Unveiling the Technological Outcomes of Microgravity Research Through Patent Analysis: Implications for Business and Policy

Unveiling the Technological Outcomes of Microgravity Research Through Patent Analysis: Implications for Business and Policy

Lorenzo Ardito, Antonio Messeni Petruzzelli, Vito Albino, and Achille Claudio Garavelli

***Abstract*—The relevance of microgravity research—i.e., research activities related to the possibility to generate and/or take advantage of an environment scantly affected by gravitational effects—is becoming more and more important for both policymakers and executives, not only in the aerospace domain but also in many other domains. However, tracing the evolution of the technological landscape deriving from microgravity research is very complex due to the fast-growing solutions emerging from such a research activity as well as their diversified nature in terms of actors and domains of relevance. This makes difficult to identify/foresee the most exploited/promising solutions related to microgravity research, set the research budget for subsequent R&D activities, recognize relevant business opportunities, and regulate access to space. Therefore, this article aims to delve into the technological outcomes of microgravity research, so revealing their main development trends (i.e., temporal trends, the geographic origins of related solutions, main technological areas, key research organizations, and the highly impacting technologies) to provide visions of the future (i.e., technology foresight) and derive implications for business and policy. To do so, we collected and analyzed a unique sample of 4401 patents, applied between 1960 and 2020, in the wide domain of microgravity research.**

***Index Terms*—Aerospace, microgravity research, patent analysis, technological landscape, technological outcomes, technology foresight.**

I. Introduction

Aerospace has always been a source of inspiration to explorers and scientists, and since Neil Armstrong took the first small step onto the lunar surface, no one could have imagined how aerospace would then affect our daily life. Science and technology have been a major beneficiaries of the aerospace age. Starting from the discovery of earth's radiation belts, scientific and technological knowledge have poured down to earth [1], [2]. The pursuit of the opportunities underlying aerospace has produced revolutionary technologies and vastly broadened humankind's scientific knowledge, not only in the specific aerospace-related domains (e.g., planetary science, astrophysics) but also in aerospace-unrelated domains (e.g., chemistry, material sciences, nanotechnology), thanks to the possibility to conduct research in the outer space [3]–[5]. The European Space Agency has, in fact, estimated that for every Euro spent in the aerospace sector there has been six Euros benefit to the society [6].

Science and technology still have much to gain from continued access to space, also considering that avenues for developing new ways of conducting research in the outer space are far from being fully recognized. Nonetheless, research activities to reach and taking advantage of the outer space have mostly been boosted by the government spending but improving (or even maintaining) the current rate of scientific and technological discovery may not be possible only through public funding. Indeed, the costs and complexity of future aerospace missions and research activities grow faster than scientific budgets, or even the GDP of interested countries [7], [8]. To compensate for this lack of public funding, a greater private sector involvement is occurring, thus, leading to the so-named "space economy" or "NewSpace" phenomenon [6], [9]. The possibility of private firms to enable (e.g., by creating the research infrastructure) or conduct research in the space has provided them with a series of (business model) innovations that have also led to positive externalities in terms of quality of life, economic growth, and scientific progress [10], [11].

In this context, particular attention is being placed on microgravity research given its past, but especially potential future impacts on scientific/technological development and business creation [12]. On one side, microgravity research pertains to the aerospace domain since it entails creating the infrastructure, vehicles, and processes enabling the possibility to carry out experiments in an environment with reduced gravitational effects (about 10^{-2}g to 10^{-6}g) that only exists in space. On the other side, microgravity research relates to aerospace-unrelated domains by allowing scientists operating in domains such as pharmaceutical, material sciences, and plant biology to better observe and control phenomena that usually remain hidden because of gravity, albeit with relevant implications on earth. For instance, the development of radically new medicines, materials,

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The authors are with the Department of Mechanics, Mathematics and Management, Polytechnic University of Bari, 70125 Bari, Italy (e-mail: lorenzo.ardito@poliba.it; antonio.messenipetruzzelli@poliba.it; vito.albino@poliba.it; claudio.garavelli@poliba.it).

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and plant varieties that can simultaneously improve the quality of life and enhance a wide variety of businesses is especially enabled by microgravity research [13]–[16].

All in all, the technological outcomes of microgravity research are fast-growing and diversified. On one hand, new technologies are due to microgravity research in the specific aerospace domain, including solutions to make microgravity research possible. On the other hand, new technologies come from aerospace-unrelated research activities that take advantage of the enabling role of the aerospace-related research to create microgravity conditions. Moreover, it is also worth noting that microgravity research is not a completely new phenomenon, with research activities started some decades ago, and that it involves major private players, the government, research centers (e.g., universities), and, more recently, start-ups increasingly interested in microgravity research [12], [17]. This makes tracing the evolution of the technological landscape deriving from microgravity research very complex. That is, it is becoming more and more difficult to create awareness of the state of the art of microgravity research in terms of developed and most relevant technologies, key players, and key domains as well as to foreshadow the directions for subsequent R&D activities. From a policy perspective, this complicates the process of regulating access to space and set budget related to microgravity research [18]. From the managerial perspective, it is more difficult for companies to comprehend the competitive landscape and identify the most exploited/promising business areas.

As a result, a comprehension of the technological evolution related to microgravity research is not straightforward because it is long-standing and involves different types of technologies, belonging to diverse industries and developed by different organizations. Despite this complexity, the extant research has mainly examined microgravity research from a technical point of view and have focused on the study of specific applications, thus, lacking a comprehensive picture of the technological outcomes of microgravity research. In other words, prior studies have paid attention to the scientific and engineering aspects behind microgravity research while disregarding questions such as: When and where the technological outcomes of microgravity research developed? Where did they originate? Which technological domains do they pertain to? Which are the most relevant solutions? Answering these questions is pivotal to comprehend microgravity research, support technology foresight, and provide insights into business and policy decision-making processes. However, to the best of our knowledge, these questions have not yet been addressed properly by a comprehensive study, as compared to finer-grained analyses on specific experiments in microgravity conditions.

This article aims to fill this gap by delving into the technological outcomes of microgravity research, so revealing respective main development trends, including temporal trends, main technological areas, the geographic origins of the developed solutions, the highly impacting technologies, and key research organizations. This recalls previous studies revealing the benefits of providing a clear picture of the technological landscape in a given domain to highlight elements that can be useful for business development, policymaking, and future R&D activities.

The methodological approach to meet the goal of the study is the patent analysis. Based on a sample of 4401 patents in the domain of microgravity research, collected through the Orbit Intelligence database, we present an overview of patents' development trends, being patents considered as suitable data for technology trend and technology foresight analyses.

The rest of this article is organized as follows. Section II discusses microgravity research and the role of patent analysis to provide implications for business and policy by analyzing patenting activity trends. Section III describes the methodology. Section IV presents the results. Section V provides discussion, implications, and future research directions and finally concludes this article.

