

Evolution of MEMS Motion Sensor Technology in China and The United States based on Patent Citation Network

-- From the Perspective of Technology Life Cycle

Fang Huang^a

Tianjin University Library, Tianjin 300350, China

^ahfsilen@tju.edu.cn

Abstract

Utilizing patent information related to MEMS motion sensors, this study employs the Logistic model to fit an S-curve for delineating the technology life cycle of MEMS motion sensor technology. It identifies the top two Chinese and American patents globally based on application volume and conducts a macro comparison between high-citation, high-value star patents from both countries. By applying the Search Path Counts (SPC) algorithm, we extract the primary trajectory of MEMS motion sensors in China and the US, subsequently proposing a technique evolution mapping method that integrates this main path with citation networks. This allows for a comparative analysis of technological trajectories between China and the US, culminating in constructive recommendations aimed at universities, enterprises, and other innovative entities within our country.

Keywords

S-curve; Technology Life Cycle; Citation Network; Main Path.

1. Introduction

MEMS sensors are a disruptive technology that combines micro machining processes with sensor technology, and are also one of the important fields in current international competition. Based on patent literature covering 95% of technical information, conducting technical intelligence analysis is an effective method to achieve technological breakthroughs in the field of MEMS sensors.

In recent years, more and more scholars have conducted patent information analysis in the field of MEMS sensors based on statistics, graph technology, and clustering methods. In 2014, Lian Lili et al. analyzed the global patent application situation, Chinese patent application situation, and major competitors of MEMS accelerometer technology, and provided opinions and suggestions on domestic innovation entities from a macro perspective. In 2016, Ling FL conducted research on the number of applications, IPC classification, patent holders, and technology lifecycle of automotive depth sensors using patent mapping technology, analyzing the technological development trends in this field [2]. Liang Qinqin et al. used statistical methods and technology lifecycle division to analyze the current status and trends of global MEMS sensor technology innovation from 2000 to 2014, and put forward corresponding suggestions for different development stages [3]. In 2017, Wanwook Ki extracted text information from patent data, used natural language processing to extract key patent information, visualized the information in matrix form, and then supported qualitative analysis of patent content by extracting functions, components, and context. The method was applied to patent data related to nanosensors for validation [4]. In 2020, Zhao Hua et al. analyzed the patent application trends, patent applicants, patent inventors, technical subjects, and patent values of grating displacement sensors, proposed the technological development trend in the field of grating displacement sensors, and

identified hot patents, key patents, and patents with infringement risks [5]. However, there is still limited analysis on the technological evolution of MEMS motion sensors based on patent citation networks.

Based on the patent citation network, scholar Hummon NP proposed the Main Path Analysis method: by focusing on the search path of the patent citation network and calculating the traversal times of links and nodes, a technical main path that runs through the patent citation network can be determined, achieving the evolution and analysis of technology [6]. Based on the main path method, scholars at home and abroad have conducted technological evolution analysis in multiple fields: rare earth field [7], 3D printing technology [8], laser display technology field [9], vaccine industry [10], wind power generation field [11], and intelligent logistics industry [12].

However, when there are a large number of nodes in the citation network, the extracted main path literature has a large annual span and cannot achieve continuous and detailed technological evolution. To overcome this problem, this article proposes a method for drawing a technology evolution diagram (Fig 1): on the one hand, key patents are obtained through the main path method, and at the same time, supplementary patents are manually selected from the citation network centered on key patents. The key patents and supplementary patents are arranged in chronological order to draw a technology evolution roadmap.

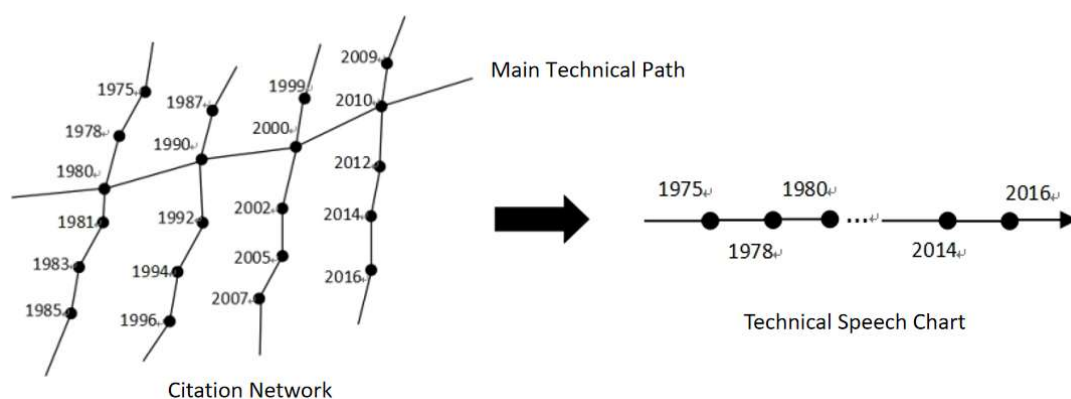


Fig. 1 Method for Drawing Technology Evolution Diagram

2. Analysis Process

The analysis process of this study (Fig 2) is as follows:

(1) Determine the search scope and develop a search strategy.

Referring to the "Analysis of the Development Situation and Investment Direction of China's MEMS Sensor Industry from 2023 to 2029" published by the Zhiyan Consulting Platform, this study limits the search scope of MEMS motion sensors to acceleration sensors, gyroscope sensors, magnetic sensors, and inertial composite sensors manufactured using MEMS technology based on their product classification. Among them, the inertial combination sensor includes a six axis inertial sensor integrated with an acceleration sensor and a gyroscope sensor, an electronic compass integrated with a magnetic sensor and an acceleration sensor, and a nine axis inertial sensor integrated with an acceleration sensor, a gyroscope sensor, and a magnetic sensor.

