomic mobile robot
32	↓↓↓	SLAM
28	↓↓↓	Avoid Obstacle
26		avoid collision
26		Feature
26	↓↓↓	vehicle
24	↓↓↓	Design
24		recognition
22	↓↓↓	path plan
21	↑↑↑	Registration
20	↑↑	photogrammetry
20		simultaneous localization
20	↓↓↓	unmaned aerial vehicles
19	↑↑	Human robot interaction
18	↓	Kalman filter
18		sensor fusion
18		Stereo vision
18	↑↑↑	Structure from Motion
17	↓↓	optimal
17		robot navigation
17	↓↓	Sensor
17	↑↑↑	Service robot

Two organizations have 300 or more autonomous vehicle research papers: Carnegie Mellon University (US) and Chinese Academy of Sciences (China). Others top autonomous vehicle paper producing organizations include MIT (US), Beihang Univ (China), Korea Advanced Institute of Science & Technology (South Korea), National University of Defense Technology (China), Harbin Institute of Technology (China), Beijing Institute of Technology (China), CNRS (France), National University of Singapore (Singapore), Nanyang Technological University (Singapore), Seoul National University (South Korea), Georgia Institute of Technology (US), and Technical University of Munich (Germany). In addition to the 158 autonomous vehicle publications produced by authors from Technical University of Munich, authors affiliated with University of Freiburg produced 151 research papers. Table 4.4 lists the top German authors by number of publications they produced in the autonomous vehicles area, alongside their organizational affiliations. All are at universities except for Heinrich H. Buelthoff at the Max Planck Institute for Biological Cybernetics.

Table 4.3. Top Organizations by Number of Autonomous Vehicle Publications

Top Global Organizations	# Publications		Top German Organizations	# Publications
Carnegie Mellon Univ	356		Tech Univ Munich	158
Chinese Acad Sci	348		Univ Freiburg	151
MIT	274		Univ Tubingen	74
Beihang Univ	231		Univ Bonn	60
Korea Adv Inst Sci & Technol	221		Univ Stuttgart	50
Natl Univ Def Technol	214		Karlsruhe Inst Technol	48
Harbin Inst Technol	206		Tech Univ Carolo Wilhelmina Braunschweig	45
Beijing Inst Technol	195		Univ Paderborn	45
CNRS	195		Univ Bremen	44
Natl Univ Singapore	182		Univ Bielefeld	42
Nanyang Technol Univ	176		Univ Hamburg	41
Seoul Natl Univ	172		Univ Siegen	41
Georgia Inst Technol	165			
Tech Univ Munich	158			

Source: Refer to Figure 4.1.

Table 4.4. Top German Affiliated Authors by Number of Autonomous Vehicle Publications

Top German Affiliated Authors	Organization	# Publications
Burgard, Wolfram	Univ Freiburg	118
Zell, Andreas	Univ Tubingen	54
Stachniss, Cyrill	Univ Bonn	39
Buss, Martin	Tech Univ Munich	32
Zhang, Jianwei	Univ Hamburg	28
Stiller, Christoph	Karlsruhe Inst Technol	28
Wuensche, Hans Joachim	University of the Bundeswehr Munich	24
Birk, Andreas	Jacobs Univ Bremen	24
Schilling, Klaus	Univ Wurzburg	24
Behnke, Sven	Univ Bonn	23
Liu, Hui	Univ Rockstock	23
Stoll, Norbert	Univ Rockstock	22
Dillmann, Ruediger	Karlsruhe Inst Technol	22
Thurow, Kerstin	Univ Rockstock	22
Grisetti, Giorgio	Univ Freiburg	22
Wollherr, Dirk	Tech Univ Munich	21
Gross, Horst-Michael	Ilmenau Univ Technol	21
Knoll, Alois	Tech Univ Munich	21
Buelthoff, Heinrich H	Max Planck Inst Biol Cybernet	20

Source: Refer to Figure 4.1.

The top 10% of highly cited autonomous vehicle publications received 12 or more citations. Germany ranks second in number of highly cited autonomous vehicle publications with 250 or 9% of all highly cited papers. This percentage is similar to the overall output share of German authored papers, suggesting that German authored-publications in the autonomous vehicle area command the attention of the global research enterprise as would be expected based on output alone (Table 4.5). The US has the largest number of highly cited autonomous vehicles papers, accounting for nearly one-third of highly cited papers. China's autonomous systems papers are not much cited compared to its overall share of output, although there are more than 200 papers with a Chinese author that are within this study's highly-cited-threshold. Japan's share of highly cited papers is slightly below its share of output as is South Korea, while India has more highly cited papers than what would be expected based on its share of output. There are 10 autonomous systems publications that received 150 or more citations (Table 4.6). These most highly cited autonomous vehicle research publications cover topics such as mobile sensing networks, real-time cameras, fuzzy control systems, robotics, nanorobots, vision, unicycles, and urban environments.

Table 4.5. Top 10% of Highly Cited Autonomous Vehicle Publications by Country

Countries	Top 10% of Highly Cited Publications (12+ times cited)* (2,919 Publications)	
	# Publications in Top 10%	% of Publications in Top 10%
USA	947	32.4%
China	229	7.8%
Germany	250	8.6%
Japan	125	4.3%
South Korea	145	5.0%
Spain	241	8.3%
France	186	6.4%
Canada	151	5.2%
Italy	173	5.9%
UK	160	5.5%
Australia	155	5.3%
Taiwan	77	2.6%
India	40	1.4%

*The top 10% of highly cited publications is across the full distribution of highly cited publications in this system (2,919 publications); this subset of highly cited publications is then broken down by country to determine which country affiliations account for the greatest share of highly cited publications.

Table 4.6. List of Most Highly Cited Autonomous Vehicle Publications (with 400 or more citations)

Title	Source	Countries	Times Cited
Coverage control for mobile sensing networks	IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION	USA, Spain	941
MonoSLAM: Real-time single camera SLAM	IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE	UK, Japan	908
A survey on analysis and design of model-based fuzzy control systems	IEEE TRANSACTIONS ON FUZZY SYSTEMS	China	793
Robotics Modelling, Planning and Control Introduction	ROBOTICS: MODELLING, PLANNING AND CONTROL	Italy	633
Distributed multi-vehicle coordinated control via local information exchange	INTERNATIONAL JOURNAL OF ROBUST AND NONLINEAR CONTROL	USA	612
A Logic-Gated Nanorobot for Targeted Transport of Molecular Payloads	SCIENCE	USA	557
A vision-based formation control framework	IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION	USA	554
Necessary and sufficient graphical conditions for formation control of unicycles	IEEE TRANSACTIONS ON AUTOMATIC CONTROL	Canada	475
A hierarchical type-2 fuzzy logic control architecture for autonomous mobile robots	IEEE TRANSACTIONS ON FUZZY SYSTEMS	UK	447
Autonomous Driving in Urban Environments: Boss and the Urban Challenge	JOURNAL OF FIELD ROBOTICS	USA	426

Source: Refer to Figure 4.1.

In sum, Germany is a top-three country in autonomous vehicles research output and highly cited research. Most of the research comes from universities. German research is particularly strong in representation technologies.

4.2. Autonomous Vehicles Patents

More than 6,000 patents related to autonomous vehicle technologies were filed and captured from the DII patent index from 2002 to 2016. During the earlier period (2002-2010), autonomous vehicle patents grew steadily until 2009, at which time their growth plateaued (Figure 4.4). During this period, some 2,000 autonomous vehicle patents were filed. The later period (2011-2016) witnessed more rapid growth with more than 4,000 patents filed. A 60% growth in patents took place from 2015 to 2016. . Patents filed by Japanese companies dominated the initial period, while the later period saw the rise of US and Chinese autonomous vehicle patents. German organizations filed 554 patents or 9% of the autonomous vehicle patent portfolio, which makes Germany fifth largest player behind Japan, the US, China and South Korea, respectively (Table 4.7).[6]

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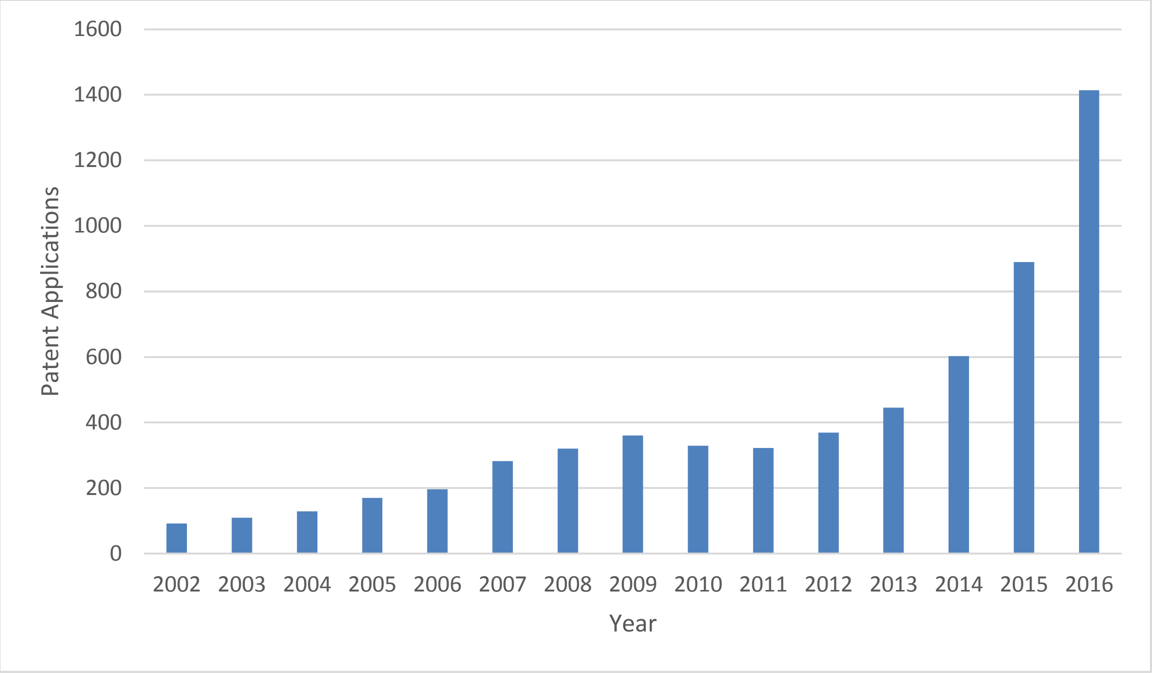
[6] A study by the Institut der deutschen Wirtschaft Köln published 28 August 2017 shows that Germany dominates the autonomous vehicle patent domain, with German organizations filing the majority of patent applications in the autonomous vehicle domain, and Bosch having filed a much larger number than any other organization. This study

Figure 4.4. Number of Autonomous Vehicle Patents by Patent Publication Year: 2002-2016



Source: Autonomous Vehicle patents, 2002–2016, (N = 6,030 Derwent Innovation Index). See text for search strategy.

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uses World Intellectual Property Office (WIPO) PATENTSCOPE searches of international patent cooperation treaty (PCT) applications. We find similar results if we only look at these PCT patent documents. Our analysis, however, is based on a search of more than 40 patent authorities worldwide. Thus it encompasses more patents from countries such as China, which rarely file internationally, and countries such as Japan and South Korea, which file internationally to a lesser extent than do US or German organizations.

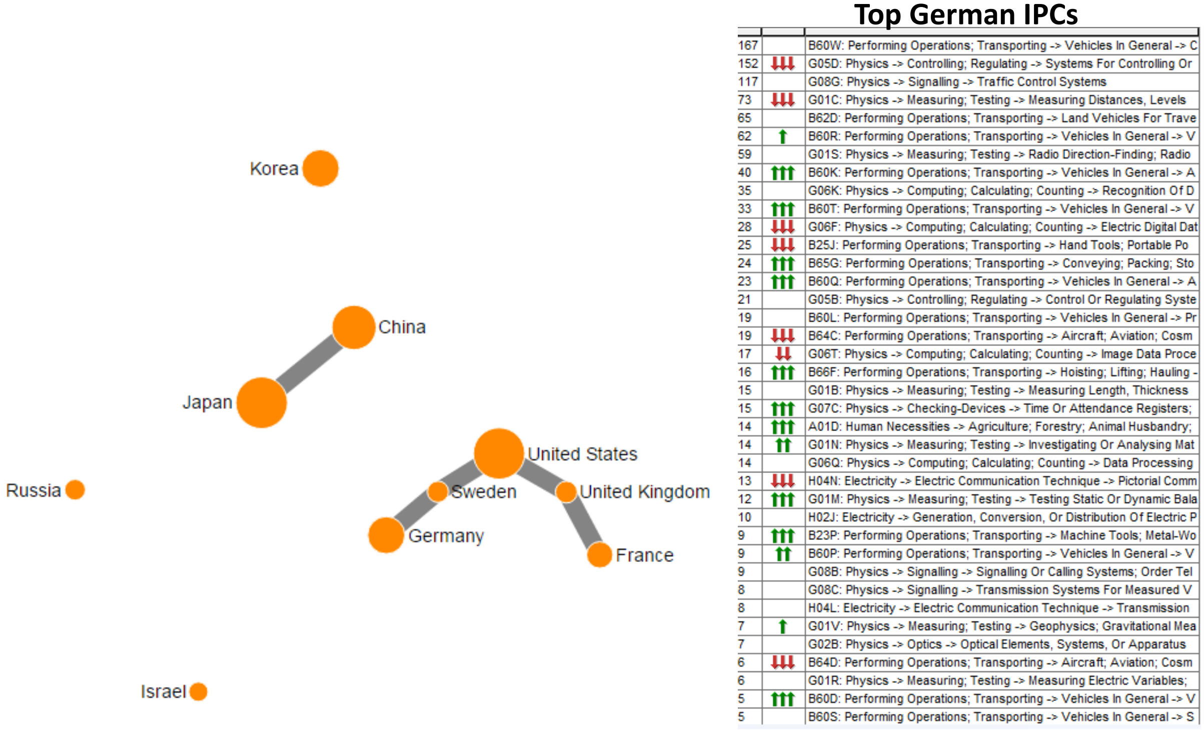
Table 4.7. Top Countries by Number of Autonomous Vehicle Patents

Countries	# Patents	Share (%)	# in 2002-2010	# in 2011-2016
Japan	1370	22.7%	886	484
United States	1347	22.3%	281	1066
China	914	15.2%	95	819
South Korea	577	9.6%	190	387
Germany	554	9.2%	130	424
India	16	0.3%	1	15

Source: Refer to Figure 4.4. Country share is based on the count of patents assigned to organizations in the country divided by the total number of patents in Figure 4.4. Note individual assignees are not included.

Based on IPC co-occurrence, German patents are most similar to Swedish, US, UK, and French patents (Figure 4.5). Japan and China comprise another distinct group of common autonomous system. The most prevalent IPC subclasses in German patents include B60W (Joint Control of Vehicle Subunits), G05D (Systems for Controlling or Regulating Non-Electronic Variables), G08G (Traffic Control Systems), and G01C (Measuring Distance, Levels or Bearings).

Figure 4.5. Autonomous Vehicle Country Co-occurrence based on Cosine IPC Similarity
Arrows next to German patent IPCs represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).