II. Literature Review

A. *Microgravity Research*

Broadly speaking, the state of a system is affected by temperature, pressure, and gravity, whose modifications may help to understand novel behaviors of the system. Accordingly, research activities have long been conducted in conditions of very high/low temperature or pressure. The results of these research activities were paramount in that some of the most relevant breakthrough innovations were discovered when research has been conducted in such nonconventional conditions. Likewise, thanks to the possibility to access (in various ways) space, carrying out research in microgravity conditions is likely to open avenues for very important technological discoveries [19]. Indeed, when the gravitational effects are removed, most of our intuitive expectations do not hold up (e.g., temperature differences in a fluid do not produce convection, buoyancy, or sedimentation) since other forces (e.g., surface tension, capillary forces) become predominant and lead to different system dynamics [20].

The effects of a microgravity environment became of interest with the dawn of the Space Age, during the Cold War space race. Research in such an environment was initially enabled by Apollo, Soyuz, the Space Shuttle, and, afterward, the International Space Station (ISS). In particular, building the ISS (the first component was launched into orbit in 1998) can be considered the most relevant public funding effort toward microgravity research and, since 2000, when the first astronauts/scientists arrived, the ISS has continuously served as a microgravity and space environment research laboratory [21].

However, government funding for microgravity research, which reached a peak of $ 100 Million [12], started declining soon after the development of the ISS (not only in the US) due to financial crises and some disasters, such as the 2003 Space Shuttle Columbia disaster. The constrained budgets for microgravity research led to a shift in the approach to the exploitation of space, calling for more research funded by the private sector, hence, relaxing government intervention. For instance, the 2005 NASA Authorization Act, subsequently reflected in the 2010 National Space Policy, set the basis for a robust US commercial space industrial base. This, together with the announced termination of the ISS program, has boosted the space economy, whereby transportation to and from space, as well as microgravity research activities, is being successfully conducted by many private companies, albeit public funding and interventions have never completely been cut [2].

Eventually, nowadays, "human spaceflight and robotic science missions can be undertaken ever more regularly and at a lower cost, improving the conditions for full-scale microgravity research programs" thanks to the joint efforts of governments in regulating access to space and investments of the private sector [12, p. 1]. On the other hand, designing regulations and public funding, for what concerns governments, and assessing/identifying business opportunities related to microgravity research, for what concerns private firms, are not straightforward due to the fast-growing research intensity, technological discoveries, and interested organizations/countries. Consequently, it becomes important to (steadily) trace the trends underlying the technological outcomes of microgravity research (aerospace-related and aerospace-unrelated ones) and involved organizations/countries [9], which is the aim of this article.

B. Patents as a Mean for Technology Trend Analysis

A patent is commonly understood as an intellectual property right granted by a governmental office, national or supranational, for the exclusive exploitation of an invention. In return, the knowledge underlying the patented invention must be disclosed [22], [23]. Once patented, features, functionalities, and drawings of the invention (plus information about owners, inventors, and technological classifications) are made publicly available. Thus, on one hand, patents seek to boost entrepreneurial activities by providing monopoly rents to the patent owner. On the other hand, they are used to diffuse technical knowledge that otherwise would remain secretly stored.

Despite the primary role of patents is to create a balance between monopoly rents and knowledge diffusion, they have also become a relevant source of information from a strategic and managerial perspective [24]. That is, they are considered signals of the performance outcomes of innovative R&D efforts at the organizational, sectorial, and country level. Accordingly, they have been used, for instance, to measure technological turbulence in a given sector, or the relative technological strengths of an organization/country over others (e.g., [25]). The emergence of this alternative perspective on the role of patents, together with the possibility to access patent information with no restrictions in terms of content and time period, has enabled the possibility to examine and map the technological outcomes of research activities at different levels of analysis, over time, and across geographic contexts (i.e., to conduct a patent analysis). In turn, the patent analysis has been deemed to be useful to support decision-making during the prioritization of strategic and/or technological areas by providing insights for technology foresight (e.g., [26] and [27]), which is concerned "with the generation of reasoned statements about the future, the interpretation of such statements in terms of informed action, and the collective learning processes that are involved in responding to challenges of the future" [28, p. 79].

In line with the foregoing discussion, many studies have underlined the value of providing a comprehensive overview of a given domain's technological outcomes, and patents have extensively been used by these studies (e.g., [29]–[33]). This article follows these prior studies and focuses on the domain of microgravity research.

III. Methods

A. Data Collection

According to the theoretical reasoning discussed in Section II-B, patents, and related bibliographic information, represent the data for addressing the goal of this article. The main source of data was the Orbit Intelligence "Fullpat" database (e.g., [34]). The "Fullpat" database is updated weekly and covers patents issued by national patent offices, regional patent issuing authorities such as the European Patent Office (EPO), and international patent issuing authorities such the World Intellectual Property Organization (WIPO). It, thus, removes any potential time and country bias. Compared to the WIPO database, the "Fullpat" database has the advantage of a more automated export of data, but no data was lost.

To collect patents related to microgravity research, a keyword approach is used since no defined classifications exist to do so. We first identified two main keywords, which are the most common terms when referring to this type of research activities, namely "microgravity" and "zero gravity." Then, we searched for all the patents including these keywords in the title, abstract, or claims. The reliability of this choice was confirmed by Xie and Miyazaki [35, p. 20], who revealed that "the most effective method of identifying patents in a specific domain through keyword search is using the patent information in the title, abstract, and claims," as this is where a patent's essential content is reported. This first search yielded a sample of 2513 patents, including granted and pending patents. Afterward, title, abstract, and claims of the identified patents were scrutinized to identify other potential keywords that may well characterize microgravity research. This process was reiterated several times since the number of patents did not grow anymore after adding additional keywords. We also asked three scientists involved in microgravity research to validate the keywords. At the end of this snowballing procedure, the final list of keywords is as follows: "microgravity," "zero gravity," "microgravitational," "microgravitation," "antigravity," "micro-g," "artificial gravity," "space condition,*" "low gravity," "microlow-gravity," "weightlessness," "no gravity"). In sum, we searched for all the patents presenting, at least, one of the mentioned keywords in the title, abstract, or claims, thus, yielding a final sample of 4401 patents filed between 1960 and 2020 (the search process ended in May 2020). Each patent is classified as either a pending patent or a granted patent.

While patenting is common in many high-tech sectors, comprising most of those engaged in microgravity research (e.g., pharmaceuticals, chemistry, material sciences), we acknowledge that patenting in the aerospace sector has not been as common as in those sectors. Nonetheless, as indicated by the OECD [9], [36], this trend is changing, with the number of aerospace-related patents almost quadrupled in 20 years. Accordingly, the OECD

[36] has provided the first examination of the outcomes of aerospace-related research through patents. Yet, other studies have adopted patents to assess more specific technological dynamics in the aerospace sector by relying on patents (e.g., [37]–[39]) thus, letting us be more confident about the chosen data source.

B. Key Indicators

Herein, we present key indicators of the patent analysis (see Section IV). Each described analysis will distinguish granted and pending patents since the former represent verified outcomes, while the latter may demonstrate different underlying mechanisms since other factors may influence patent applications (e.g., government/institution policies that award patent applications rather than awarded patents). Nonetheless, most of the pending patents are demonstrated to lead to granted patents; thereby, pending patents may support technology foresight by informing about potential future technology trends (e.g., [40]).

First, we adopt patent count per year to depict the temporal trends characterizing the development of microgravity-related technologies. The filing year is used to date the patents since it better reflects the inventing period as compared to the issue year (e.g., [31]).

Second, to examine the geographic origins of the identified patents, each patent is assigned to the country where the patent protection was initially claimed, i.e., the priority country (e.g., [34]). Still, to control for events such as the establishment of quotas about the number of patents that should be filed per year nationwide (e.g., in China), which leads to the application of patents that are not actually intended to be exploited, we grouped the patents in patent families (PFs) through the Orbit Intelligence "Fampat" database [34]—3704 PFs were identified. PFs are examined to assess the extent to which patents originated in a given (priority) country have been (or are intended to be) applied in other countries (i.e., the family size). Indeed, the greater the family size of a patent, the greater the market coverage, value, and, hence, the likelihood that the patent is (or will be) actually exploited (e.g., [41]).

Third, by looking at the International Patent Classification (IPC) codes associated with each patent, we analyze how the patenting activity is widespread across diverse technological domains. In doing so, we highlight aerospace-related and aerospace-unrelated domains.

Fourth, we identify the most proficient organizations in turning microgravity research into technological outcomes by counting the number of patents owned by each organization recognized as a patent assignee. We complement this analysis by providing measures of impact and relevance of the patents developed by each organization. To do so, on one side, we consider the average number of citations received by an organization's patents. Indeed, forward citations have widely been considered a reliable proxy for the impact of patents on subsequent technological developments [42]. On the other side, recalling the discussion about PFs made earlier in this section, we count the number of patents owned by an organization with a family size greater than 1. Furthermore, we looked at the technological diversification of the most patent-intensive organizations by identifying the variety of IPC codes assigned to their patents.

Fifth, through the Orbit Intelligence IP Business Intelligence module, we construct coassignee networks to unveil collaboration patterns among patenting organizations with social network analysis. The coassignee network reflects actual collaboration between patenting organizations since it is constructed on the basis of the patents jointly owned by more organizations, which are often the result of joint research efforts [43].

Finally, we delve into the subsample of highly impacting patents (top 10%), still considering their forward citations. However, a temporal bias in counting forward citations exists due to the different points in time when patents are applied. Thereby, instead of counting the forward citations of each patent, we assess and homogenize their value by calculating the share between the number of forward citations received by a patent and the mean citations received by all the sample patents filed in the same year [25], [42].

IV. Results of the Patent Analysis

Fig. 1 depicts the patenting activity trend over time (1960–2020) for both granted and pending patents. It reveals that the patenting activity had a boost in the late eighties, most probably as a result of the increased funding schemes of governments and their increasing interest in microgravity research, which had led to the decision to develop the ISS, for instance.

Until the mid-twenties, the patenting activity trend was almost constant but afterward presents a growing trend, likely fostered by the concurrent efforts made by public and private organizations given the increasing microgravity-related business opportunities. After 2016, for what concerns granted patents, the patenting activity seems to decrease. However, this is likely because patents more recently applied are still under the review process, hence, not granted yet. The number of pending patents may confirm this assumption, as they are more than the granted ones and concentrated in the period 2014–2020 (93% of all pending patents), suggesting that the patenting activity trend will continue to grow even though some of the pending patents, of course, will not be granted. Overall, we may contend that the identified trend is growing, and it is likely to keep with this growth rate.

Fig. 2 complements the previous analysis by adding information on the geographic distribution of granted and pending patents. The top ten countries are highlighted. These have originated 97% of all the patents. Almost 40% of the patents have origins in China (CN), which is the most productive area. The United States (US) and Japan (JP) follow with 16.87% and 11.32% of the sample patents, respectively. Republic of Korea (KR) (2.37% of the patents) and Taiwan (TW) (1.18% of the patents) also appear to be relevant areas, stressing the significance of the Asian context. It is interesting to note that the Russian Federation (RU) represents the fifth top patenting geographic area (6.38% of the patents). The European context, mainly represented by France (FR), Germany (DE), the United Kingdom (UK), and Italy (IT), lags behind the countries abovementioned, presenting a total share of 5.79% of the patents,

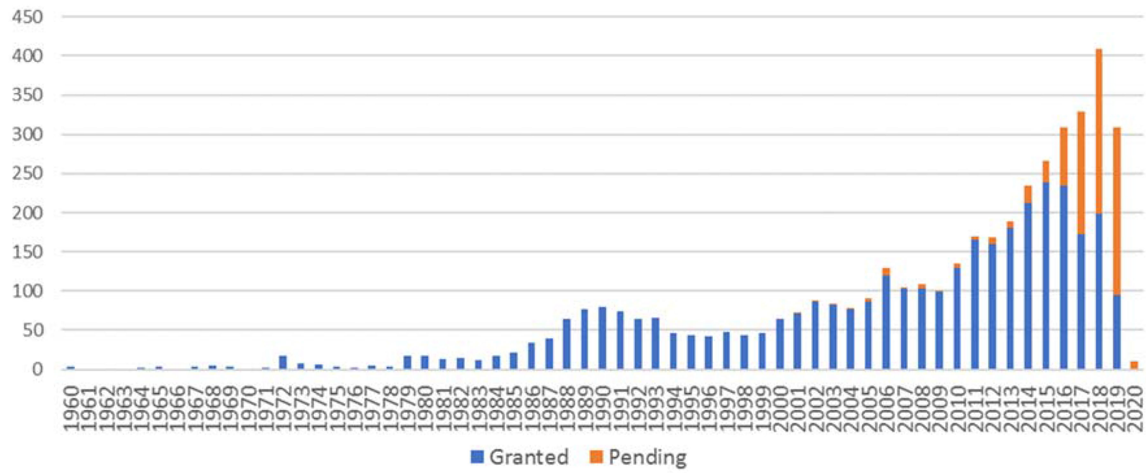
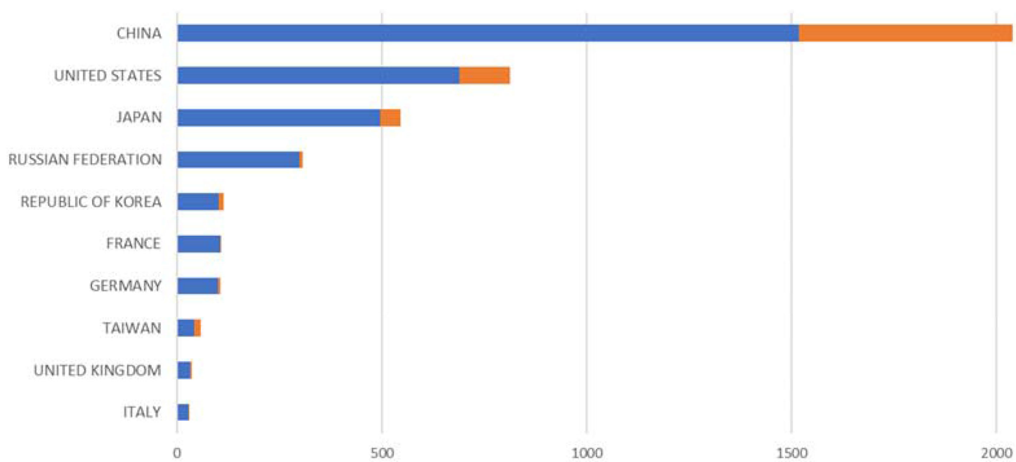


Fig. 1. Temporal trends per filing year.