Top German IPCs

167		B60W: Performing Operations; Transporting -> Vehicles In General -> C
152	↓↓↓	G05D: Physics -> Controlling; Regulating -> Systems For Controlling Or
117		G08G: Physics -> Signalling -> Traffic Control Systems
73	↓↓↓	G01C: Physics -> Measuring; Testing -> Measuring Distances, Levels
65		B62D: Performing Operations; Transporting -> Land Vehicles For Trave
62	↑	B60R: Performing Operations; Transporting -> Vehicles In General -> V
59		G01S: Physics -> Measuring; Testing -> Radio Direction-Finding; Radio
40	↑↑↑	B60K: Performing Operations; Transporting -> Vehicles In General -> A
35		G06K: Physics -> Computing; Calculating; Counting -> Recognition Of D
33	↑↑↑	B60T: Performing Operations; Transporting -> Vehicles In General -> V
28	↓↓↓	G06F: Physics -> Computing; Calculating; Counting -> Electric Digital Dat
25	↓↓↓	B25J: Performing Operations; Transporting -> Hand Tools; Portable Po
24	↑↑↑	B65G: Performing Operations; Transporting -> Conveying; Packing; Sto
23	↑↑↑	B60Q: Performing Operations; Transporting -> Vehicles In General -> A
21		G05B: Physics -> Controlling; Regulating -> Control Or Regulating Syste
19		B60L: Performing Operations; Transporting -> Vehicles In General -> Pr
19	↓↓↓	B64C: Performing Operations; Transporting -> Aircraft; Aviation; Cosm
17	↓↓	G06T: Physics -> Computing; Calculating; Counting -> Image Data Proce
16	↑↑↑	B66F: Performing Operations; Transporting -> Hoisting; Lifting; Hauling -
15		G01B: Physics -> Measuring; Testing -> Measuring Length, Thickness
15	↑↑↑	G07C: Physics -> Checking-Devices -> Time Or Attendance Registers;
14	↑↑↑	A01D: Human Necessities -> Agriculture; Forestry; Animal Husbandry;
14	↑↑	G01N: Physics -> Measuring; Testing -> Investigating Or Analysing Mat
14		G06Q: Physics -> Computing; Calculating; Counting -> Data Processing
13	↓↓↓	H04N: Electricity -> Electric Communication Technique -> Pictorial Comm
12	↑↑↑	G01M: Physics -> Measuring; Testing -> Testing Static Or Dynamic Bala
10		H02J: Electricity -> Generation, Conversion, Or Distribution Of Electric P
9	↑↑↑	B23P: Performing Operations; Transporting -> Machine Tools; Metal-Wo
9	↑↑	B60P: Performing Operations; Transporting -> Vehicles In General -> V
9		G08B: Physics -> Signalling -> Signalling Or Calling Systems; Order Tel
8		G08C: Physics -> Signalling -> Transmission Systems For Measured V
8		H04L: Electricity -> Electric Communication Technique -> Transmission
7	↑	G01V: Physics -> Measuring; Testing -> Geophysics; Gravitational Mea
7		G02B: Physics -> Optics -> Optical Elements, Systems, Or Apparatus
6	↓↓↓	B64D: Performing Operations; Transporting -> Aircraft; Aviation; Cosm
6		G01R: Physics -> Measuring; Testing -> Measuring Electric Variables;
5	↑↑↑	B60D: Performing Operations; Transporting -> Vehicles In General -> V
5		B60S: Performing Operations; Transporting -> Vehicles In General -> S

Source: Refer to Figure 4.4.

The top five assignee organizations are Toyota (Japan), Google (USA), Matsushita (Japan), Daimler (Germany), and iRobot (USA) respectively (Table 4.8). The top German organizations based on autonomous vehicle patents consist of major automobile or automobile parts manufacturers: Daimler, Bosch, Audi, Volkswagen and Siemens (Table 4.9).

Table 4.8. Top Global Organizations by Number of Autonomous Vehicle Patents

Name	Country	# Patents
Toyota Motor CO LTD	Japan	349
Google INC	USA	218
Matsushita Electric Works LTD	Japan	108
Daimler AG	Germany	98
iRobot CORP	USA	84

Source: Refer to Figure 4.4.

Table 4.9. Top Five German Organizations by Number of Autonomous Vehicle Patents

Name	# Patents
Daimler AG	98
Bosch GMBH	81
Audi AG	36
Volkswagen AG	27
Siemens AG	25

Source: Refer to Figure 4.4.

The top 5% most highly cited autonomous vehicle patents received eight or more citations. Roughly 9% of this "influential" group of inventions was assigned to German organizations. This percentage is lower than that of the US and Japan but higher than that of China, South Korea and India (Table 4.10). The top four most cited patents with 100 or more citations are from Sweden and US. For example, the most cited patent (US 2004158355), receiving 144 citations, is assigned to the Swedish company Arnex Navigation Systems AB (Figure 4.11). With regard to non-patent literature (NPL), 15% of German patent citations were to NPL (Figure 4.12). This rate is just behind that of China (20%) while greater than that of the US (14%), South Korea (9%) and Japan (4%).

Table 4.10. Top 5% of Highly Cited Autonomous Vehicle Patents by Country (8 + citations)

Countries	Top 5% of Highly Cited Patents (8+ times cited) (212 Patents)*	
	# Patents in Top 5%	% of Patents in Top 5%
United States	70	33.0%
Japan	44	20.8%
Germany	20	9.4%
China	18	8.5%
South Korea	9	4.2%
India	0	0.0%

*The top 5% of highly cited patents is across the full distribution of patents in this system (212 patents); this subset of highly cited patents is then broken down by country to determine which country affiliations account for the greatest share of highly cited patents. Samples are restricted to 4,060 patents with citation information available from PatStat database.

Table 4.11. List of Highly Cited Autonomous Vehicle Patents (100 + citations)

Patent Publication Number	Title	Assignees	Country	Times Cited
US 2004158355	Intelligent methods, functions and apparatus for load handling and transportation mobile robots	Arnex Navigation Systems AB	Sweden	144
US 6690134	Confinement system for mobile robot used for e.g. lawn care, floor cleaning, inspection, transportation	iRobot CORP	USA	130
US 7102496	Multi-sensor integration for a vehicle	Yazaki North America	USA	103
US 2010117456	Applications of Wireless Energy Transfer Using Coupled Antennas	MIT	USA	102

Source: Refer to Figure 4.4.

Table 4.12. List of Countries by number and share of Non-Patent Literature (NPL)

Country	NPL	Patent Citations	Total Citations	Share of NPL
United States	1347	8356	9703	13.9%
Germany	306	1677	1983	15.4%
China	260	1021	1281	20.3%
Japan	79	1815	1894	4.2%
South Korea	56	593	649	8.6%
India	7	9	16	43.8%

Source: Refer to Figure 4.4. Samples are restricted to 4,060 patents with citation information available from PatStat database.

Almost 11% of German patents were filed with five or more patent authorities (Table 4.13). The US (30%) has the greatest number of patents filed with five or more patent authorities, followed by Japan and Germany. Meanwhile, only one Chinese and Indian patent was filed with five or more patent authorities.

Table 4.13. Top 5% of Patent Families by Country (5+ Patent Families)

Countries	Top 5% of Patent Families by Country (5+ Families) (484 Patents)*	
	# Patents in Top 5%	% of Patents in Top 5%
United States	145	30.0%
Japan	118	24.4%
Germany	52	10.7%
South Korea	26	5.4%
China	1	0.2%
India	1	0.2%

*The top 5% of patent families is across the full distribution of patents in this system (484 patents); this subset of patents with multiple families is then broken down by country to determine which country affiliations account for the greatest share of the top 5% family patents. Samples are restricted to 4,060 patents whose citation information was available from the PatStat database.

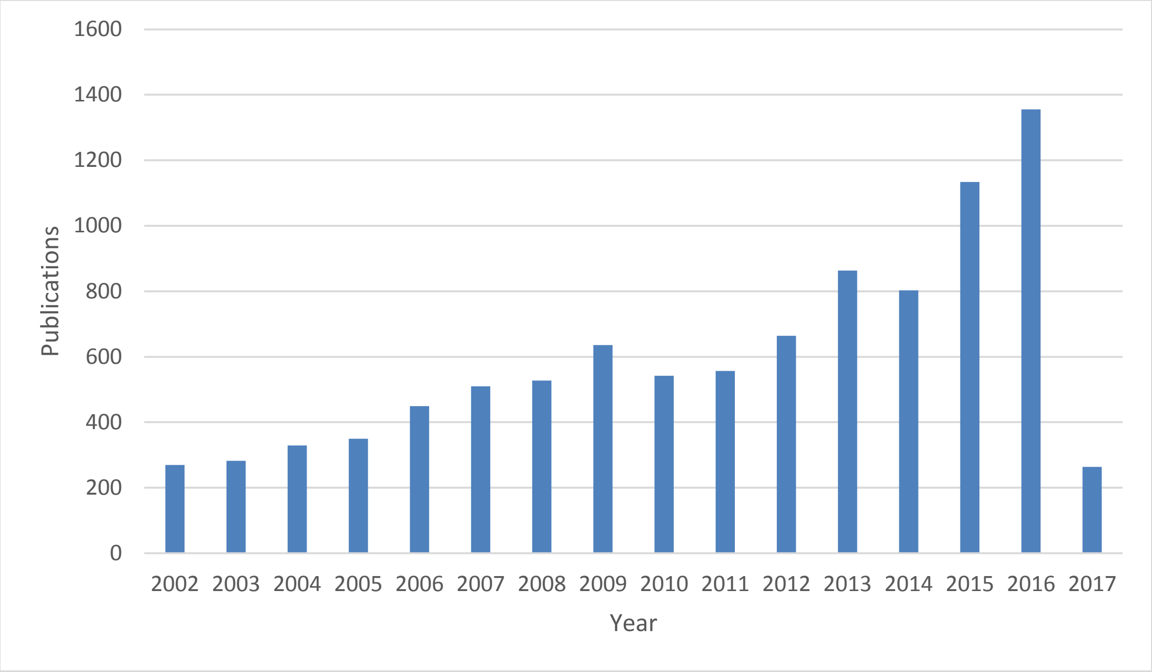
Overall, Germany is among the leading autonomous vehicle patenting players. Although the US and Japan have larger numbers of autonomous vehicles patents overall and larger numbers of highly cited patents, German automakers are well represented among the top autonomous vehicle patent filing organizations. German patents have more science linkages and larger family sizes than comparator countries indicating the value of German patents in this autonomous system.

Chapter 5. Autonomous Vehicles in Hostile Environments

5.1. Autonomous Vehicles in Hostile Environments Publications

There are more than 9,500 research publications that concern autonomous vehicles in hostile environments. Although the field grew by 44% from 2002-2010 to 2011-2017, it had two points of growth, followed by decline: from 2009 to 2010 and from 2013 to 2014. The biggest year-over-year increase was from 2014 to 2015, in which more than 300 publications were added representing a 41% increase (Figure 5.1).

Figure 5.1. Number of Autonomous Vehicle in Hostile Environments Publications by Publication Year: 2002-2017 (May)



Source: Autonomous vehicle publications, 2002–2017 (May), (N = 9,536 Web of Science records). See text for search strategy.

Germany had the seventh largest number of publications over the 2002-2017 time period. German authors comprised nearly 5% of all publications having to do with autonomous vehicles in hostile environments. This share has doubled, from 3% in 2002-2010 to 6% in 2011-2017 (Table 5.1). Germany is particularly strong in representation technologies much as it was in the previous section on autonomous vehicles in non-hostile environments. Eleven percent of German-authored publications in the autonomous vehicles in hostile environments area have to do with representation (Table 5.2). The US is by far the strongest country in output, with 29% of research publications in this area having a US author. China ranks second with 16% of research publication output, followed by Japan with 7%. The US is particularly strong in the data analysis area; 37% of all research output in this area has a US author.

Table 5.1. Top Countries by Number of Hostile Environment Publications

Countries	# Publications	Share (%)	# in 2002-2010	# in 2011-2017
USA	2733	28.7%	1383	1350
China	1484	15.6%	1061	423
Japan	645	6.8%	284	361
UK	507	5.3%	281	226
Italy	481	5.0%	328	153
South Korea	467	4.9%	285	182
Germany	455	4.8%	340	115
Spain	383	4.0%	241	142
Australia	365	3.8%	237	128
Canada	348	3.6%	194	154
France	314	3.3%	181	133
India	285	3.0%	232	53

Source: Refer to Figure 5.1. Country share is based on the count of publications with an author affiliated with an organization in the country divided by the total number of records in Figure 5.1. Percentages cannot be summed to a total because a publication may involve multiple subareas and author-affiliated countries.

Table 5.2. Countries by Hostile Environment Research Subarea

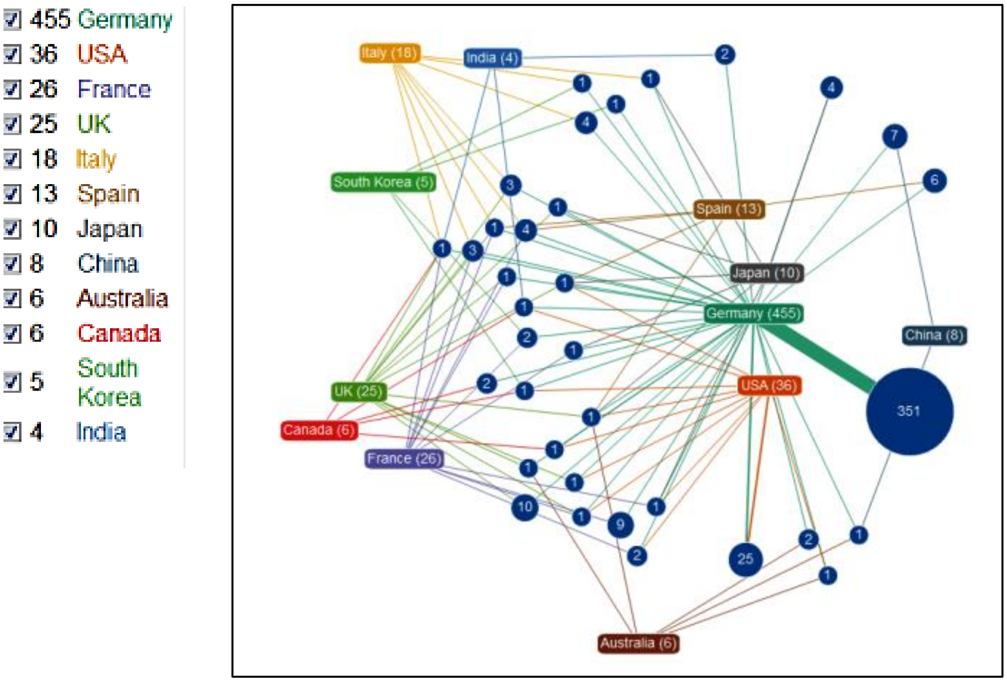
Country	Autonomous Vehicle Research Subarea					
	localization	data analysis	representation	sensor fusion	computer vision	machine learning
USA	25.7%	37.1%	28.4%	25.4%	24.8%	23.4%
China	13.3%	16.6%	4.9%	14.3%	8.3%	12.5%
Japan	7.5%	4.2%	2.2%	4.2%	4.1%	9.4%
UK	4.0%	6.3%	9.5%	5.8%	5.0%	9.4%
Italy	5.9%	6.1%	5.6%	5.8%	2.5%	4.7%
South Korea	7.4%	2.3%	3.2%	10.6%	4.1%	3.1%
Germany	5.6%	5.9%	11.2%	5.8%	1.7%	3.1%
Spain	7.9%	3.2%	6.6%	3.2%	7.4%	6.3%
Australia	3.8%	6.9%	5.6%	2.6%	8.3%	7.8%
Canada	3.8%	2.7%	3.9%	2.1%	2.5%	6.3%
France	3.8%	3.2%	5.6%	3.2%	1.7%	1.6%
India	1.8%	2.3%	2.7%	2.1%	3.3%	3.1%
Number of Publications	1,045	525	409	189	121	64

Source: Refer to Figure 5.1. Percentages are based on the number of records associated with each subarea divided into the number with an author affiliated with an organization in the country.