	ITALY	UNITED KINGDOM	TAIWAN	GERMANY	FRANCE	REPUBLIC OF KOREA	RUSSIAN FEDERATION	JAPAN	UNITED STATES	CHINA
Granted	27	32	42	99	106	102	299	495	689	1517
Pending	2	4	15	7	2	12	8	50	123	523
Granted share	0,68%	0,80%	1,05%	2,48%	2,66%	2,56%	7,49%	12,41%	17,27%	38,02%
Pending share	0,24%	0,48%	1,78%	0,83%	0,24%	1,43%	0,95%	5,95%	14,63%	62,19%
Total share	0,60%	0,75%	1,18%	2,20%	2,24%	2,37%	6,38%	11,32%	16,87%	42,39%

Fig. 2. Geographic distribution of patents per priority country.

which is below the share of Russian patents only. A finer-grained look at pending patents, which are among the most recent, may suggest that CN, the US, JP, and TW are, and will be actively involved in microgravity research as the share of pending patents is comparable with or higher than the total share of patents (see the last two rows of the summary table of Fig. 1). Conversely, for the other areas, especially for RU and European countries, the share of pending patents is lower than the total share of patents.

Fig. 3 reveals temporal trends per geographic area in the period 1960–2020, distinguishing between granted (blue bubbles) and pending (orange bubbles) patents. The figure shows that until the late nineties microgravity-related patents are mainly due to the US, Japanese, and Russian research activities. FR and DE slightly contributed between mid-eighties and mid-nineties. Then, while the US, Japanese, and Russian performance outcomes remained more or less constant, CN has caught up and surpassed all in the last decade. Fig. 3 also makes more evident that CN, the US, and JP will likely be the most productive countries in the next years, as revealed by the number of pending patents applied in the last few years.

To provide further insights at the country level, the family size of the patents originated in a given geographic area is analyzed (see Table I). This helps to control for potential country-specific phenomena that may over/underestimate the relevance of a geographic area. From Table I, it emerges that the family size of the majority of Asian- and RU-based patents has a value of

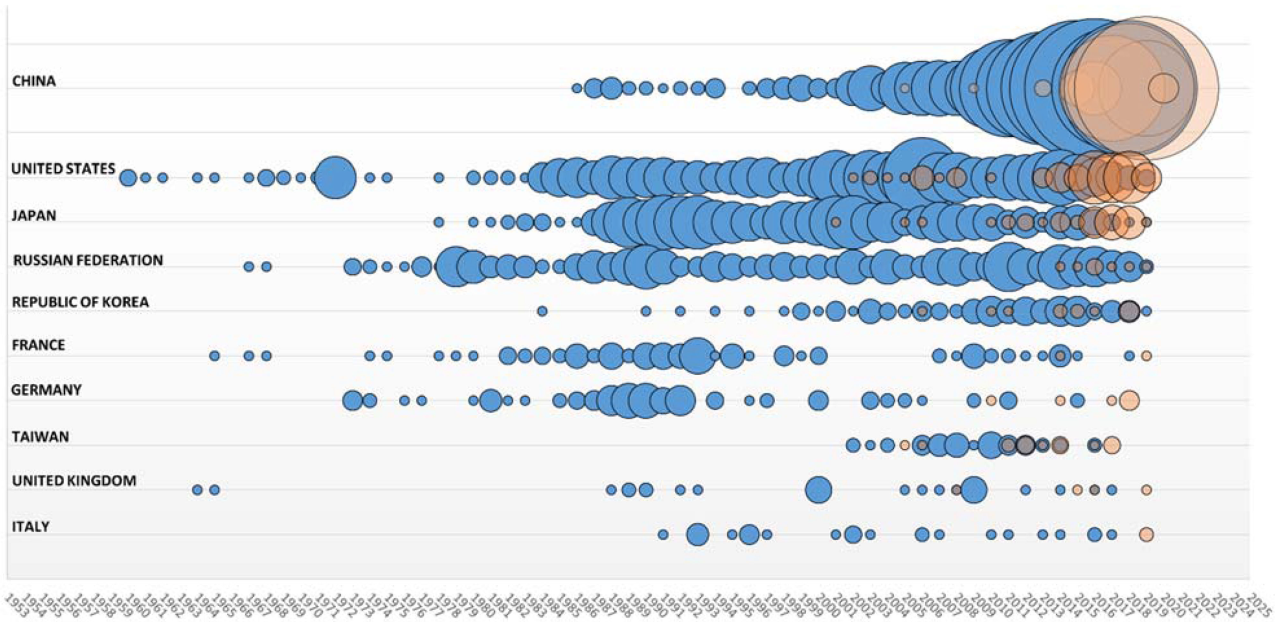


Fig. 3. Temporal trends per geographic area (priority country). Note: the dimension of the bubbles represents the number of patents; the color of the bubbles indicates whether the patents are granted (blue) or pending (orange).

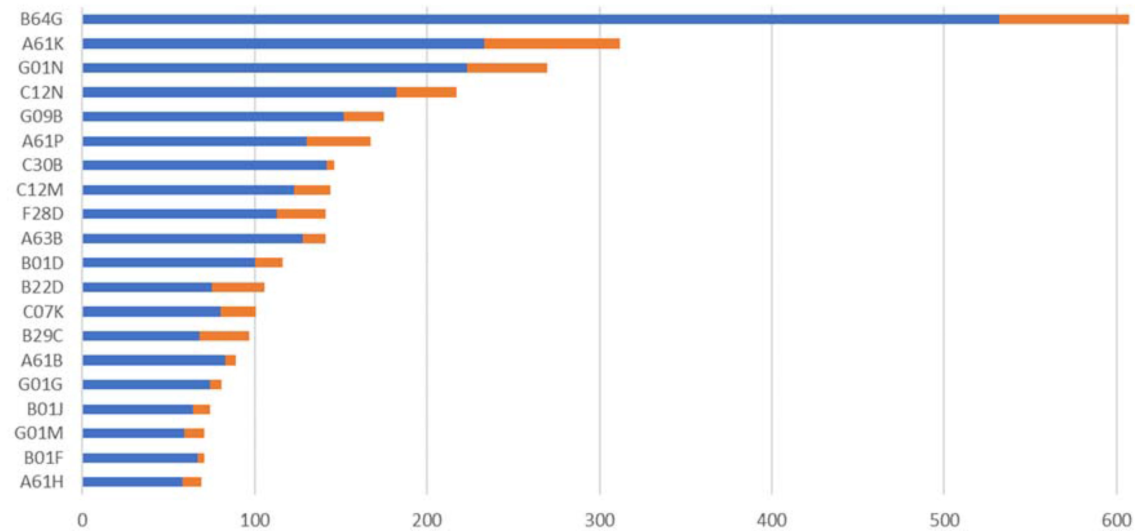
TABLE I
PFs Pergeographic Area (Top Ten Geographic Areas)

Family size	PFs	Share	CN share	US share	JP share	RU share	KR share	FR share	DE share	TW share	UK share	IT share
1	3189	86,10%	98,29%	53,57%	76,71%	90,98%	82,18%	39,58%	45,45%	92,86%	64,00%	35,71%
2	149	4,02%	0,75%	8,10%	7,76%	8,02%	10,89%	2,08%	13,64%	3,57%	8,00%	21,43%
3	82	2,21%	0,35%	8,33%	3,65%	0,50%	0,99%	14,58%	10,61%	3,57%	4,00%	7,14%
4	63	1,70%	0,10%	3,81%	5,48%	0,25%	1,98%	6,25%	10,61%	0,00%	4,00%	7,14%
5	51	1,38%	0,10%	4,29%	2,74%	0,00%	1,98%	12,50%	4,55%	0,00%	4,00%	7,14%
6	33	0,89%	0,05%	3,57%	1,37%	0,00%	1,98%	4,17%	7,58%	0,00%	0,00%	0,00%
7	26	0,70%	0,00%	3,10%	0,68%	0,00%	0,00%	4,17%	4,55%	0,00%	4,00%	7,14%
8	20	0,54%	0,05%	1,90%	1,14%	0,00%	0,00%	4,17%	1,52%	0,00%	0,00%	0,00%
9	15	0,40%	0,10%	1,19%	0,23%	0,00%	0,00%	4,17%	0,00%	0,00%	8,00%	0,00%
10	14	0,38%	0,15%	1,90%	0,00%	0,25%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
>10	62	1,67%	0,05%	10,24%	0,23%	0,00%	0,00%	8,33%	1,52%	0,00%	4,00%	14,29%
Total share		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Total PFs	3704		1994	420	438	399	101	48	66	56	25	14

Note: Each country share (columns 4–13) considers both granted and pending PFs; still, such a share reflects the share of granted and pending PFs considered separately.

1. Stated differently, these patents are applied/published only in the originating country. Conversely, US- and European-based patents have a greater tendency to be applied/published in countries different from the originating one. That is, they have a larger market coverage and, probably, they are more relevant from a business perspective, at least.

As discussed in Section II, microgravity research is pervasive. Thus, we scrutinize the technological domains assigned to the related patented inventions. More than 100 different IPC codes can be identified, thus, confirming the pervasiveness of microgravity research. Fig. 4 presents the top 20 IPC codes (Table II describes the top 20 IPC codes). The code B64G (Cosmonautics; Vehicles or Equipment therefore) reflects the leading technological domain by far, followed by a first set of codes (A61K to B22D) assigned to 100–300 patents and a second set of codes (C07K onward) assigned to less than 100 patents. There are some IPC codes whose number of pending patents is sensibly higher than the others; some of them are not even in the highest positions. These are A61K (Preparations for Medical, Dental, or Toilet Purposes) (79 pending patents), B64G (75 pending patents), G01N (Investigating or Analysing Materials by Determining their Chemical or Physical Properties) (47 pending patents), A61P (Specific Therapeutic Activity of Chemical Compounds or Medicinal Preparations) (37 pending patents), C12N (Microorganisms or Enzymes; Compositions Thereof; Propagating, Preserving, or Maintaining Microorganisms; Mutation or Genetic Engineering) (35 pending patents), B22D (Casting of Metals; Casting of other Substances by the Same Processes or Devices) (31 pending patents), and B29C (Plastic State, Not otherwise Provided For; After-Treatment of The Shaped Products) (29 pending patents). Moreover, there are some IPC codes not (yet) in the top 20 list but associated with



	A61H	B01F	G01M	B01J	G01G	A61B	B29C	C07K	B22D	B01D	A63B	F28D	C12M	C30B	A61P	G09B	C12N	G01N	A61K	B64G
Granted	58	67	59	64	74	83	68	80	75	100	128	113	123	142	130	152	182	223	233	532
Pending	11	4	12	10	7	6	29	21	31	16	13	28	21	4	37	23	35	47	79	75
Total	69	71	71	74	81	89	97	101	106	116	141	141	144	146	167	175	217	270	312	607

Fig. 4. Top 20 technological domains.

a high number of pending patents, i.e., C08L (Compositions of Macromolecular Compounds) (26 pending patents), C08K (Use of Inorganic or Non-Macromolecular Organic Substances as Compounding Ingredients) (21 pending patents), and B33Y (Additive Manufacturing) (21 pending patents). All these IPC codes may indicate the future domains upon which investing in the near future.

Table II, in the last two columns, identifies key domains/application areas for the identified IPC codes as well as their relation to the aerospace sector, hence, unveiling aerospace-related and aerospace-unrelated domains. As predictable, both aerospace-related and aerospace-unrelated domains can be recognized, with aerospace-unrelated domains including chemistry, material sciences, human necessities, pharmaceutical, and physics. It is worth noting that, except for the domain related to the code B64G, aerospace-unrelated domains are those with the highest number of pending patents. In addition, IPC codes related to applications within and beyond the aerospace domain, especially general research methods can be identified (see last rows of Table II).

At the organizational level, several patent owners can be recognized, including companies, research centers, universities, and governmental organizations. Table III presents the top 20 patent-intensive organizations. It is worth stating that, as opposed to other domains (e.g., alternative energy and IoT) (e.g., [31] and [44]), many universities and research centers are among the top 20 organizations, and a national agency (i.e., the NASA—National Aeronautics & Space Administration) ranks fourth. This may hint that basic research activities are still an important driver of new technologies in the context under investigation. In turn, the application of microgravity research can be likely considered distant from commercial opportunities or, at least, still too risky, as revealed by the relative dominance of research centers over firms.