This autonomous area has more co-authorships among the five comparison countries plus the other contextual countries with similar publication outputs than do the other three autonomous systems (Figure 5.2). Twenty-three percent of German research papers have a co-author from one of these countries.

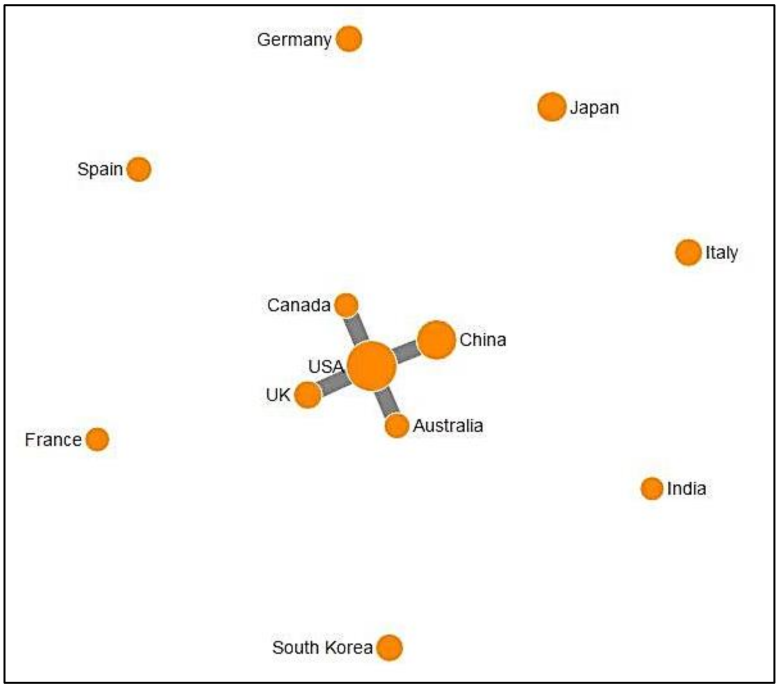
German co-authors most commonly collaborate with authors from the US, France, and the UK while there are only four papers with Indian co-authors. The French collaboration may be explained by the proximity of the two nations. Most of these co-authorships are bilateral, involving a German author and a co-author from another country. Twenty-five of the 36 Germany-US co-authored papers are solely between these two countries, with the rest involving Germany, the US, and a third country such as France. Only four of the 10 German-Japanese papers are bilateral. A group of five countries – the US, China, UK, Canada, and Australia—are working on similar topics in the autonomous vehicles in hostile environments area, while Germany, South Korea, Japan, India, and three other countries work on different topics (Figure 2.3). German authors working on autonomous vehicles in hostile environments most commonly work on topics concerning the Mid-Atlantic ridge, images, indoor issues, and the rise of the East Pacific.

Figure 5.2. German Co-author Affiliations by Selected Countries



Source: Refer to Figure 5.1.

Figure 5.3. Hostile Environment Country Co-occurrence based on Cosine Keyword Similarity
Arrows next to German article keywords represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).



Top German Article Keywords

44		Mobile robot
28	↓↓↓	autonomous underwater vehicl
28		system
24		navigation
19		UAV
17	↓↓↓	AUV
15		path plan
14		environment
13		Algorithm
13		localization
13	↑↑↑	Mid-Atlantic Ridge
13		obstacle avoidance
13		Robot
13	↑↑	SLAM
10		Model
10	↑↑	motion
10	↑↑	Simulator
9	↑↑↑	Image
8		vision
7		Autonomous vehicle
7	↓↓	Design
7	↑↑↑	Indoor
7		network
7		optimal
7		space
7	↓	track
7	↓↓	vehicle
6	↑↑	Calibration
6		classification
6	↑↑↑	East Pacific Rise
6	↑	Explorer
6		map
6		Underwater robot
6		Unmanned Aerial Vehicle UAV

Harbin Engineering University (China) and MIT (US) are the top two organizations in research output in this area. These universities are followed by Woods Hole Oceanographic Institute (US), University of Tokyo (Japan), Chinese Academy of Science (China), Monterey Bay Aquarium Research Institute (US), and Carnegie Mellon University (US). The top German organizations with 10 or more publications in this area are Technical University of Munich, University of Freiburg, University of Bremen, Jacobs University Bremen, Ilmenau University of Technology, University of Bonn, Technical University of Berlin, and German Aerospace Center (DLR). There seems to be a cluster of research activity around Bremen, which includes the two universities plus the business Atlas Elektronik GmbH which has employees involved with nine research papers. Table 2.4 lists the top German authors by number of publications in the autonomous vehicles in hostile environments area, alongside their organizational affiliations. Two of the 10 authors are affiliated with the German Research Center for Artificial Intelligence (DFKI) and the Max Planck Institute for Biological Cybernetics. Some of these individuals were also involved with research in other autonomous system areas profiled in this report, suggesting crossovers among the autonomous system technologies.

Table 5.3. Top Organizations by Number of Hostile Environment Publications

Top Global Organizations	# Publications		Top German Organizations	# Publications
Harbin Engn Univ	239		Tech Univ Munich	34
MIT	237		Univ Freiburg	24
Woods Hole Oceanog Inst	168		Univ Bremen	18
Univ Tokyo	160		Jacobs Univ Bremen	17
Chinese Acad Sci	135		Ilmenau Univ Technol	16
Monterey Bay Aquarium Res Inst	116		Tech Univ Berlin	15
Carnegie Mellon Univ	108		Univ Bonn	14
Univ Sydney	89		German Aerosp Ctr DLR	10
Univ Girona	86		ATLAS ELEKT GmbH	9
Northwestern Polytech Univ	83		Leibniz Univ Hannover	9
Univ Porto	81		Karlsruhe Inst Technol	8
Heriot Watt Univ	76		Rhein Westfal TH Aachen	8
Univ Southampton	74		Univ Hamburg	8
USN	73		Univ Paderborn	8
Univ Michigan	72			
Univ Pisa	70			
CALTECH	64			
Georgia Inst Technol	62			
Nanyang Technol Univ	62			
Korea Adv Inst Sci & Technol	59			

Source: Refer to Figure 5.1.

Table 5.4. Top German Affiliated Authors by Number of Hostile Environment Publications

Top German Affiliated Authors	Organization	# Publications
Birk, Andreas	Univ Bremen	17
Burgard, Wolfram	Univ Freiburg	11
Behnke, Sven	Univ Bonn	8
Knoll, Alois	Tech Univ Munich	7
Albiez, Jan	German Res Ctr Artificial Intelligence	6
Buelthoff, Heinrich H	Max Planck Institute for Biological Cybernetics	6
Eichhorn, Mike	Ilmenau Univ Technol	6
Gross, Horst-Michael	Ilmenau Univ Technol	6
Kalwa, Joerg	ATLAS ELEKT GmbH, Bremen, Germany	6
Maehle, Erik	Univ Lubeck	6

Source: Refer to Figure 5.1.

The top 10% of highly cited autonomous vehicles in hostile environment publications received 13 or more citations. Germany’s share of these highly cited papers is about the same as its share of overall output in the field, with 5% of German publications falling into this highly cited group. This share of highly cited papers is another indicator of the esteem in which German authored publications in this area held. The US and China have the two largest numbers of highly cited papers, but the US accounts for

44% of all highly cited publications. Japan's number of highly cited papers is slightly less than its output share, while South Korea has a slightly higher share of highly cited papers than one might expect based on their share of overall output and India's is much lower than its overall output share (Table 5.5). Eight publications concerning autonomous vehicles in hostile environments have received 250 or more citations (Table 5.6). All but one have an author affiliated with a US institution. These papers concern multi-agent dynamic systems, fault tolerance, mobile robot navigation, optimal motion planning, localization and mapping, multirobot localization, ocean sampling, the Deepwater Horizon oil spill disaster, and motion planning and obstacles.

Table 5.5. Top 10% of Highly Cited Hostile Environment Publications by Country

Countries	**Top 10% of Highly Cited Publications (13+ times cited)***	
	# Publications in Top 10%	% of Publications in Top 10% (970 Publications)
USA	431	44.4%
China	62	6.4%
Japan	47	4.8%
UK	74	7.6%
Italy	56	5.8%
South Korea	39	4.0%
Germany	46	4.7%
Spain	51	5.3%
Australia	56	5.8%
Canada	54	5.6%
France	41	4.2%
India	18	1.9%

*The top 10% of highly cited publications is across the full distribution of highly citedc publications in this system (970 publications); this subset of highly cited publications is then broken down by country to determine which country affiliations account for the greatest share of highly cited publications.

Table 5.6. List of Most Highly Cited Autonomous Vehicle Publications (with 250 or more citations)

Title	Source	Countries	Times Cited
Flocking for multi-agent dynamic systems: Algorithms and theory	IEEE TRANSACTIONS ON AUTOMATIC CONTROL	USA	1668
Bibliographical review on reconfigurable fault-tolerant control systems	ANNUAL REVIEWS IN CONTROL	Canada	735
Vision for mobile robot navigation: A survey	IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE	USA	532
Sampling-based algorithms for optimal motion planning	INTERNATIONAL JOURNAL OF ROBOTICS RESEARCH	USA	503
FAB-MAP: Probabilistic localization and mapping in the space of appearance	INTERNATIONAL JOURNAL OF ROBOTICS RESEARCH	UK	394
Collective motion, sensor networks, and ocean sampling	PROCEEDINGS OF THE IEEE	USA, Belgium	370
Tracking Hydrocarbon Plume Transport and Biodegradation at Deepwater Horizon	SCIENCE	Australia, USA	342
Distributed multirobot localization	IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION	USA	283
Randomized kinodynamic motion planning with moving obstacles	INTERNATIONAL JOURNAL OF ROBOTICS RESEARCH	USA	261

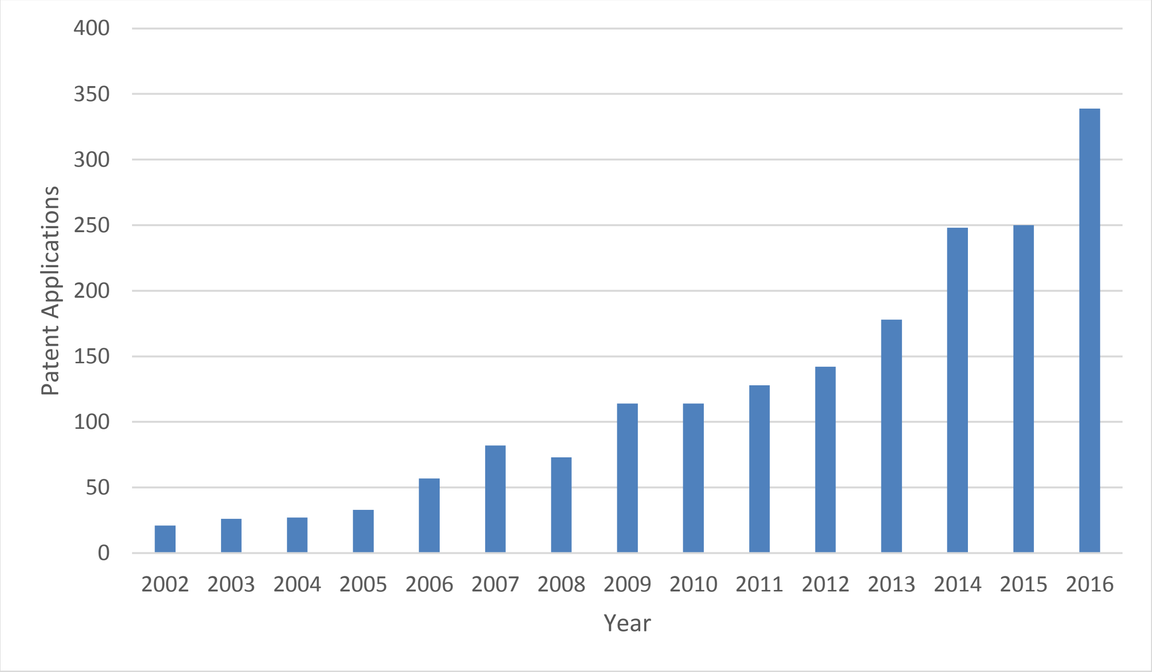
Source: Refer to Figure 5.1.

In sum, Germany is not the dominant producer of scholarly works in this autonomous system, although its share of publications has doubled from the first to the second half of the study period. German research is particularly strong in representation technologies in this system. German publications in this autonomous system have a larger share of co-authored papers with one of the other study countries than any of the other autonomous systems, and Germany has a higher share of highly cited works than one would expect on the basis of output alone. Most German research in this domain comes from universities located throughout the country, and there also appears to be an interesting cluster of research activity from organizations in the Bremen area.

5.2. Autonomous Vehicles in Hostile Environments Patents

The DII patent index yielded more than 1,800 patents related to autonomous vehicles in hostile environments in the 2002-to-2016 period. A steady increase of patents during the earlier 2002-2010 period was followed by a slight decline in 2008, potentially due to the last Great Recession (Figure 5.4). Subsequent to this slowdown, a robust growth in these patents occurred during the 2011-to-2016 period. Germany produced 7% of the total patents related to autonomous vehicle in hostile environments (Table 5.7). This percentage is below that of the US, China, South Korea and Japan. Germany's share of patents in this domain increased (as did that of China) between the first and second periods, while Japan's share declined.

Figure 5.4. Number of Autonomous Vehicles in Hostile Environments Patents by Patent Publication Year: 2002-2016



Source: Autonomous Vehicles in Hostile Environments patents, 2002–2016, (N = 1,832 Derwent Innovation Index). See text for search strategy.

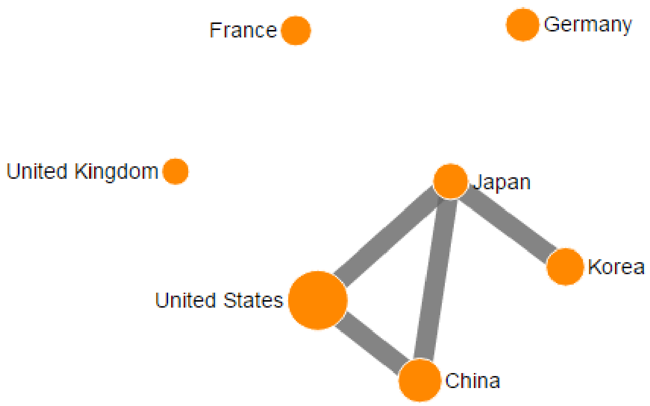
Table 5.7. Top Countries by Number of Autonomous Vehicles in Hostile Environments Patents

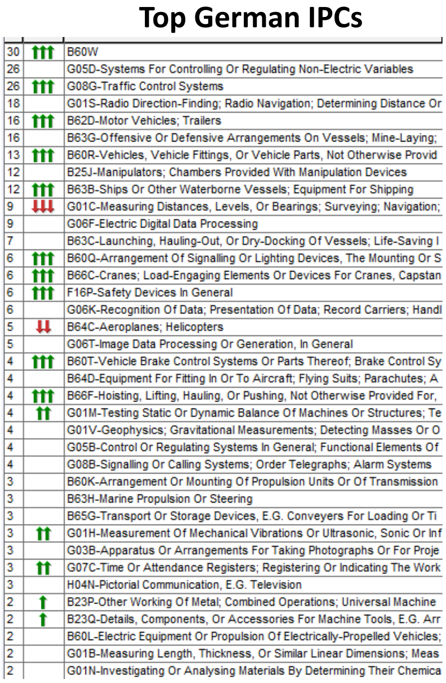
Countries	# Patents	Share (%)	# in 2002-2010	# in 2011-2016
United States	620	33.8%	216	404
China	271	14.8%	30	241
South Korea	184	10.0%	58	126
Japan	151	8.2%	76	75
Germany	131	7.2%	25	106
India	5	0.3%	0	5

Source: Refer to Figure 5.4. Country share is based on the count of patents assigned to organizations in the country divided by the total number of patents in Figure 5.4. Note individual assignees are not included.

Technological similarities based on IPC co-occurrence suggest that German patents in this domain are more likely to be in different patent classes than patents in other comparator countries' patents. The greatest IPC similarities are among the US, China, Japan and South Korea (Figure 5.5). The most common IPCs in German patents include B60W (Conjoint Control of Vehicle sub-units of Different Type or Different Function), G05D (Systems for Controlling or Regulating Non-Electric Variables), G08G (Traffic Control Systems) and G01S (Radio Direction-Finding). Among these patent classes, B60W and G08G IPCs are significantly more frequent in German patents.

Figure 5.5. Autonomous Vehicles in Hostile Environments Country Co-occurrence based on Cosine IPC Similarity
Arrows next to German patent IPCs represent three/two/one standard deviations from the mean, either more similar (pointing north) or less similar (pointing south).





Top German IPCs

30	↑↑↑	B60W
26		G05D-Systems For Controlling Or Regulating Non-Electric Variables
26	↑↑↑	G08G-Traffic Control Systems
18		G01S-Radio Direction-Finding; Radio Navigation; Determining Distance Or
16	↑↑↑	B62D-Motor Vehicles; Trailers
16		B63G-Offensive Or Defensive Arrangements On Vessels; Mine-Laying;
13	↑↑↑	B60R-Vehicles, Vehicle Fittings, Or Vehicle Parts, Not Otherwise Provid
12		B25J-Manipulators; Chambers Provided With Manipulation Devices
12	↑↑↑	B63B-Ships Or Other Waterborne Vessels; Equipment For Shipping
9	↓↓↓	G01C-Measuring Distances, Levels, Or Bearings; Surveying; Navigation;
9		G06F-Electric Digital Data Processing
7		B63C-Launching, Hauling-Out, Or Dry-Docking Of Vessels; Life-Saving I
6	↑↑↑	B60Q-Arrangement Of Signalling Or Lighting Devices, The Mounting Or S
6	↑↑↑	B66C-Cranes; Load-Engaging Elements Or Devices For Cranes, Capstan
6	↑↑↑	F16P-Safety Devices In General
6		G06K-Recognition Of Data; Presentation Of Data; Record Carriers; Handl
5	↓↓	B64C-Aeroplanes; Helicopters
5		G06T-Image Data Processing Or Generation, In General
4	↑↑↑	B60T-Vehicle Brake Control Systems Or Parts Thereof; Brake Control Sy
4		B64D-Equipment For Fitting In Or To Aircraft; Flying Suits; Parachutes; A
4	↑↑↑	B66F-Hoisting, Lifting, Hauling, Or Pushing, Not Otherwise Provided For,
4	↑↑	G01M-Testing Static Or Dynamic Balance Of Machines Or Structures; Te
4		G01V-Geophysics; Gravitational Measurements; Detecting Masses Or O
4		G05B-Control Or Regulating Systems In General; Functional Elements Of
4		G08B-Signalling Or Calling Systems; Order Telegraphs; Alarm Systems
3		B60K-Arrangement Or Mounting Of Propulsion Units Or Of Transmission
3		B63H-Marine Propulsion Or Steering
3		B65G-Transport Or Storage Devices, E.G. Conveyers For Loading Or Ti
3	↑↑	G01H-Measurement Of Mechanical Vibrations Or Ultrasonic, Sonic Or Inf
3		G03B-Apparatus Or Arrangements For Taking Photographs Or For Proje
3	↑↑	G07C-Time Or Attendance Registers; Registering Or Indicating The Work
3		H04N-Pictorial Communication, E.G. Television
2	↑	B23P-Other Working Of Metal; Combined Operations; Universal Machine
2	↑	B23Q-Details, Components, Or Accessories For Machine Tools, E.G. Arr
2		B60L-Electric Equipment Or Propulsion Of Electrically-Propelled Vehicles;
2		G01B-Measuring Length, Thickness, Or Similar Linear Dimensions; Meas
2		G01N-Investigating Or Analysing Materials By Determining Their Chemica

Source: Refer to Figure 5.4.

The top organizations with 25 or more autonomous vehicles patents for hostile environments were mostly American and Chinese organizations (Table 5.8). The largest patent filer was iRobot (US) followed by Boeing (US), Lockheed Martin (US), Harbin Engineering University (China), Shenyang Institute of Automation (China) and Honeywell (USA). Interestingly, the top Chinese organizations were either universities or public research institutes, while the top American organizations were private companies. The top German patent filers were automobile manufacturers or major automobile parts manufacturers: Atlas Elektronik, Bosch, Daimler, Siemens and Audi. These five companies accounted for 45% of German patents in this domain (Table 5.9).

Table 5.8. Top Global Organizations by Number of Autonomous Vehicles in Hostile Environments Patents

Name	Country	# Patents
iRobot CORP	USA	63
Boeing CO	USA	35
Lockheed Martin CORP	USA	34
Harbin Engineering University	China	29
Shenyang Institute Of Automation (CAS)	China	27
Honeywell Int Inc	USA	2

Source: Refer to Figure 5.4.

Table 5.9. Top Five German Organizations by Number of Autonomous Vehicles in Hostile Environments Patents

Name	# Patents
Atlas Elektronik GMBH	21
Bosch GMB	13
Daimler AG	12
Siemens AG	8
Audi AG	6

Source: Refer to Figure 5.4.

The top 5% of highly cited autonomous vehicles in hostile environments patents received 11 or more citations (Table 5.10). The US has the largest share of highly cited patents at 54% followed by China at 8%, Germany and Japan each at 5%, and South Korea at 3%. Unlike other autonomous technologies, the top cited patents in autonomous vehicles in hostile environments technologies include many individual assignees. For example, among highly cited patents with 60 or more citations, three patents belonged to individual assignees while one patent belonged to a university (Table 5.11).

Table 5.10. Top 5% of Highly Cited Autonomous Vehicle Patents by Country (11 + citations)

Countries	Top 5% of Highly Cited Patents (11+ times cited) (63 Patents)*	
	# Patents in Top 5%	% of Patents in Top 5%
United States	34	54.0%
China	5	7.9%
Japan	3	4.8%
Germany	3	4.8%
South Korea	2	3.2%
India	0	0.0%

*The top 5% of highly cited patents is across the full distribution of patents in this system (63 patents); this subset of highly cited patents is then broken down by country to determine which country affiliations account for the greatest share of highly cited patents. Samples are restricted to 1,194 patents with citation information available from PatStat database.

Table 5.11. List of Highly Cited Autonomous Vehicles in Hostile Environments Patents (60 + citations)

Patent Publication Number	Title	Assignees	Country	Times Cited
US 6754370	Real-time range scanning method for moving scenes	Stanford University	USA	115
US 2007061041	Mobile robot with wireless location sensing apparatus	Individual	USA	87
US 2010277121	WIRELESS ENERGY TRANSFER BETWEEN A SOURCE AND A VEHICLE	Individual	USA	84
US 6804607	Collision avoidance method for vehicle	Individual	USA	66

Source: Refer to Figure 5.4.

Seventeen percent of the citations to prior art in German patents were to NPL (Table 5.12). This share was higher than that of US, Japan and South Korea patents but lower than that of China.

The top 5% patents were filed with six or more patent authorities. Nearly 10 percent of German patents fell into this top category. Only US has a larger share than Germany. Table 5.13 indicates that the German organizations' patent portfolios are much more internationally oriented than one might expect based on output share.

Table 5.12. List of Countries by number and share of Non-Patent Literature (NPL)

Country	NPL	Patent Citations	Total Citations	% NPL
United States	480	2691	3171	15.1%
China	110	403	513	21.4%
South Korea	7	221	228	3.1%
Japan	15	149	164	9.1%
Germany	101	504	605	16.7%
India	0	0	0	

Source: Refer to Figure 5.4 and Table 5.7 for totals by country. Samples are restricted to 1,194 Patstat patents whose citation information was available

Table 5.13. Top 5% of Patent Families by Country (6+ Patent Families)

Countries	Top 5% of Patent Families by Country (6+ Families)* (102 Patents)	
	# Patents in Top 5%	% of Patents in Top 5%
United States	34	33.3%
Germany	10	9.8%
Japan	5	4.9%
Korea	1	1.0%
China	0	0.0%
India	0	0.0%

*The top 5% of patent families is across the full distribution of patents in this system (102 patents); this subset of patents with multiple families is then broken down by country to determine which country affiliations account for the greatest share of the top 5% family patents. Samples are restricted to 1,194 patents whose citation information was available from the PatStat database.

Overall, Germany is among the top five patent players in the autonomous vehicles in hostile environment technologies. German patent ownership in this domain is concentrated among a few large firms. The German patent portfolio is much more international and yet distinctive in terms of technological emphasis than that of other major comparator countries.

Chapter 6. Strengths and Weaknesses

The publication and patent analysis suggests several strengths, as well as some weaknesses, in Germany's research and application position. Germany's greatest research and patenting strengths are in the smart factory and autonomous vehicles systems. Germany is among the top countries in terms of publications in these two systems with authors affiliated with German organizations. The growth of German research publications has been prominent in the smart factory domain, stemming in part from the release of Industrie 4.0 in the second decade of the 2000s. German publications across all four systems are particularly strong in "hard technology" intensive areas in the representation subdomain, as well as in localization, computer vision, sensor fusion. Germany also benefits from a strong and diverse research environment including multiple universities (including universities of technology), research institutes, and private sector companies and associations. Robotics centers at German universities and research institutes have established a track record of publications around several German researchers. Likewise, German patents originate from diverse sectors in the smart factory and autonomous vehicles systems, including industrial automation, electronics, telecommunication, semiconductor, and automotive industries. Although German patent counts in these autonomous systems are not as high as they are in larger countries such as China, German patents are more likely to exhibit characteristics of valuable patents in that they cite more NPL and are more likely to be taken in multiple countries/patent authorities.

Germany has less comparative publication output in smart home and autonomous vehicles in hostile environment systems. Although Germany is part of a global network of countries working on similar smart home research applications such as autonomous assisted living and patents relating to electricity and power, its output is smaller than that of comparator countries. Likewise, Germany has fewer publications and patents dealing with hostile environments (such as war, natural disasters, or manmade disasters in areas such as nuclear or oil spills) and these publications and patents tend to be in distinctive research areas and patent classes from those commonly pursued by researchers in the rest of the world's leading countries in the hostile environment area. In addition, while Germany has research strengths in "hard technology" areas across the technology catalogue, it has weaknesses in analytic domains such as data analysis and, for some of the systems, machine learning.

Opportunities and threats are examined in this report from the perspective of Germany's comparator countries. China and India are large markets with extensive research and (in less so in the case of India) patenting capabilities. China itself is among the top two largest producers of research and patenting (except for autonomous vehicle patenting, where it ranks third). This size offers an opportunity for collaborations with Germany. Moreover, Germany and China patent in similar smart factory areas. However, there also are threats associated with these markets in the event that they adopt German autonomous systems R&D for their own autonomous sector development.

The US is a mature research and patent country as a top-three producer across all four autonomous systems, and is the largest collaborator with Germany. Germany and the US also publish on common topics in the smart home area, and patent in common application areas in smart home and autonomous vehicle systems. Japan and South Korea are also mature research and patenting exporters, albeit with fewer collaborations with Germany outside of the autonomous vehicles area.

The implications of research and patenting for the German market are uncertain. The US, Japan, and South Korea have established pathways from research and application capabilities to market through small firms and large companies such as (for the US) IBM, AT&T, Google, IRobot, Boeing; (for Japan) Mitsubishi Electric, Omron, Yaskawa Electric, Sharp, Matsushita; (for South Korea) Samsung, LG. However, China's and India's market pathways are more uncertain. Some of the Chinese patents are assigned to companies (e.g., Sichuan Changhong Electric Co., Ltd.) but many are assigned to public research institutes such as Chinese Academy of Science and to various Chinese universities. Some of these Chinese institutes and universities may spinoff important autonomous systems startups, as could research institutes, universities, and large companies Germany, the US, Japan, and South Korea. Tata Consultancy is important in India’s autonomous systems market pathway albeit with a smaller patent portfolio than its large company counterparts in other countries. Regardless, Chinese and Indian R&D could move more downstream, which has the potential to increase demand for German applications. On the other hand, these countries’ growing research and application capabilities could move them into areas where Germany has traditionally been strong.

7. US Autonomous Systems Policies

7.1. Smart Homes

7.1.1. Policy Issue. The US does not have specific legislation for smart home system governance. Smart home policy activity is clustered around two smart home systems: smart grid technology, and "always on" devices made possible by Internet of Things technologies. Securing personal information about the public utility customer from unauthorized access is the main policy issue in smart grid regulation. This issue includes transparency in how the smart grid technology works and shares information, individual consent for the public utility to share information about service usage, purpose for sharing information outside of providing utility services, breadth of information disclosed, information accuracy, and security from unauthorized access. The Internet of Things technologies raise similar issues: data security attacks enabling unauthorized access to and use of personal information (e.g., identity theft); ability of customers to assent to use of their private information; and storage and retention of the minimum amount of data needed to operate the Internet of Things application.

7.1.2. Smart Grid Actors and Legislation. Key governmental smart grid policy actors at the national level are: the Federal Energy Regulatory Commission (interstate electricity transmission), Department of Energy (R&D support), and the National Institute of Standards and Technology (interoperability standards). Title XIII of the Energy Independence and Security Act of 2007 promoted R&D and standards creation to develop smart grid infrastructure. The National Institute of Standards and Technology led a standards process that resulted in the publication of the Smart Grid Framework and Roadmap for Interoperability. The first edition of this framework was published in 2010, with the most recent, third edition, published in beta form in 2014.[7] The third edition of the framework bundles relevant standards and families of standards, lays out an architecture, develops a cybersecurity strategy and set of requirements, and establishes testing and certification accrediting.

States primarily act on smart grid policy through legislation and implementation by state public utility commissions. More than 20 states adopted smart grid legislation on topics such as smart grid infrastructure funding, smart meters, and net metering to give credit for renewable energy usage. Other key policy system actors include state and local utilities, telephone companies, and public utility commissions. Also involved are non-profit consumer watch organizations such as the Center for Democracy and Technology, and civil liberties organizations such as the Electronic Frontier Foundation.

7.1.3. Internet of Things Actors and Legislation. Key governmental actors in the Internet of Things area are those involved, by extension, with enforcing privacy legislation authorized through several federal acts operating in diverse domains: the Federal Trade Commission Act of 1914 to protect against unfair commerce practices; the Fair Credit Reporting Act passed in 1970 to safeguard consumer financial information; the Family Educational Rights and Privacy Act passed in 1974 to protect student education records; the Electronic Communications Privacy Act which was passed in 1986 to govern electronic surveillance; and the Health Insurance Portability and Accountability Act of 1996 designed to protect patient medical records.