According to Table III, some organizations, even in the highest positions (e.g., Mitsubishi Heavy Industries) do not own pending patents, hence, hinting that these organizations are disregarding microgravity research. By contrast, other organizations (e.g., Harbin Institute of Technology, Made Space, Center for Space Utilization) own a high number of pending patents, which means they are investing in microgravity-related research and will likely be key players and reference organizations in the next future. Table III also presents the average number of citations received by an organization's patents. It is not evident any particular difference between types of organization. For instance, among the most cited organizations appear the NASA—National Aeronautics & Space Administration (a national agency) and Smithkline Beecham (a company). Differences exist, instead, when looking at the number of PFs applied/published in more than one country since, except for NASA—National Aeronautics & Space Administration, Japan Aerospace Exploration Agency, and Agency of Industrial Science & Technology, only companies own patents with a family size greater than 1.

Fig. 5 informs about the technological domains in which the top 20 patent-intensive organizations are active.[1] Most of them are highly diversified, albeit some sensibly focus on one key domain (e.g., Mitsubishi Heavy Industries, Made Space), while others sensibly focus on more than one domain (e.g., Amgen, NASA—National Aeronautics & Space Administration).

[1]The distinction between granted and pending patents has been underestimated since both types of patents are the result of research activities in a given domain regardless of the ultimate outcome.

TABLE II
DESCRIPTION OF IPC CODES AND RELATION TO THE AEROSPACE SECTOR

IPC code	Description[1]	Application	Domain
B64G	COSMONAUTICS; VEHICLES OR EQUIPMENT THEREFOR	Aerospace	Specific aerospace-related domains
G09B	EDUCATIONAL OR DEMONSTRATION APPLIANCES; APPLIANCES FOR TEACHING, OR COMMUNICATING WITH, THE BLIND, DEAF OR MUTE; MODELS; PLANETARIA; GLOBES; MAPS; DIAGRAMS	Aerospace	
G01M	TESTING STATIC OR DYNAMIC BALANCE OF MACHINES OR STRUCTURES; TESTING OF STRUCTURES OR APPARATUS, NOT OTHERWISE PROVIDED	Aerospace	
C12N	MICROORGANISMS OR ENZYMES; COMPOSITIONS THEREOF; PROPAGATING, PRESERVING, OR MAINTAINING MICROORGANISMS; MUTATION OR GENETIC ENGINEERING	Chemistry Biotechnology	Aerospace-unrelated domains
C07K	PEPTIDES	Chemistry Metallurgy	
B01J	CHEMICAL OR PHYSICAL PROCESSES, e.g. CATALYSIS, COLLOID CHEMISTRY; THEIR RELEVANT APPARATUS	Chemistry Physics	
A61H	PHYSICAL THERAPY APPARATUS, e.g. DEVICES FOR LOCATING OR STIMULATING REFLEX POINTS IN THE BODY; ARTIFICIAL RESPIRATION; MASSAGE; BATHING DEVICES FOR SPECIAL THERAPEUTIC OR HYGIENIC PURPOSES OR SPECIFIC PARTS OF THE BODY	Human necessities	
G01N	INVESTIGATING OR ANALYSING MATERIALS BY DETERMINING THEIR CHEMICAL OR PHYSICAL PROPERTIES	Material sciences	
C30B	CRYSTAL GROWTH	Material sciences	
B22D	CASTING OF METALS; CASTING OF OTHER SUBSTANCES BY THE SAME PROCESSES OR DEVICES	Material sciences Manufacturing	
B29C	SHAPING OR JOINING OF PLASTICS; SHAPING OF MATERIAL IN A PLASTIC STATE, NOT OTHERWISE PROVIDED FOR; AFTER-TREATMENT OF THE SHAPED PRODUCTS, e.g. REPAIRING	Material sciences Manufacturing	
A61B	DIAGNOSIS; SURGERY; IDENTIFICATION	Human necessities	
A61K	PREPARATIONS FOR MEDICAL, DENTAL, OR TOILET PURPOSES	Pharmaceutical Chemistry	
A61P	SPECIFIC THERAPEUTIC ACTIVITY OF CHEMICAL COMPOUNDS OR MEDICINAL PREPARATIONS	Pharmaceutical Chemistry	
C12M	APPARATUS FOR ENZYMOLOGY OR MICROBIOLOGY	Pharmaceutical Chemistry	
B01D	SEPARATION	General research	Pervasive domains, including aerospace
G01G	WEIGHING	General research	
B01F	MIXING, e.g. DISSOLVING, EMULSIFYING, DISPERSING	General research	
F28D	HEAT-EXCHANGE APPARATUS, NOT PROVIDED FOR IN ANOTHER SUBCLASS, IN WHICH THE HEAT-EXCHANGE MEDIA DO NOT COME INTO DIRECT CONTACT; HEAT STORAGE PLANTS OR APPARATUS IN GENERAL	Aerospace Energy	
A63B	APPARATUS FOR PHYSICAL TRAINING, GYMNASTICS, SWIMMING, CLIMBING, OR FENCING; BALL GAMES; TRAINING EQUIPMENT	Aerospace Human necessities	

[1]The description of the IPC codes is available at the World Intellectual Property website: https://www.wipo.int/classifications/ipc/ipcpub/?notion=scheme&version=20170101&symbol=none&menulang=en&lang=en&viewmode=f&fipcpc=no&showdeleted=yes&indexes=no&headings=yes&notes=yes&direction=o2n&initial=A&cwid=none&tree=no&searchmode=smart

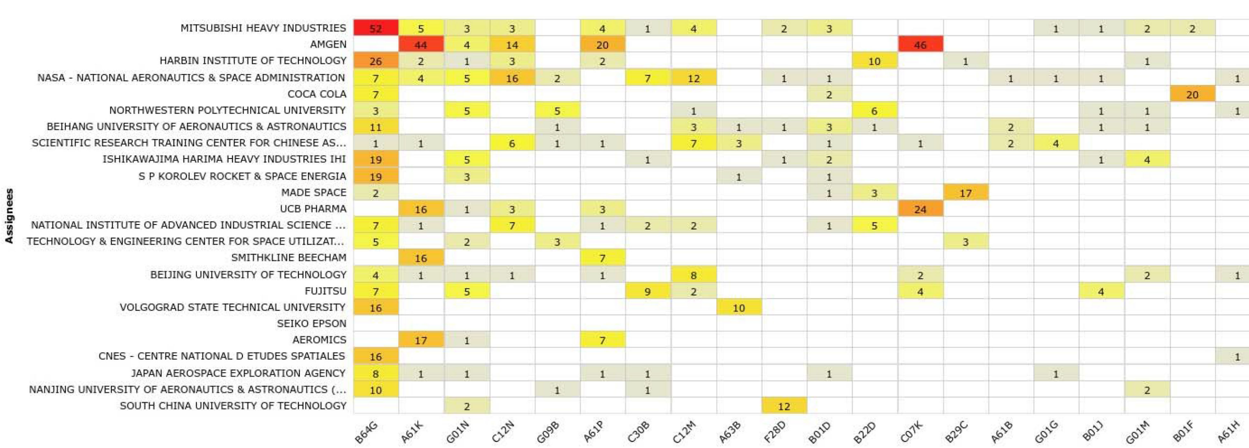


Fig. 5. Top 20 technological domains covered by the top 20 patent-intensive organizations. Note: the darker the color, the more the patents owned by an organization assigned to a given IPC code.