The Federal Communication Commission supported a pre-emptive Internet privacy regulation in 2016. This regulation, which was passed but not put into place, required Internet Service Providers to obtain consumer consent before sharing electronic information. It was subsequently rolled back by Congress in 2017. In response, several states have considered their own Internet privacy and security protection legislation. Two states (Minnesota and Nevada) had legislation regulating Internet Service Providers

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[7] https://www.nist.gov/el/smartgrid/nist-framework-and-roadmap-smart-grid-interoperability-standards-release-30-draft

disclosure of customer information prior to the Congressional rollback vote. Following this vote, Colorado adopted Internet Service Provider consent legislation and 20 other states plus the District of Columbia introduced such measures. In addition to privacy of personal information held by Internet Service Providers, several states have adopted legislation protecting children's online privacy (California and Delware); e-Reader Privacy (Arizona, California, Delaware, and Missouri), false or misleading website privacy statements (Nebraska and Pennsylvania), notice of employee email monitoring (Connecticut, Delaware, Colorado, and Tennessee), and state government website privacy (17 states).[8]

National governmental actors include the Federal Trade Commission, Federal Communication Commission, Department of Education, Department of Health and Human Services, and the US Justice Department. The National Telecommunications and Information Administration acts as an advisor on infrastructure development issues such as interoperability, spectrum congestion, digital divide, and engagement with other countries on standards specification. The National Science Foundation's Directorate for Computer and Information Science and Engineering awards research and education grants concerning cyber-physical systems to investigators in universities and non-profit organizations. State level actors include state and local education departments, law enforcement, state attorneys general, and state health departments. Also involved are information technology companies, private credit reporting agencies, medical practices, educational institutions, Internet and non-profit organizations such as the American Civil Liberties Organization, Consumers Union, the Center for Democracy and Technology, and the Electronic Frontier Foundation among others.

Although the policy debate is focused on privacy and security, other issues have been raised but either not settled or not been as contentious. Product liability for malfunctioning Internet of Things devices is raised by the legal community but not explicitly legislated. Liability determinations are mostly addressed in criminal and civil courts on a case-by-case basis depending on the particular facts of the disputes involved. Internet of Things infrastructure and standards development has occurred through "notice of comment" processes where the federal government convenes stakeholders in the development of frameworks such as the aforementioned smart grid roadmap, the National Telecommunications and Information Administration's green paper, "Fostering the Advancement of the Internet of Things," and the National Institute of Standards and Technology's Framework for Improving Critical Infrastructure Cybersecurity.[9]

7.1.4. Analysis and Conclusions. US policy relating to smart homes is taken up at the national level but also decentralized across US states. It is also fragmented among existing laws and new activity taken at the national level to promote R&D and standards, and at the state level to address standards, privacy, and security concerns. Prioritization is given to engaging in diverse stakeholders while at the same time avoiding overregulation which may limit innovation.

7.2. Smart Factories

7.2.1. Policy Issue. The Great Recession drew attention to structural weaknesses in the US manufacturing economy. These weaknesses included employment loss, decline in capital investment, declining manufacturing output and productivity, and trade deficits. Renewed attention to manufacturing through an innovation initiative was viewed as important policy measure in the Obama administration's economic recovery efforts. The problem with US manufacturing innovation was not viewed as being one of a lack of basic scientific research or private industry product development, but rather a lack of institutional

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[8] http://www.ncsl.org/research/telecommunications-and-information-technology/state-laws-related-to-internet-privacy.aspx

[9] https://www.ntia.doc.gov/files/ntia/publications/iot_green_paper_01122017.pdf; https://www.nist.gov/sites/default/files/documents/cyberframework/cybersecurity-framework-021214.pdf

capacity to address the gap between these two in areas such as technology development, demonstration of a prototype system in a relevant environment, and development of technology standards.

7.2.2. Key Policy System Actors. The Office of Science and Technology Policy, located in the Executive Office of the President, launched the Advanced Manufacturing Partnership in 2011. The Advanced Manufacturing Partnership involved presidents of five major engineering universities, large manufacturing companies, and multiple government agencies: National Institute of Standards and Technologies, Department of Energy, Department of Defense, National Economic Council, and Department of Commerce. The National Aeronautics and Space Administration, National Science Foundation, Department of Agriculture, and Department of Labor were also involved.

7.2.3. Federal Policy. The centerpiece of the Advanced Manufacturing Partnership report,[10] authored primarily by the President's Council of Advisors on Science and Technology, was the creation of manufacturing innovation institutes, which were modeled in part on the Fraunhofer Institutes and designed to address the gap between basic research and private industry development. This report was updated in 2014[11] and this update encouraged creation and scale up of manufacturing innovation institutes into a National Network of Manufacturing Institutes. The institutes were funded as a result of legislation (the Revitalize American Manufacturing and Innovation Act) that authorized the National Institute of Standards and Technology to administer the institutes and fund them, mostly through reprogramming of federal funds from Department of Defense manufacturing and Department of Energy clean energy programs, for an initial five year period after which the institutes were to be self-sustaining. Five-year federal award amounts to the institutes ranged from US$70m-$80m. The resulting institutes, now known as Manufacturing USA institutes, were not as fully focused on cyber physical systems as was Industrie 4.0, but most had an information technology enabling orientation. These institutes were designed to be public-private partnerships typically administered by a private non-profit organization and supported (in addition to the initial five-year federal funding) through membership fees from private sector companies and universities and other matching funds (including funds from state and local governments). Some of these institutes have geographically regional nodes of activity. The institutes include:

- Advanced Functional Fabrics of America, which promotes innovation in fabrics through projects that combine sensors with traditional and advanced materials
- American Institute for Manufacturing Integrated Photonics, which uses silicon photonics technology to produce high speed communication transmissions and medical imaging
- America Makes, which accelerates 3D printing R&D
- Advanced Robotics Manufacturing, which encourages development in artificial intelligence and machine learning in robotics
- Advanced Regenerative Manufacturing Institute, which seeks to improve integration of robotics and automation in tissue engineering to improve repair of cells and tissues
- Clean Energy Smart Manufacturing Innovation Institute, which fosters greater use of sensors and digital process controls for real time analytics in manufacturing energy use and production
- The Digital Manufacturing and Design Innovation Institute, which encourages cloud manufacturing platforms and standards development
- The Institute for Advanced Composites Manufacturing Innovation, which pursues lower cost and less energy intensive manufacturing of composite materials

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[10] President's Council of Advisors on Science and Technology (2012). Capturing Domestic Competitive Advantage in Advanced Manufacturing. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast_amp_steering_committee_report_final_july_27_2012.pdf.

[11] President's Council of Advisors on Science and Technology (2014). Accelerating U.S. Advanced Manufacturing, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/amp20_report_final.pdf.

- Lightweight Innovations for Tomorrow, which works on acceleration of lightweight metals into production and application across a range of industries
- NextFlex, which fosters R&D in flexible hybrid electronics
- The National Institute for Innovation in Manufacturing Biopharmaceuticals, which advances biomanufacturing and workforce training
- Power America, which develops wide bandgap semiconductor technology for energy applications
- Rapid Advancement in Process Intensification Deployment Institute, which conducts R&D to reduce energy costs in chemical processing
- Reducing Embodied-energy And Decreasing Emissions, which works to reduce energy consumption in reuse and recycling of materials

7.2.4. State Policy. Although the institutes were regionally headquartered, state governments did not play a major role in the development or operation of these institutes, with a few exceptions such as the involvement of the Michigan Economic Development Corporation in the Lightweight Innovations for Tomorrow institute. Initial state and local government matching funds provided for these institutes will need to be secured to sustain these centers.

7.2.5. Conclusions. US smart factory policy was established after the Great Recession to revitalize manufacturing by creating an institutional capacity to address the gap between basic research and private sector product development through the establishment of Fraunhofer-inspired institutes. Several of these institutes, for example the Digital Manufacturing and Design Innovation Institute and the Advanced Robotics Manufacturing institute, perform cyber physical systems related technology work. A review of the institutes suggested several strengths, such as the ability of the institute to attract diverse participants and make progress on technology development targets, as well as some ongoing challenges such as sustainability, under-emphasis on prototype systems demonstration in relevant environments, and the operation of the institutes as individual bodies rather than a network for enabling sharing of best practices.[12]

7.3. Smart Vehicles

7.3.1. Policy Issues. Smart vehicles (including smart vehicles for regular as well as hostile environments) has been a topic of growing policy, legislative, and regulatory interest in recent years at federal, state and local levels in the US. Although systematic implementation of autonomous vehicle technology remains many years away, there are already partial applications and many experiments. Policy, legislation, and regulation can perhaps similarly be regarded as partial in an evolving process at present concerning smart vehicles on the road and in the air; unmanned underwater vehicles remain governed by existing domestic and international laws of the sea. Key issues related to smart vehicles include defining autonomy and its various levels, how such vehicles should be regulated, licensing, and operated, how to address issues of liability and safety, standards for both vehicles and associated infrastructure, smart vehicle information and accident recording, security and the potential for nefarious activities. Conventionally, the federal government's Department of Transportation regulates how road vehicles are built and their safety features (the Federal Aviation Agency does the same for the air, see below), while states regulated vehicle operation, driver licensing, and traffic safety. However, smart vehicles complicate this arrangement as the rules of operation are designed into the vehicle. In addition to the federal-state tensions this creates, there are also state-level issues of how to avoid patchwork regulation (conflicting rules in different states).

7.3.2. Key Actors and Stakeholders. In the US federal system, there are multiple actors and stakeholders involved in smart vehicle policy and associated legislation and regulation. At the federal level, a series of

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[12] William Bonvillian, (2017).The rise of advanced manufacturing institutes in the United States, In Alistair Nolan (Ed), *The Next Production Revolution: Implications for Government and Business*, (pp. 360-396), Paris: OECD Publishing, http://dx.doi.org/10.1787/978926471036-en

federal agencies are involved in a range of ways, including through R&D and infrastructure spending, policies and regulations, and federal lead procurement of smart vehicles. In the Department of Transportation (DOT), key agencies include the National Highway Traffic Safety Administration (NHTSA) which deals with vehicle and road safety and the Federal Highway Administration (FHA) which funds highways and intelligent infrastructure systems. The Federal Communications Commission governs the smart vehicle wireless spectrum. The Department of Energy (DOE) sponsors R&D on efficient smart vehicle drive technologies. Defense agencies, including the Defense Advanced Research Projects Agency (DARPA) seek the development of advanced and robust autonomous vehicle technologies, primarily for applications in hostile combat environments but which often also have civilian technologies. In addition to its grant program, DARPA uses prize competitions such as the DARPA Grand Challenge competitions to advance autonomous vehicles. Federal R&D agencies, such as the National Science Foundation (NSF), sponsor research on smart vehicles (e.g. NSF Smart Vehicles Concept Center at Ohio State University) as well as on smart cities and transportation networks. Congress, and key committees such as the House Energy and Commerce Committee, sponsor legislation and provide oversight. At the state level, some states have been pro-active in developing legislation for smart vehicle use on public highways, in part because they see potential economic development and business support benefits. In other states, there is a "hands-off" approach, in some cases driven by the view that existing vehicle and road safety legislation is adequate. Other stakeholders involved at both federal and state levels include not only established automotive industry interests (such as vehicle and truck manufacturers, trucking associations, insurance companies, and workplace unions) but also new entrants such as Tesla, ride-sharing transportation services Uber and Lyft, data, software, mapping and electronics companies including Google and Apple, and consumer, road-safety and medical advocates.[13]

7.3.3. State Legislation and Policy. In 2011, Nevada became the first state to allow the operation of autonomous vehicles. 17 other states and the District of Columbia have since (by mid-2017) passed legislation on autonomous vehicles, while four additional states have issues related executive orders.[14] The types of actions taken at the state level vary. For example, Florida's legislation is broadly permissive: autonomous vehicles can be operated on public roads and a driver does not have to be present in the vehicle. Virginia has established a partnership of the state's transportation and motor vehicles departments with Virginia Tech, Transurban (an Australian-based operator of toll roads in Virginia), and Nokia's mapping division to develop "Automated Corridors" on selected state highways. Some states, such as California and Michigan, only permit testing (not unlimited operation) of autonomous vehicles on publics roads and require the presence of a driver able to take control. California has legislated to permit the testing of driverless shuttles (buses) on public roads. Other states, including Massachusetts, Washington, and Wisconsin have established working groups or commissions to investigate issues related to registration, licensing, safety, traffic laws, and liability for autonomous vehicles.[15] Significantly, some states (e.g. Florida and Michigan) that were early movers in broadly encouraging autonomous vehicles have returned to update early smart vehicle legislation. This is also the case in Nevada, which is now considering licensing and liability implications of major ride-sharing and trucking companies launching fleets of autonomous vehicles (in addition to individual purchasers).[16]

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[13] For example, the Self-Driving Coalition for Safer Streets brings together Ford, Waymo, Lyft, Uber and Volvo with other partners including MADD (Mothers Against Drunk Driving), the National Federation of the Blind, and R-Street (a free-market think tank), see http://www.selfdrivingcoalition.org/

[14] National Conference of State Legislatures. Autonomous Vehicles – Self-Driving Vehicles Enacted Legislations. http://www.ncsl.org/research/transportation/autonomous-vehicles-self-driving-vehicles-enacted-legislation.aspx

[15] National Conference of State Legislatures. Autonomous Vehicles, op.cit.

[16] Nevada, once a leader for self-driving cars, is now playing catch up with other states, Reno Gazette-Journal, April 20, 2017. http://www.rgj.com/story/money/business/2017/04/20/nevada-once-leader-self-driving-cars-now-playing-catch-up-other-states/305481001/

7.3.4. Federal Legislation and Policy. The federal government has sponsored R&D on autonomous vehicle technologies and, more recently, has begun to promulgate policy guidance. In September 2016, DOT and NHTSA issued a major policy document on automated vehicles, with four main elements. First, best practices for the design, development and testing of automated vehicles, as well as procedures for use by members of the public. A 15-topic safety assessment for manufacturers and operators for automated vehicles was detailed, including such topics as data sharing and privacy, crashworthiness, human-machine interfaces, and ethical considerations (on the latter, the federal policy seeks transparency of the algorithms used to determine vehicle decision criteria in the event of an unavoidable crash that might also affect other parties). Second, a model autonomous vehicle policy for states was put forward that confirmed the role of states in regulating vehicle licensing, traffic laws, insurance and liability yet also outlined a national framework to avoid incompatible state legislation. Third, the policy bolstered the preeminence of the NHTSA in such areas as autonomous vehicle safety and recalls, even where there was no applicable Federal standard. Finally, the policy outlined the importance of developing more flexible and nimble regulatory tools to address fast-moving autonomous vehicle technological developments. These included addressing issues of pre-market approval, vehicle certification, testing exemptions, data sharing, cyber security, and the post-certification capability of automated vehicles to receive performance-changing software updates.[17] The overriding approach of the federal policy is to ensure safety while also allowing innovation, enhanced mobility, and sustainability. In 2017, the US Congress has increased its attention to automated vehicles, with legislative proposals underway (but not yet enacted) to enforce preemption of federal over state rules and increases in the allowed number of automated vehicles that do not meet current federal vehicle standards (for example, vehicles without steering wheels) to facilitate testing on public road.[18] Additionally, while the Obama administration was broadly encouraging of automated vehicles, the perspective of the Trump administration is not yet clear. The September 2016 federal automated policy is being re-reviewed, as part of the administration's effort to reduce federal regulation and return responsibilities to the private sector. The administration's overall regulatory policy has reportedly stymied a new regulation related to vehicle data sharing for collision avoidance (as this would require two existing regulations to be eliminated).[19]

7.3.5. Unmanned Aircraft Systems. While automated cars and trucks have been a focus in the US, policy and regulatory attention has also been given to unmanned aircraft systems (or drones). The Federal Aviation Authority (FAA) has established a rule-making committee to facilitate identification, standards, and flight safety in the operation of drones). Using existing legislation and new federal rules, procedures have been established for employment-related drone operation (where pilots must be certified, over 16 years of age, and vetted by the Transportation Safety Administration) and for recreational or educational done flying (no pilot certification but there are multiple requirements related to drone aircraft and their operation including near airports). The FAA also imposes Temporary Flight Restrictions on drones for security and other reasons, and regulates accident reporting.[20] While the US approach to drones is generally to encourage research, and development, large-scale commercial applications have been limited due to the FAA's requirement to keep drones in operator sight, notwithstanding that waivers are permissible. Additionally, 40 states enacted legislation related to drones to address safety, privacy, and training concerns. Some states have taken action to define criminal use of drones (including reckless

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[17] US Department of Transportation, Federal Automated Vehicles Policy, September 2016. https://www.transportation.gov/AV

[18] Marshall, A. Congress finally gets serious about regulating self-driving cars. Wired. July 19, 2017. https://www.wired.com/story/congress-autonomous-self-driving-car-regulations/. See also: Congress Unveils 14 Proposed Pieces of Self-Driving Vehicle Legislation, Government Technology, June 27, 2017. http://www.govtech.com/fs/Congress-Unveils-14-Proposed-Pieces-of-Self-Driving-Vehicle-Legislation.html

[19] Trump's Regulation Limit Hits Transportation Department Head-On, Meri-Talk, March 29, 2017. https://www.meritalk.com/articles/dot-holds-off-on-new-rules-trump-regulation-limit-drones-autonomous-vehicles/

[20] https://www.faa.gov/uas/.

operation and harassment), to prohibit the weaponization of drones, and to facilitate the use of drones by law enforcement and search and rescue personnel.[21]

7.3.6. Analysis and Conclusions. A wide array of companies in the US are actively engaged in developing and testing automated vehicle technologies. The sector comprises established automakers and multiple new entrants ranging from start-ups to giant technology companies. Individual vehicles with partial automation (and driver present) are already in operation. Operators, including ride-sharing and trucking companies, are piloting projects with vehicles deploying higher levels of automation. In terms of policy and legislation, as is often the case in the US decentralized federal system, states have taken the lead in facilitating testing and early deployment of automated vehicle technologies. Federal agencies have undertaken a first round of steps in establishing a national framework for automated vehicles. Although the White House leadership is currently not seeking to add to the federal regulatory burden, it is possible that the US Congress will enact legislation to establish a broadly facilitative framework for automated road vehicles in the US.