TABLE III
TOP 20 PATENT-INTENSIVE ORGANIZATIONS

Organization	Type	No. of patents	Granted	Pending	Mean citations	No. of patents with family size > 1	Mean authorities (patents with family size > 1)
MITSUBISHI HEAVY INDUSTRIES	Company	79	78	1	6,52	11	4,09
AMGEN	Company	59	48	11	4,21	8	17,50
HARBIN INSTITUTE OF TECHNOLOGY	University	58	42	16	2,71	0	0,00
NASA - NATIONAL AERONAUTICS & SPACE ADMINISTRATION	Research center / National agency	46	44	2	27,33	4	5,25
COCA COLA	Company	44	44	0	6,90	12	4,42
NORTHWESTERN POLYTECHNICAL UNIVERSITY	University	40	29	11	1,43	0	0,00
BEIHANG UNIVERSITY OF AERONAUTICS & ASTRONAUTICS	University	35	28	7	1,50	0	0,00
SCIENTIFIC RESEARCH TRAINING CENTER FOR CHINESE ASTRONAUTS	Research center / National agency	31	20	11	1,50	0	0,00
ISHIKAWAJIMA HARIMA HEAVY INDUSTRIES IHI	Company	27	27	0	5,67	1	4,00
S P KOROLEV ROCKET & SPACE ENERGIA	Company	27	26	1	3,48	0	0,00
MADE SPACE	Company	26	7	19	0,43	3	5,33
UCB PHARMA	Company	26	19	7	0,00	5	10,60
NATIONAL INSTITUTE OF ADVANCED INDUSTRIAL SCIENCE & TECHNOLOGY	Research center / National agency	24	23	1	1,45	8	7,75
TECHNOLOGY & ENGINEERING CENTER FOR SPACE UTILIZATION CHINESE ACADEMY OF SCIENCES	Research center / National agency	24	11	13	0,91	0	0,00
SMITHKLINE BEECHAM	Company	23	23	0	22,33	10	6,60
BEIJING UNIVERSITY OF TECHNOLOGY	University	22	16	6	3,00	0	0,00

Finally, we find that about 5% of the patents resulted from joint research efforts. This is not a small share even though it may appear so. Fig. 6 illustrates collaboration networks between patent owners. Many collaborations involve a noncompany organization, further corroborating the key role played by such organizations and the science-based nature of related research activities. In detail, it is shown that most relationships are exclusive between two or three collaborating partners. Only Japanese organizations form a more cohesive network (red circle), thus, revealing that the Japanese context is peculiar in how it carries out microgravity research activities by showing a more intense collaboration strategy.

To conclude our analysis, in the following, we redirect the attention to the 10% of highly cited patents, showing their specific trends. The temporal trends (see Fig. 7) reflect the more general one (see Fig. 1). It is worth noting that pending patents are among the most cited in the last few years. Fig. 8 adds that, considering granted patents (external circle crown), the US own as many highly impacting patents as CN despite CN owns many more patents overall. Yet, considering pending patents (internal circle crown), CN outperforms the US, which may imply that CN is terminating the catch-up process and is starting R&D activities actually devoted to improve the current state of the art and become a strong competitor in the microgravity research landscape.

Regarding the organizations developing highly impacting patents (three at least). Most of them also figure as the most patent-intensive organizations, except for OJAI Energetics PBC, Bristol Myers Squibb, Lockheed Martin, China Academy of Launch Vehicle Technology, which are not so involved in microgravity research but had a relevant impact.[2]

V. DISCUSSION

Given the growing relevance of the aerospace sector for our daily life, with particular regard to research activities enabling or conducted in a microgravity environment [6], this article presents an overview of the technological outcomes of microgravity research through patent analysis. Based on 4401 patents related to microgravity research recorded in the Orbit Intelligence database, we provide an in-depth analysis of the patenting activity trends at the temporal, country, sectorial, and organizational level. Our findings provide relevant theoretical, managerial, and policy implications for microgravity research.

From a theoretical perspective, except for a few notable exceptions (e.g., [12]), most of the existing studies about microgravity research have placed attention on the scientific theories, engineering design, and technical aspects underlying such research

[2]The list of organizations owning highly impacting patents is available upon request.

Fig. 6. Collaboration networks. Note: organizations with no less than five patents are considered; a minimum of one coassigned patent should have been applied.

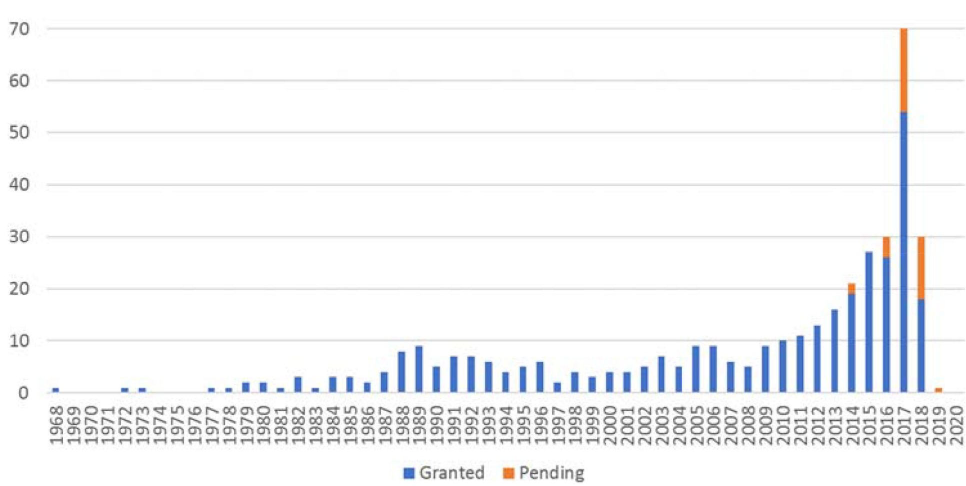


Fig. 7. Temporal trends of the top 10% highly impacting patents.

domain, while neglecting its business and policy implications. Conversely, this article aims to improve our understanding on how to design and proceed with microgravity research by providing relevant insights for academics, executives, and policymakers; that is, with a lens on the managerial/policy aspects rather than the scientific/technical ones. Indeed, our study shows when and where microgravity research has led to technological outcomes, key technological domains (aerospace-related and aerospace-unrelated), which organizations have a leading role in developing microgravity-related technologies, what the patterns of collaboration are, and a picture of the most relevant solutions. In this way, in addition to a picture of the current state of the art of microgravity research, we may generate reasoned statements about the future and the interpretation of such statements in terms of informed action.