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[21] http://www.ncsl.org/research/transportation/current-unmanned-aircraft-state-law-landscape.aspx

Appendix: Autonomous Systems Project Search Process

Search Strategy Overview

The Georgia Tech project proposal noted several pertinent studies; carved out initial term-based search ideas to be tested; identified candidate databases; and sketched our analytical plans. Those are included as Appendix 1.

Initial searching in WoS helped us clarify our criteria for inclusion of publication records. "Autonomous systems" engage a very wide range of component technologies and applications. Related terms, such as "smart" and "intelligent," have extensive usage concerning diverse research topics, so can include much research that is not central to the present interests. These include mature technologies such as "sensor" and "actuator," which are among the building blocks of autonomous systems but are used even more in non-autonomous technologies such as semiconductors. This makes crafting a viable search strategy challenging. Unless we take care to delimit the search phrasing, we could retrieve huge datasets (e.g., orders of magnitude greater than desirable for an autonomous systems focus).

Several principles stand forth to guide our searching:

- Maintain a system level focus; do not limit the search to specific, cutting edge technological components
- Focus on "Autonomy" (in contrast to other terms like "automatic" or "unmanned" that can well refer to remote human operator controlled systems)
- Weigh Precision somewhat more than Recall – we seek well-targeted, representative "autonomous systems" datasets to draw accurate conclusions to benchmark German competitive position in a representative manner. [In other words, better to miss some portion of relevant R&D than to process noisier data.]
- Check to include terminology that fairly captures German contributions. We have checked with the sponsor to make sure this is the case and, besides Industrie 4.0, no other German terminology has been included.

Present results are based on the Web of Science (WoS), as accessed through the Georgia Tech Library. We search for the **years 2002--2017** (through March, 2017). We considered enlarging the time period for sectors such as "smart homes" which have developments prior to 2002, but analyzing across this time period will facilitate comparability across the four sectors. Moreover, there are still enough records in each of the four sectors to enable robust comparisons. WoS regularly updates the content so that the number of records located by a search formulation increases frequently (e.g., weekly). Our search includes the Web of Science Core Collection: Citation Indexes:

- Science Citation Index Expanded
- Social Sciences Citation Index
- Arts & Humanities Citation Index
- Conference Proceedings Citation Index – Science
- Conference Proceedings Citation Index – Social Sciences & Humanities
- Book Citation Index – Science [2005 on]
- Book Citation Index – Social Sciences & Humanities [2005 on]
- Emerging Sources Citation Index [2015 on]

Note that the Book Citation Index and the Emerging Sources Citation Index do not cover the full time period. [Also nominally included are Current Chemical Reactions and Index Chemicus.[22]]. The Web of Science Core Collection indexes more than 12,000 journals.

We develop separate search routines for each of the three target types of autonomous systems: Smart Homes, Smart Factories, Autonomous Vehicles, and Autonomous Systems in Hostile Environments. The following sections report on each, in turn. Generally, we search in the WoS field "TS" – Topic Search, that includes Title, Abstract, Keywords Plus[23], and Keywords-Author (which is a field comprised of the keywords that authors include in their journal submission – as opposed to keywords that the journal or indexer may assign).

Our strategy is to try out alternative search formulations. Many of these are contingent Boolean searches, requiring the presence of more than a single term to accept a given record as appropriate. That is critical given that much autonomous systems terminology shares widespread, common usage (e.g., terms like "smart"). We compare variants of search formulations. For instance, we may run

1) term A AND term B; then try
2) term A NEAR/4 term B; then use
3) term A NEAR/1 term B.

We often check the records "in between" – i.e., records retrieved by (2) NOT (3), to see whether those records in which term A appears 2-4 words away from term B are on target (e.g., to capture a record addressing "smart and energy-efficient homes"). The searcher (here, Alan Porter) would peruse a small sample of 5-20 publication titles, plus read some abstracts where warranted, to judge whether those records are sufficiently related to autonomous systems to warrant inclusion. The criterion for that judgment is that some 75% or more of the records appear to be on target. This 75% threshold does not imply that 25% will be false positives (i.e., included when they should not be). The percentage of false positives is usually quite small (less than 5%). The 75% threshold is more of a practical guideline.

We then downloaded record sets, imported those into *VantagePoint* software,[24] and examined results. In particular we were interested to see the prominent terms compiled from titles and abstracts using Natural Language Processing (NLP), along with author keywords and Keywords-Plus. Those provided leads for investigation as additional search terms.

We also used "TFIDF" (Term Frequency, Inverse Document Frequency) in seeking topically descriptive terms. The notion is to distinguish terms that are used more heavily in relevant research abstract records than in more general records. Here, we used a 50,000 record set that reflects an approximately random sample from WoS as the comparison against which to look for terms that are relatively more prominent in our three autonomous systems searches. For details, see Appendix 3.

Drawing upon the UKIPO search strategy for Autonomous Systems and Robotics,[25] the patent search strategy for this project combines patent class codes at the subclass level with Boolean term searching of patent titles and abstracts comparable to what is used for the publications. The subclasses define the initial boundary and the Boolean term searching refines this boundary to produce the four systems. The subclasses are: Cooperative Patent Classes (CPC) B25J (home robots, controllers), B60W (control systems for cars), Y01S (robots), G05D (control/unmanned/driver-less land, water, air, space vehicles);

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[22] In a check, no records are added by inclusion of the Chemical Indexes.

[23] Web of Science creates the Keywords-Plus field from cited reference source titles.

[24] *VantagePoint* is desktop (Windows environment) software designed for text analyses of field-structured data, emphasizing science and technology information resources – see www.theVantagePoint.com.

[25] UKIPO (2014). Search Strategy: Robotics and autonomous systems. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/431896/Robotics_and_autonomous_systems.pdf.

and International Patent Classes (IPC): B25J (program control for manipulators), B60W (road vehicle control systems), G05D (control of position of vehicles in land, water, air, space). The publications and patents will not directly be connected, because only a small minority (usually less than 20%) of patents refers to non-patent scientific literature. However, there will be a broad connection because we are using similar keywords to define both (also see Appendix 1).

Smart Homes

Appendix 1 notes some of the initial candidate terms tried; that set expanded as we explored early returns and shared ideas. Appendix 2 provides notes on stepwise development of our current search algorithm for Smart Homes. The main intent was to look for additional candidate search terms, but also watching for extraneous material that should be removed. Some points of interest:

- Research relating to Smart Homes appears throughout the 2002-2017 period (i.e., it is not just a recent phenomenon and terminology pertains reasonably over the period).
- One specific technology, zigbee mentioned in the literature[26], provided a substantial number of on-target hits (using “AND home” as a contingent requirement).
- We found considerable room for judgment as to how tightly to constrain search phrasing – e.g., “smart near/1 home” vs. “smart near/2 home.” As noted in the previous section, we examined the “in-between” record sets to make such judgment calls.
- Examination of initial search results in *VantagePoint* led to relatively minor augmentation.

The present preferred Smart Home search algorithm is:

- TS = ((smart near/1 home) or (intelligent near/1 home) or ((“internet of things”) and (home)) or (iot near/4 home) or (zigbee and home))[27] or
- TS = ((activity near/1 recognition) near/3 home)) or
- TS = (("wireless sensor network" near/3 home)).

The combined search of these three Boolean terms yielded some 5405 Smart Home records. Appendix 2 provides stepwise notes to help understand the logic behind this particular search phrasing.

Upon further review (on 12 June, 2017), the Georgia Tech team determined that a parallel search that substitutes “house” for “home” in the above search should also be conducted as follows:

- TS = ((smart near/1 house) or (intelligent near/1 house) or ((“internet of things”) and (house)) or (iot near/4 house) or (zigbee and house))[28] or
- TS = ((activity near/1 recognition) near/3 house)) or
- TS = (("wireless sensor network" near/3 house)).

This search yielded 473 additional records, which, combined with the above, yields 5878 records for Smart Homes based on this final search query:

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[26] Puri, P., & Jog, Y. (2016). SMART HOME ENVIRONMENT-A BIBLIOMETRIC REVIEW. We tried other network terms such as petri net, but did not find many additional records to include.

[27] We checked whether “zigbee” suited the smart factory search as well. “zigbee and (factory or manufactur*)” yielded 117 hits not captured by the current “smart factory” search (5/8/217). Checking 10 abstracts, only 2 seemed on target (way below our 75% threshold), so we don’t include “zigbee” in the smart factory search.

[28] We checked whether “zigbee” suited the smart factory search as well. “zigbee and (factory or manufactur*)” yielded 117 hits not captured by the current “smart factory” search (5/8/217). Checking 10 abstracts, only 2 seemed on target (way below our 75% threshold), so we don’t include “zigbee” in the smart factory search.

- TS = (((smart near/1 home) OR (intelligent near/1 home) OR ((“internet of things”) and (home)) OR (iot near/4 home) OR (zigbee and home) OR ((activity near/1 recognition) near/3 home)) OR (("wireless sensor network" near/3 home)))
- TS = (((smart near/1 house) OR (intelligent near/1 house) OR ((“internet of things”) and (house)) OR (iot near/4 house) OR (zigbee and house) OR ((activity near/1 recognition) near/3 house)) OR (("wireless sensor network" near/3 house)))

A separate document, “Autonomous Systems Preliminary Research Profiles,” offers selected tabulations from the Smart Home, Smart Factory, and Autonomous Vehicle searches. It shows, for each:

Smart Factories

A similar process was followed for this topic as for Smart Homes. Appendix 4 details our experimentation with alternative search formulations. The current search algorithm has multiple parts (with the search term and resulting records highlighted):

- TS = ((intelligen* near/1 (factory or manufactur*)) or (smart near/1 (factory or manufactur*)) or (autonomous* near/1 (factory or manufactur*))) or
- TS = (("automat* factory") or ("automat* manufactur*") or ("factory automat*") or (autonomous* near/1 (factory or manufactur*))) or
- TS = ((iot near/4 (manufactur*)) or ("internet of things" near/4 (manufactur*)) or (iot and (factory)) or ("internet of things" and (factory)) or (“industry 4.0”) or ("cyber physical" and (factory or manufactur*))) or
- TS = ("petri net" near/4 manufactur*)[29] or ts = (("flexible manufacturing system" or FMS) near/4 (intelligen* or smart or automat* or autonomous))
- The combined search yielded some 3729 Smart Factory records.

The final search query is:

- TS = ((intelligen* near/1 (factory or manufactur*)) or (smart near/1 (factory or manufactur*)) or (autonomous* near/1 (factory or manufactur*))) or (("automat* factory") or ("automat* manufactur*") or ("factory automat*") or (autonomous* near/1 (factory or manufactur*))) or TS = ((iot near/4 (manufactur*)) or ("internet of things" near/4 (manufactur*)) or (iot and (factory)) or ("internet of things" and (factory)) or (“industry 4.0”) or ("cyber physical" and (factory or manufactur*))) or TS = ("petri net" near/4 manufactur*) or ts = (("flexible manufacturing system" or FMS) near/4 (intelligen* or smart or automat* or autonomous))

Again, we hope that readers will check the preliminary results in the research profile document and review Appendix 4 to address questions about our choices of search phrasing.

Autonomous Vehicles

This search generally follows the same thinking as the prior two, but the behavior of many terms is somewhat different and the search development includes multiple parts. Appendix 5 provides details on our development of the first search part (with the search terms for the first part highlighted):

Table 1. Autonomous Vehicle Search Components

- TS= (((Self-driving or autonomous) near/4 (car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) not (underwater or marine)) or

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[29] We tried: “petri net near/4 factory” or “petri net near/4 home” – each yielded only 2 hits, so we did not include this term in the Smart Factories search.

- TS = (((drone near/2 autonomous) or (uav near/4 autonomous))) or
- TS = ((robot* near/1 (car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) AND (autonomous or self-driving))
- NOT (underwater or marine)
- This combined search using the first three terms, "not" the fourth term, produces 6661 records.

We did separate searches in WoS, combining searches on: "autonomous driving, autonomous public transportation, autonomous vehicles, mobile robot, robotic vehicle, self-driving, and driverless car." We processed 33603 unique records retrieved, using VantagePoint, working with their topical terms to delimit the searches. We combined Title NLP phrases, Abstract NLP phrases, keywords—author, and Keywords-Plus into one field; then removed terms appearing in 5 or fewer records.[30] We applied various stopword thesauri to concentrate the topical coverage [including our WoS stopwords; common & basic terms; and scientific & academic terms]. We then ran a list cleanup routine (general.fuz in VantagePoint). We browsed those combined terms to understand the topical emphases reflected and focus on "autonomous systems" therein.

After various explorations, we conducted 3 separate searches within the 33603 downloaded dataset: 1) "autonom*" and "driverless." Browsing the content terms, we decided that these records could be combined with the "autonomous vehicle" search results summarized just above. We also searched for the following highlighted search terms: 2) "path or planning or planner or plan (whole word only)." And then searched for 3) "2D or 2-D or 3D or 3-D or map or localization or tracking or navigat or obstacle or avoiding." We decided that searches 2) and 3) fit together. Combining searches (2) and (3) yielded 10537 records with a general theme of "navigating" by autonomous vehicles/robots.

From the first search, we then removed those "navigating" (by robotics/vehicles) records from the search. That resulted in downloading 7182 records plus 2986 autonomous records subset, which yielded 10112 records (after removing duplicates); we recreated a cleaned, combined terms field (as per footnote 1), retaining low frequency terms; and extracted 327 "hostile environment" records, leaving 9785 records.