From a business and policy perspective, we reveal that the number of technologies patented has sensibly grown, especially in the last decade, with many patents recently filed still under the review process, hence, signaling the growing trend will continue. On one hand, this is of interest for executives concerning

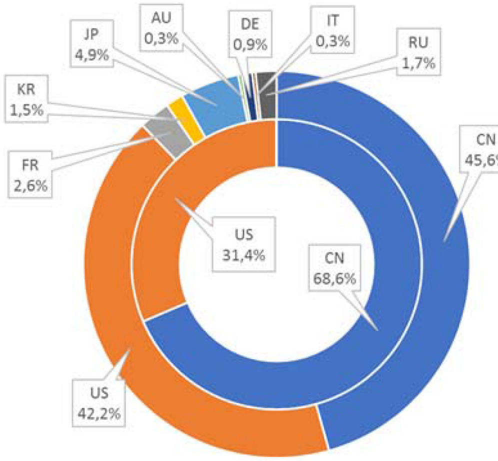


Fig. 8. Geographic distribution of the top 10% of highly impacting patents (granted: external circular crown; pending: internal circular crown).

business opportunities and technological competitiveness. Indeed, the growing patenting activity trend should be recognized by managers as an indicator (and confirmation) of the increasing expectations about microgravity research in terms of business opportunities. This is corroborated by the fact that some companies are developing new solutions thanks to microgravity-related research activities. All in all, this trend will likely make fiercer technological competitiveness in the near future, so making more relevant a first-mover strategy. On the other hand, since the access to space must be regulated, policymakers should be aware that the intensity of microgravity research is growing, and access regulations should be better specified with logical rules. Together with the increase of technological development per se, it should be recognized that the outcomes of microgravity research originate in different countries and pertain to a wide variety of technological domains. Some domains are more exploited than others and, more importantly, microgravity research will mainly concern domains beyond the aerospace one in the next future. This highlights the pervasiveness of microgravity research not only in terms of technological evolution but also in terms of business opportunities. That is, many types of businesses may be boosted, and these businesses will likely compete on a global scale, albeit it seems that the US, Japanese, and, particularly, the Chinese contexts will act as main geographic areas. In fact, according to our results, the RU is patenting less than in the past, and European countries, which already lagged behind the US, JP, and CN, do not appear to have pushed for higher levels of microgravity-related research activities. Anyway, the complexity of the future competitive landscape cannot be underestimated. Furthermore, the analysis concerning the most patent-intensive organizations unveils that research centers, universities, and national agencies own most of the developed patents, including some of the highly impacting ones. This may lead to two different, not necessarily substitutive scenarios. The first is the necessity for companies to build upon and/or acquire solutions developed by organizations that do not usually enter the market. The second is the upsurge of, for instance, university spin-offs or government-owned corporations. However, the risks to fall into the valley of death, i.e., to develop technologies without exploiting them in the market, can be high since solutions developed by nonprivate companies may be more science-based, so more distant from actual applications. Thereby, policymakers should create an institutional environment that supports the commercialization of microgravity-related technologies not developed by private companies by, first, facilitating technology transfer from research centers/universities/national agencies to private firms, further supporting the latter in the innovation process, or, second, stimulating the creation of spin-offs and government-owned corporations.

This may be also attained by promoting collaborations between private companies and other types of organizations. Indeed, our results reveal that joint research efforts are not absent but can increase since these are often at the dyadic level, except for the Japanese case, and often include research centers and universities. Thus, policies aimed at stimulating collaborations involving companies might be pivotal to have a better balance between more basic and applied research.

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Lorenzo Ardito received the M.Sc. degree in management engineering from the Polytechnic University of Bari, Italy, in 2011.

He is currently an Assistant Professor of Technology and Innovation Management with the Politecnico di Bari, Bari, Italy. He is also an External Fellow with the Mount Royal University, Calgary, AB, Canada, and a Visiting Ph.D. Student with the WHU—Otto Beisheim School of Management, Vallendar, Germany. He was an Editorial Board Member and/or a Guest Editor for several journals. His main research interests include innovation management, sustainable development, and digital transformation, in which his studies are made in collaboration with scholars worldwide and have been published in several leading international journals.

Prof. Ardito was the recipient of several awards for his research activities, including the Best Paper Award, Outstanding Contribution in Reviewing, and a Research Grant from the Ermenegildo Zegna Founder's Scholarship Program.

Antonio Messeni Petruzzelli received the M.Sc. degree in management engineering from the Polytechnic University of Bari, Italy, in 2003.

He is currently an Associate Professor of Innovation Management and the Founder of the Innovation-Management Group, Politecnico di Bari, Bari, Italy. He is also a Visiting Professor and a Member of the Advisory Board of the Digital Leadership Research Centre, Cass Business School, London, U.K., and a Visiting Scholar with the Beijing Normal University, Beijing, China, and the Paris School of Business, Paris, France. He is the author of more than 100 international publications published in leading journals and three international books on the topic of innovation management and technology strategy.

Prof. Petruzzelli belongs to the editorial team of the *Journal of Knowledge Management and Technological Forecasting and Social Change*. His studies have been awarded the Nokia Siemens Network Award in Technology Management for Innovation Into the Future.

Vito Albino received the M.Sc. degree in mechanical engineering from the University of Bari, Italy, in 1982.

He is currently a Professor of Innovation and Project Management with the Politecnico di Bari, Bari, Italy, where he founded the Knowledge Management Laboratory, Chaired the Dipartimento di Ingegneria Meccanica e Gestionale, and was a Vice-Rector for research and technology transfer. Since 2014, he has been involved in the development process of the spaceport of Grottaglie (TA), the first Italian spaceport. He is also the President of the Board of the Italian Association of Business Engineering (AiIG) and the Agency for Technology and Innovation (ARTI) of the Apulian Region (Italy). His current research interests include innovation processes in production chains and industrial clusters with particular interest to environmental aspects and, more recently, to new space economy.

Prof. Albino has authored/coauthored nearly 150 scientific papers and books.

Achille Claudio Garavelli received the M.Sc. degree in engineering from the University of Bari, Italy, in 1991.

He is currently a Full Professor of Management Engineering with the Polytechnic University of Bari, Bari, Italy. He is also an Assistant Professor with the University of Basilicata, Potenza, Italy, an Associate Professor with the University of Lecce, Lecce, Italy, and a Visiting Scholar with the University of South Florida, Tampa, FL, USA, during 1995–1996, and with the University of Wisconsin, Madison, WI, USA, in 2005. In 2006, he promoted the start-up of a University SpinOff, namely "Ingenium Srl," and is currently the President of the Management Board of the company. He is also the President of the Inter-Departmental Startup Laboratory, Politecnico, and is a coordinator of several projects on startup development. His main research interests include knowledge management, organization networks, operations management, engineering, and innovation management.

Prof. Garavelli is also involved in many national and international research projects and is the author of more than 100 papers published in national and international journals and conference proceedings.