From the second and third search, (Autonomous Vehicle Navigating), we downloaded 10537 records and extracted 71 "hostile environment" records using the same approach as above, resulting in 10466 records.

When we combine these two datasets, the results are 20,220 records (31 records overlapped between the two datasets, which were removed) representing autonomous vehicles. When we removed a further 65 records representing "disaster," "military*," or "battlefield," (see below in the autonomous systems in hostile environments section), this removal yielded a total of 20,155 records in autonomous vehicles. An updated query yielded 29,045 records:

- TS= (((Self-driving or autonomous or driverless) near/4 (transport* or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane))) or
- TS = (((drone near/2 autonomous) or (uav near/4 autonomous))) or
- TS = ((robot* near/1 (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) AND (autonomous or self-driving or driverless)) or
- TS = ("autonomous driv*") or
- TS = (((robot* near/1 (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) OR (drone or uav)) AND (path or planning or planner or plan)) or

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[30] It is difficult to clean/group every word from an abstract or title, especially the multitude of words with 5 or fewer records, so we set our grouping threshold to five or fewer records.

- TS = (((robot* near/1 (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) OR (drone or uav)) AND (2D or 2-D or 3D or 3-D or map or localization or tracking or navigat* or obstacle or avoid*))
- NOT HAZARDOUS SEARCH

This approach yields three discrete datasets:

A. Smart Homes – 5878 WoS records
B. Smart Factories – 3729 records
C. Autonomous Vehicles – 29,045 records

Autonomous Vehicles in Hostile Environments

Based on feedback received from the sponsor in May, 2017, we enhanced our search to capture hostile environment autonomous system developments, where "autonomous systems in hostile environments" refers to "autonomous vehicles in hostile environments." We redid the autonomous vehicles search (Table 1), removing the "underwater or marine" exclusions; then downloaded the complementary records to the initial search by replacing NOT "underwater or marine" by AND "underwater or marine" which resulted in 4342 records. We combined these records with those extracted from autonomous vehicles (i.e., combined the separate "hostile environment"31 autonomous records (327 + 71 + 4342) to get 4610 records.

We received further feedback to consider "submarine," "disaster," "space," "chemical facilit*," "biotech facilit*," "military*," and "battlefield," for defining autonomous vehicles in hostile environments. Of these, "disaster," "military*," or "battlefield," were associated with unique records not in the 4610 record file. Taken together, these three keywords represent 65 total records out of the autonomous vehicles dataset. We removed these records from the autonomous vehicles dataset and added them to the 4610 record dataset, resulting in a total "autonomous vehicles in hostile environments" dataset of 4674 records (because one of the 65 records was already in the 4610 record dataset). An updated query yielded 9,536 records:

- TS = ((hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea) OR (submarine or disaster or space or "chemical facility*" or "biotech* facility*" or military or battlefield))

The final datasets are

- Smart Homes – 5878 WoS records
- Smart Factories – 3729 records
- Autonomous Vehicles – 29,045 records
- Autonomous Vehicles in Hostile Environments – 9,536 records

2. Patents

We originally planned to download applications and grants from the PatStat database, version Fall, 2016. Under this original plan, we proposed to select all patent documents in the following Cooperative Patent Classification (CPC) subclasses: B25J (CPC – home robots, controllers), B60W (CPC — control systems for cars), Y01S (CPC – robots), G05D (CPC – control/unmanned/driver-less land, water, air, space vehicles). We also selected all patent documents in the following International Patent Classification (IPC) subclasses: B25J (IPC – program control for manipulators), B60W (IPC – road vehicle control systems),

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[31] Finding records with the terms: hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea.

G05D (IPC – control of position of vehicles in land, water, air, space). This approach suggests a stable set of CPCs and IPCs, which is not the case, but stability appeared relatively good at the four-digit subclass level, which we tested with co-assigned patents (patents assigned to two or more subclasses). Then our plan was to reduce the dataset to a single patent for each invention by combining records in VantagePoint using the "Family_ID_Inpadoc" field. This field combines families as well as application and grant documents.

This approach did not work well in that it produced only a few thousand patent documents. One reason for the low numbers was the PatStat interface. We then changed our approach to conduct our initial patent search using Derwent Innovation Index (provided through many university libraries' Web of Science service) and using nearly the same keyword search strategies for each of the four autonomous systems used in the publication search. Derwent Innovations Index is a Web of Science product, so roughly the same key search interface used to search the Web of Science can be applied to patents. The only difference between the two is that the "near" operator available in Web of Science is not available for use in Derwent Innovations Index, so we used the "and" operator instead. Then we linked the resulting Derwent Innovation Index autonomous systems records with PatStat using the Patent Publication ID to do analyses of the use of non-patent literature in citations of prior art for which PatStat had the necessary data. Derwent Innovations Index truncates Patent Publication IDs of some countries (e.g., India and South Korea), so we had to manually search and add in those patents to our dataset. Refer to Appendix 7 for details about the method and the resulting search query.

Appendices

Appendix 1. Literature Review

An initial review of the literature highlighted several relevant bibliometric studies:

(1) a study of the Korean position on autonomous driving (Park, J. K., Choi, J. D., & Bae, Y. C., 2013. Scientometric analysis of Autonomous Vehicle through paper analysis of each nation. *The Journal of the Korea institute of electronic communication sciences*, *8*(2), 321-328.);

(2) an analysis of autonomous driving literature (Rosenzweig, J., & Bartl, M., 2015. A Review and Analysis of Literature on Autonomous Driving. *E-Journal Making-of Innovation*.);

(3) a bibliometric analysis focusing on smart homes (Puri, P., & Jog, Y. (2016). SMART HOME ENVIRONMENT-A BIBLIOMETRIC REVIEW);

(4) a bibliometric study of Industry 4.0 (Tonta, Y., & Doğan, G. Industry 4.0: Mapping the Structure and Evolution of an Emerging Field);

(5) a bibliometric study done by members of this project team on unmanned vehicles for a Georgia Tech researcher.

(6) For applications, we will begin from the search strategy used by the UK Intellectual Property Office at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/318236/Robotics_Autonomous.pdf.

Appendix 2. Smart Homes Search Development

Initial candidate terms to weave into an effective search included:

- Smart (not same as autonomous)

- Intelligent
- “Internet of things” or IoT
- Automation
- Sensors – which we ultimately did not include because this term, although it is a mature technology and building block of autonomous systems, concerned much non-autonomous system research. We prefer to search within the autonomous system dataset for these technologies.
  ~AND
- home
  plus:
- zigbee = **ZigBee** [1] is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection.

Steps, with observations, included the following.

1. Did not find “smart near/2 home” results acceptable (as differentiated from “smart near/1 home”); highly diverse – e.g., product recommendation for smart phones…; resource-constrained home area networks; consumer-end energy management system in smart grid.
2. “**smart near/1 home**” → look quite on target; search results cover the 2002-2017 period (not limited to a few years); early records also look on target.
    a. Strong growth over time
    b. WoSCs – EE top one; CS dominates top 10
    c. Of **4154 hits,** 2860 proceedings papers = 1264 articles (we want to make sure that some proceedings papers are included in the dataset because they are known to be important in this field).
    d. By country: China, US, So Korea, Germany, France, Taiwan
    e. Of top 20 organizations, only 2 are US; ~none German
    f. Downloaded most recent 500 – scanned TI phrases + Keywords → terms to consider: sensor network
3. “**intelligent near/1 home**” – 527 hits – look on target
4. Combining these → 4527 hits to download = (**smart near/1 home**) or (**intelligent near/1 home)**
5. “**autonomous near/1 home**” = 47; these are noisy – don’t include.
6. ts = ((**internet of things) and (home))** = 941; better to use ((“internet of things”) and (home)) = 854 – looks pretty much on target; tried (("internet of things") near/2 (home)) = 70 (those look good).
   tried “internet of things” near/4 home → 117; the extra 47 look on target.
   examining the records in the 854 that are not in the 117, look pretty good; many include “Smart Home” – so try setting those aside since they would be captured by #5 already. Removing those leaves 362 hits for “internet of things” and home (not smart or intelligent homes) – these are pretty much on target → so, we want (“internet of things” AND home) = 854
7. “iot and home” = 637 – pretty related, but somewhat diffuse. Tried “iot near/1 home” = 57 – look on target. Went in between: iot near/4 home = 128 (the additional ones beyond iot near/1 home look pretty much on-target. Let’s go with those.
   889 hits to download = **(((“internet of things”) and (home)) or (iot near/4 home));**
   It makes sense to combine these with #4 results to get 4927
8. Zigbee = 5188 hits, of which 4895 are unique from the 4927 noted in #7;
   (**zigbee and home**) = 696.
   The 696 look on target; the zigbee search without home seems way too encompassing.
   Combining searches for #8 (zigbee and home) and #7 yields 5330.

9. (**home near/1 automat***) = 1694; of those, unique to this (and not included in the 5330) are 1094. Those are pretty noisy (well below the 75% on target criterion); so don't include.
10. Try (sensor near/4 home) = 1076, of which 623 are distinct from the 5330 of #9. Those are mainly off target; do not include.
11. Combining allows a single "home part" search to get a proposed "all in one" Smart Home search 5330 here → **TS = ((smart near/1 home**) or (**intelligent near/1 home) or ((“internet of things”) and (home)) or (iot near/4 home) or (zigbee and home**))
12. To grab, need to get <5000; divided into 2002-2015; and 2015-2017; downloaded in chunks of 500; then imported all together as 5330 as one VP file successfully.
13. Inspecting the "combined keywords and phrases" field for candidate additional candidate search terms; here are some with total records in which they appear:
    a. Smart grid
    b. Wireless sensor network
    c. Activity recognition

    ** I don't find them compelling to pursue, but we can explore further later if warranted.
14. We further worked to refine the search terms by applying "TFIDF" analyses, described in Appendix 3. That generated candidate terms for review.
15. Candidate Smart Home search terms from the TFIDF analysis:
    a. Activity recognition
    b. Appliances
    c. Home appliances
    d. Internet of things
    e. IOT
    f. Smart Home or Smart Home environment or Smart Homes
    g. Zigbee

    Of the remaining 55 terms, lower TFIDF scores in the 50K file correspond to more relevance to Smart Homes – those < 25 are

    h. Homes ["home" is at 28]
    i. Smart and smart grid
    j. Things and things (IOT)
    k. Wireless sensor networks

    Reviewing the initial Smart Home search), seems worth taking a look at some of these 94/28/17):

    l. Activity recognition
    m. Appliances
    n. Wireless sensor networks
16. Reran the Main search = TS = ((smart near/1 home) or (intelligent near/1 home) or ((“internet of things”) and (home)) or (iot near/4 home) or (zigbee and home)) – yield increased slightly to 5379 records (from several days earlier search)
    a. Of those, 118 were published in 2017 – download & remove dups to get an additional 49
    b. TS = ((activity near/1 recognition) near/3 home)) not in the main search = 24 hits – look good
    c. TS = ((appliance near/3 (intelligent or smart)) near/3 home) not in the main search = 38 hits (so, 215 of these are in the main search which suggests it is generally on target). The 38 feel a bit broad – lots of energy management. Certainly not silly to include, but I'd opt NOT to do so.
    d. TS = ("wireless sensor network" near/3 home) yields 35 not in the main search; I think they add value.
    e. Downloaded 177 records = a + b + d [will need to remove dups when combine with the 5330 already downloaded] – (twice) did this and get 151 records; did dataset fusion to get a new Home file of 5405 records. Call it home 5405-ver3. This is the current search that we profile in the other file.

    f. 5/1/17 up to 5494 – running as 3 separate searches “OR’ed” together

17. Added 473 records with a parallel search performed on 12 June 2017 to step 16 that substituted “house” for “home” and excluded duplicates.

Appendix 3. TFIDF

“TFIDF” stands for Term Frequency Inverse Document Frequency. The principle is to identify how pervasive a term is in a given subset of records versus its rate of appearance in another set. That comparison could be a subset vs. the full set from which it is drawn. Or, it could be one dataset vs. an independent other. In this case, we examine frequency of occurrence in one of the three autonomous systems datasets vs. frequency in a 50,000 record, approximately random sample drawn from WoS.

We then use results to help filter terms. For instance, as listed in “Autonomous Systems Preliminary Research Profiles,” “results” is a leading term, occurring in 655 of 5405 Smart Home records. However, it is also in widespread use in WoS records generally, so not a useful search term. In contrast, we identified a number of terms not appearing above our threshold of 5 records in the 50,000 record WoS sample, such as “zigbee,” thus supported as candidate search terms.

Using the 50,000 (**50K**) record WoS random sample as the comparison dataset, we have:

- ~835,000 terms in a field we composed by merging Title NLP (Natural Language Processing) & Abstract NLP phrases with Author Keywords and Keywords Plus
- To expedite processing, removed terms appearing in <=5 records- [renamed field as a combination of terms >5 records]
- For Smart Home, used Combined Keywords + Phrases field (i.e., essentially the same term composition); then reduced that to terms appearing in >5 records

Applied “List Comparison” on the Smart Home terms (>5) vs. the 50K’s – those not in the 50K look good. So try to use TFIDF to extend the discovery of home-special terms. Interested in relatively high frequency terms that could prove to be candidates to incorporate into our search strategy. So, investigate the home terms >200 records (= 65 of them).

Ran TFIDF on all records for those Combo Terms >5 in each dataset (using the Square Root TFIDF option).

- In the Smart Homes file, made a field of the top 65 terms
- In the 50K file, used List Comparison to separate those of the 65 terms present in the 26248 >5 records terms field – got 55 hits; made a new field composed of them
- Ran TFIDF on those 55 in the 50K file [note that values are the same as in running the full terms>5 field – no surprise]
- Of the 65 terms, the 10 absent from the 50K (>5 records) term set look on target to be considered as candidate Smart Home search terms:
    - Activity recognition
    - Appliances
    - Home appliances
    - Internet of things
    - IOT
    - Smart Home or Smart Home environment or Smart Homes
    - Zigbee
- Of the remaining 55 terms, lower TFIDF scores in the 50K file correspond to more relevance to Smart Homes – those < 25 are
    - Homes [“home” is at 28]

    - Smart and smart grid
    - Things and things (IOT)
    - Wireless sensor networks

Reviewing the initial Smart Home search), seems worth taking a look at some of these 94/28/17):

- Activity recognition
- Appliances
- Wireless sensor networks

We performed TFIDF analysis for Smart Factory in the same manner as we did for the Home search.

- 2615 terms >5 for 3542 records; made field of top 51 terms >150 records
- 44 of the 51 terms appear in the 50K >5.
- In 50K, made field of the 44 Factory terms; ran TFIDF
- The 7 terms not in the 50K >5 set are
    - Factory automation
    - Industry 4.0
    - Automated manufacturing systems
    - manufacturing systems
    - intelligent manufacturing
    - cyber-physical systems
    - petri nets -- Petri nets offer a graphical notation for stepwise processes that include choice, iteration, and concurrent execution; strong cooccurrence with automated manufacturing systems
    - ** the first 6 are included in the initial search; now try **petri nets** to add
- Looking at the TFIDF scores of the 44 factory terms – the 3 lowest are: automation, manufacturing, and flexibility. The first two are included in the initial search. Let's check out **FMS = flexible manufacturing system.** See end of Smart Factory Part.

Appendix 4. Smart Factory Search Development

This followed the same approach as used for Smart Homes. Initial candidate terms are noted in Appendix 1. Here are observations as we stepped through search development.

18. Tracking on the Home Part – smart near/1 (factory or manufactur*) = 479 – these look good. Using TS = (intelligen* near/1 (factory or manufactur*)) = 751 – these look good. They capture intelligent and intelligence. I think sticking to near/1 is prudent though – results could drift pretty quickly I think if we go toward "and." Also, the parallel with Smart Home is appealing.
    TS = ((intelligen* near/1 (factory or manufactur*)) or (smart near/1 (factory or manufactur*)) or (autonomous* near/1 (factory or manufactur*))) = 1290

19. TS = (autonomous* near/1 (factory or manufactur*)) = 88 – look good;
    TS = (automat* near/1 (factory or manufactur*)) = 2430 – rich, but noisy; try more conservative:
    TS = (("automat* factory") or ("automat* manufactur*") or ("factory automat*") or (autonomous* near/1 (factory or manufactur*)))
    = 1671 (marked list = 1670)– pretty encompassing coverage, but seems solidly related (but not all "far out" or full automation).
    [only ~31 overlap with #1, so seems better to keep separate for sanity; remove dups in VantagePoint later]

20. zigbee and (factory or manufactur*) = 140; surprisingly, a number seem too wide – manufacturing being quite distinct from zigbee in the abstracts. Tighten to near/1 → 3 hits; near/4 → 13 hits. So, don't include.

21. TS = ("internet of things" and (factory or manufactur*)) = 532 – "manufactur" anywhere in the abstract seems to pull in too-broad results. Restricting to factory (=100) look pretty on-target. Tighten the manufactur* part to near/2 yields only 34 – look good. Using near/4 = 67 – look good.
    Iot and factory = 60; look pretty good. Iot near/4 manufactur* = 64 [parallels iot use in Smart Home search] look good.
    TS = ((iot near/4 (manufactur*)) or ("internet of things" near/4 (manufactur*)) or (iot and (factory)) or ("internet of things" and (factory))) = 213
22. industry4.0 → only 4 hits; ignore it. "industry 4.0" → 473 – look good.
    TS = ((iot near/4 (manufactur*)) or ("internet of things" near/4 (manufactur*)) or (iot and (factory)) or ("internet of things" and (factory)) or ("industry 4.0")) = 654 [combines #17 & #18]

23. "cyber physical" or "cyber-physical" yield the same 4104 hits – including "and system" only reduces to 3954, so seems non-helpful. But these seem very broad. Need factory/manufacturing contingency. Try "and factory" → 119 – seem good. Tried near/4 mfg → 70; seem good. Tried AND mfg – examined those this adds beyond "near/4 mfg" – look good. So, let's go with:
    TS = ("cyber physical" and (factory or manufactur*)) = 375
24. Combining #17 and #18 and #19 -- TS = ((iot near/4 (manufactur*)) or ("internet of things" near/4 (manufactur*)) or (iot and (factory)) or ("internet of things" and (factory)) or ("industry 4.0") or ("cyber physical" and (factory or manufactur*))) = 924
25. Downloaded 1290 + 1671 + 924 = 3885; removed dups → 3542 records = "Factory"
    Browsing combined keywords & phrases for possible search terms – petri nets (160); flexible manufacturing systems (89); cloud (82) with mfg?
26. "future factory" → only 23 hits; ignore.
27. We performed TFIDF analysis for Factory in the same manner as we did for the Home search.
    - 2615 terms >5 for 3542 records; made field of top 51 terms >150 records
    - 44 of the 51 terms appear in the 50K >5.
    - In 50K, made field of the 44 Factory terms; ran TFIDF
    - The 7 terms not in the 50K >5 set are
        a. Factory automation
        b. Industry 4.0
        c. Automated manufacturing systems
        d. manufacturing systems
        e. intelligent manufacturing
        f. cyber-physical systems
        g. petri nets -- Petri nets offer a graphical notation for stepwise processes that include choice, iteration, and concurrent execution; strong cooccurrence with automated mfg systems

      ** the first 6 are included in the initial search; now try **petri nets** to add
    - Looking at the TFIDF scores of the 44 factory terms – the 3 lowest are: automation, manufacturing, and flexibility. The first two are included in the initial search. Let's check out **FMS = flexible manufacturing system.** See end of Factory Part.
28. Some additional ideas that could warrant search experimentation, but seem less promising to me:
    - 5 levels of 'smartness' in autonomous cars -- ~general agreement – maybe useful 'autonomous' framework to check out
    - Sensor networks

Plus:

- Flexible manufacturing system (FMS)
- Integrated manufacturing system (IMS)
- Computer integrated manufacturing (CIM)
- [above 3 fit G05B 19/418]

29. 4/29/17 enhancement of the Smart Factory search
    - Redo Factory search – first reran above search – each increased a bit, for total of 3587. In 2017, get 93 hits (to download to update; then remove dups)
    - “petri net” and factory = 35; these seem somewhat too broad; tried near/4 factory = 2 hits; so do not pursue. Try “petri net” near/4 manufacturing = 134; look pretty good. 109 of those are unique from the main factory search; so add.
    - Try “flexible manufacturing system” or FMS = 6751 hits, of which 6659 are unique from main factory search (scary degree of differentiation). Most of the main factory search includes “mfg” already. So, explore what contingencies seem suitable for FMS. Try near/4 various terms. Got 115 hits. Look quite good. 100 are unique from main factory search. So decided to add
    - TS = ("petri net" near/4 manufactur*) or TS = (("flexible manufacturing system" or FMS) near/4 (intelligen* or smart or automat* or autonomous))
    - Additional download of 297 records from #24 & #27. But, as with the smart home search, actually got fewer records (275). Did Data Fusion; then removed duplicate records to get 3729 Factory records. Call it factory 3729-ver3 (to stay aligned with the Home file naming). This is the Factory file profiled in the other document.

Appendix 5. Autonomous Vehicles Search Development

This followed a similar approach to the prior two search development processes. Initial candidate terms are noted in Appendix 1. Here are observations as we stepped through search development.

30. Drone – could well be human operated, so delimit by autonomous. This seems the best of the candidate modifiers. It may narrow down too much, but prefer that to being too inclusive, given initial search counts for vehicles are huge in WoS. Near/1 autonomous drops the hits from 2557 to 37. With ‘autonomous’ we don’t need to “not bagpipe.” Near/4 autonomous ups the hits a bit – to 70 – seem somewhat noisy. Near/2 yields 50; these look pretty on-target (heavy on weaponry).
    = TS = ((drone near/2 autonomous)) = 50
31. UAV search yields 10,501. Let’s try to narrow using autonomous. UAV near/4 autonomous = 419 – look on-target. Inspection of a few of the 10,501 not captured in the 419 suggests they are mainly NOT autonomous systems oriented (but clearly we’ll miss some such).
    TS = (uav near/4 autonomous) = 419
32. Smart car (etc.) yielded 856; I do not like these.
33. Intelligen* vehicle (etc.) yielded 2412; some on-target, but generally too wide of the mark. Drop this.
34. Robo car – yielded 1878 – given our non-marine focus, we’ll want to NOT (underwater or marine, etc.). Scanning records, I think these are too broad. Let’s add unmanned or autonomous, etc.
    - TS = (robot* near/1 ((car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane))) AND
    - TS = (unmanned or autonomous or self-driving) NOT
    - TS = (underwater or marine)
      These yield 583 hits – look good.
      Let’s check what “unmanned” contributes

35. Mobile robot got 24,787. I think we want to delimit to get toward more autonomous attributes. TS= ((mobile near/1 robot) near/4 autonomous) yields 2763. These look good. Without unmanned, this becomes 481. The unmanned 102 record set does grab "remote controlled"; so let's leave out. Instead to with
    - TS = (robot* near/1 ((car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane))) AND
    - TS = (autonomous or self-driving) NOT
    - TS = (underwater or marine)

    These yield 481 hits.
36. TS= ((Self-driving or driverless or autonomous or automat* or unmanned) near/4 (car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) yielded 28,593. As with UAV, "unmanned" may be too encompassing, in the absence of "autonomous." Let's drop it. Likewise drop "driverless."
    a. Reducing to self-driving or autonomous near/4 = 10821; try separately. Autonomous gets 10613. Looking at self-driving (only 208), look good, but calls attention that our search picks up basic research where the abstract mentions this as a target for future application. Both self-driving and autonomous look good.
    b. Autonomous includes underwaters. Excluding those drops the 10821 to 6508.
    c. Check "automat* with vehicles, etc. → 5211 -- this gets at AGVs. This is relevant, but broader – e.g., "an automatic parking system" or "automatic steering" or "automatic vehicle location." I favor leaving out.
    d. TS= (((Self-driving or autonomous) near/4 (car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) not (underwater or marine)) = 6508 – look good.
    e. TS = (((drone near/2 autonomous) or (uav near/4 autonomous))) = 469
    f. TS = ((robot* near/1 (car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) AND (autonomous or self-driving)) = 590
    g. (underwater or marine)
    h. (d or e or f) not g = 6972 download in 2 time periods to be <5000 limit; actually got 6661 records. ?? not sure why losing some? [looked at the 2d period portion, as still a 'marked list' in WoS – got 3355 of 3536 for 2002-2012. So seems roughly proportional.] Disquieting, but not critical. This 6661 record file is profiled in the other document as "vehicles."
37. We subtracted "autonomous systems in hostile environments" search terms from the autonomous vehicles search to obtain a trial record count of 20,155. We streamlined the search and re-ran it a few weeks later, which provided a final record count of 29,045.

Appendix 6. Autonomous Vehicles in Hostile Environment Search Development

Based on feedback received from the sponsor in May, 2017, we enhanced our search to capture hostile environment autonomous vehicles developments. We redid the autonomous vehicles search (Table 1), removing the "underwater or marine" exclusions; then downloaded the complementary records to the initial search by replacing NOT "underwater or marine" by AND "underwater or marine" which resulted in 4342 records. We combined these records with those extracted from autonomous vehicles (i.e., combined the separate "hostile environment"[32] autonomous records (327 + 71 + 4342) to get 4610 records.

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[32] Finding records with the terms: hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea.

We received further feedback to consider “submarine,” “disaster,” “space,” “chemical facilit*,” “biotech facilit*,” “military*,” and “battlefield,” for defining autonomous vehicles in hostile environments. Of these, “disaster,” “military*,” or “battlefield,” were associated with unique records not in the 4610 record file. Taken together, these three keywords represent 65 total records out of the autonomous vehicles dataset. We removed these records from the autonomous vehicles dataset and added them to the 4610 record dataset, resulting in a trial “autonomous vehicles in hostile environments” dataset of 4674 records (because one of the 65 records was already in the 4610 record dataset). An updated query based on the update of the autonomous vehicles search run several weeks later yielded 9,536 records:

Appendix 7. Search Strategy for Patents

1. The “near” operator does not work in the Derwent Innovations Index query interface.
2. So, we first used simplified query (Table 2), which substituted “near” with the “and” operator.
3. Then we used VantagePoint Software to apply the “near” operator to narrow patent search (Table 3).
4. Notice that some of the search queries do not work in VantagePoint software when there are two consecutive “near” operators. Luckily, there was only one of this case from “Smart Home” patents.

Table 1. Original Search Query Example (Smart Home)

TS = ((smart near/1 home) or (intelligent near/1 home) or ((“internet of things”) and (home)) or (iot near/4 home) or (zigbee and home)) or
TS = ((activity near/1 recognition) near/3 home)) or
TS = (("wireless sensor network" near/3 home))

Table 2. Derwent Innovations Index Search Query Example (Smart Home) (2017.06.21)

TS = ((smart AND home) OR (intelligent AND home) OR ((“internet of things”) AND (home)) OR (iot AND home) OR (zigbee AND home))
14768 records
TS = ((activity AND recognition) AND home)
53 records
TS = ("wireless sensor network" AND home)
178 records
Total Records: 14896 records = (14999 –103 duplicates)

Table 3. Filtering Through VantagePoint Software Example (Smart Home)

TS = ((smart near/1 home) or (intelligent near/1 home) or ((“internet of things”) and (home)) or (iot near/4 home) or (zigbee and home))

- ((smart near/1 home) : 1421
- (intelligent near/1 home) : 3174
- ((“internet of things”) and (home)) : 387
- (iot near/3 home) : 30
- (zigbee and home)) : 1044

TS = ((activity near/1 recognition) near/3 home)*
TS = ("wireless sensor network" near/3 home)
- ("wireless sensor network" near/3 home) : 34

Final Records: **5417** (unions of the searched records)

*This strategy was not applied because this expression cannot be performed under Vantage Point. Since the records obtained from this query (broad search) was very small (53), it wouldn't make big difference.

The specific Derwent Innovations Index Search Query for the Four Autonomous Systems Patents.

1. Smart Homes

TS = ((smart near/1 home) or (intelligent near/1 home) or ((“internet of things”) and (home)) or (iot near/4 home) or (zigbee and home))
TS = ((activity near/1 recognition) near/3 home))
TS = (("wireless sensor network" near/3 home))

2. Smart Factory

TS = ((intelligen* AND (factory OR manufactur*)) OR (smart AND (factory OR manufactur*)) OR (autonomous* AND (factory OR manufactur*)))
TS = ((("automat* factory") OR ("automat* manufactur*") OR ("factory automat*") OR (autonomous* AND (factory OR manufactur*))) OR ((iot AND manufactur*) OR ("internet of things" AND manufactur*) OR (iot AND factory) OR ("internet of things" AND factory) OR (“industry 4.0”) OR ("cyber physical" AND (factory OR manufactur*))) OR ("petri net" AND manufactur*) OR (("flexible manufacturing system" OR FMS) AND (intelligen* OR smart OR automat* OR autonomous)))

3. Autonomous Vehicle

(TS= (((Self-driving or autonomous or driverless) AND (transport* or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane))) or TS = (((drone AND2 autonomous) or (uav AND autonomous)))) NOT (TS = ((hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea) OR (submarine or disaster or space or "chemical facility*" or "biotech* facility*" or military or battlefield)))

(TS = ((robot* AND (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) AND (autonomous or self-driving or driverless)) or TS = (“autonomous driv*”) or TS = (((robot* AND (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) OR (drone or uav)) AND (path or planning or planner or plan))) NOT (TS = ((hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea) OR (submarine or disaster or space or "chemical facility*" or "biotech* facility*" or military or battlefield)))

(TS = (((robot* AND (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) OR (drone or uav)) AND (2D or 2-D or 3D or 3-D or map or localization or tracking or navigat* or obstacle or avoid*))) NOT (TS = ((hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea) OR (submarine or disaster or space or "chemical facility*" or "biotech* facility*" or military or battlefield)))

4. Autonomous Vehicle (Hostile Environments)

(TS= (((Self-driving or autonomous or driverless) AND (transport* or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane))) or TS = (((drone AND2 autonomous) or (uav AND autonomous)))) AND (TS = ((hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea) OR (submarine or disaster or space or "chemical facility*" or "biotech* facility*" or military or battlefield)))

(TS = ((robot* AND (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) AND (autonomous or self-driving or driverless)) or TS = ("autonomous driv*") or TS = (((robot* AND (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) OR (drone or uav)) AND (path or planning or planner or plan))) AND (TS = ((hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea) OR (submarine or disaster or space or "chemical facility*" or "biotech* facility*" or military or battlefield)))

(TS = (((robot* AND (transport* or mobile or car or motorcar or vehicle or automobile or aircraft or airplane or aeroplane)) OR (drone or uav)) AND (2D or 2-D or 3D or 3-D or map or localization or tracking or navigat* or obstacle or avoid*))) AND (TS = ((hazard or underwater or marine or UUV or AUV or NPP or nuclear or deep-sea) OR (submarine or disaster or space or "chemical facility*" or "biotech* facility*" or military or battlefield)))