Based on the above search scope, a search formula was developed to search on the Incopat patent platform. The search period was from 1980 to 2022, and the search date was October 16, 2023. The search results were 13405, and after merging the application numbers, 9307 were obtained.

(2) Divide the technology lifecycle.

Retrieve the global patent application accumulation in the MEMS motion sensor field from 1980 to 2022 from the Incopat patent database, and use the logistic model to fit the annual distribution curve of global patent application accumulation to define and predict the technology lifecycle.

(3) Macro level data analysis and comparison of the quantity and quality of patents between China and the United States.

Obtain global regional rankings of patents in the field of MEMS motion sensors, select China and the United States, which have the highest and second highest number of global patent applications, as research objects, compare the number of patents, value stars, and cited patents between China and the United States, and analyze and compare the quantity and quality of patents between China and the United States from a macro perspective.

(4) Analyze and compare the similarities and differences in the technological evolution process between China and the United States at the micro technical level.

Obtain patent citation data in the MEMS motion sensor field between China and the United States from Incopat, process the data through Python self programming, import the processed data into the Pajek software to generate a citation network, use the Search Path Statistics (SPC) algorithm to analyze the main path of the China US citation network, manually screen for supplementary patents, and draw a China US technology evolution diagram based on the results of technology lifecycle division. Analyze and compare the current situation, focus, and gap of technological development in this field between China and the United States from a micro technical perspective.

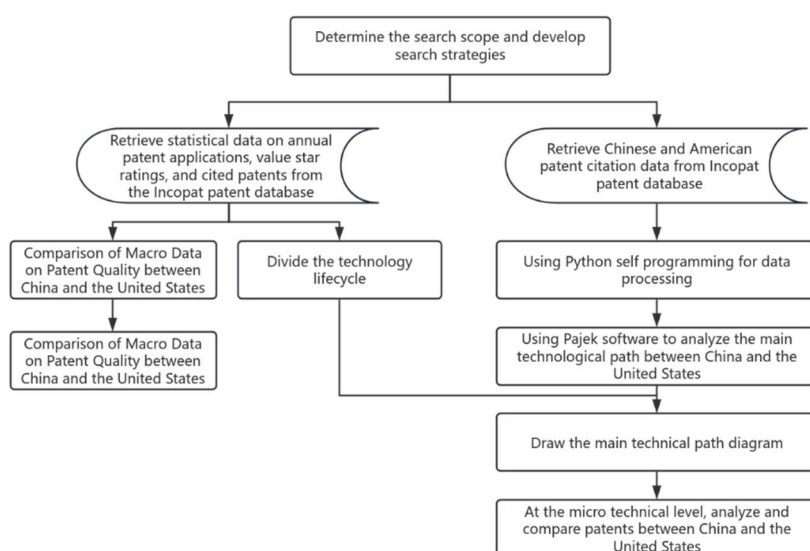


Fig. 2 Analysis Process

3. Analysis of Patent Information for MEMS Motion Sensors

3.1 Technology Lifecycle Division

The technology lifecycle includes four stages: germination, growth, maturity, and decline. This study used the Logistic model of Loglet Lab 4.0 software to perform S-curve fitting on the annual distribution curve of global patent application accumulation. The fitting results obtained the S-curve of the motion sensor (Figure 3) and the Logistic model parameters (Table 3). The Logistic model parameters showed a goodness of fit R^2 of 0.982, indicating high reliability of the fitting results.

Table 1 shows the division basis of the technology lifecycle in this study: the germination stage is the period when patent accumulation increases from 0 to 1% of the total amount, the growth stage is divided into low-speed growth stage I and high-speed growth stage II. The low-speed growth stage I is the period when patent accumulation increases from 1% to 10% of the total amount, the rapid growth stage II is the period when patent accumulation increases from 10% to 90% of the total amount, the maturity stage is the period when patent accumulation increases from 90% to 99% of the total amount, and then enters the decline stage.

Table 1. Technical Lifecycle Classification Standards

Stage	Classification Basis
Sprout Stage	The accumulation of patents ranges from 0% to 1% of the total amount
Growth Stage	Slow Growth Phase I: Patent Accumulation from 1% to 10% of the Total
	Rapid Growth Phase II: Patent Accumulation from Total 10% to Total 90%
Mature Stage	The cumulative amount of patents has increased from 90% to 99% of the total amount
Decline Stage	After the cumulative amount of patents reaches 99% of the total amount

Based on the S-curve of the motion sensor (Fig 3), logistic model parameters (Table 2), and the technical lifecycle judgment criteria (Table 1), it can be roughly divided into three stages for the development of MEMS motion sensors:

- (1) The 1980s to 1990s were the embryonic stage. During this period, MEMS microelectromechanical systems entered people's field of vision as a new industry. With the continuous development of related science, MEMS technology was successfully applied to the measurement of motion acceleration, ushering in the era of miniaturization of motion sensors.
- (2) The period from the 1990s to the early 21st century was the low-speed growth phase I. During this period, the annual number of patent applications showed a clear growth trend, but it is still in a low-speed growth state. In 1991, ADI (Analog Devices) in the United States commercially produced the world's first MEMS accelerometer, marking the transition of MEMS motion sensors from the laboratory to practical and market-oriented applications.
- (3) After 2002, MEMS motion sensors entered the high-speed growth phase II, and MEMS motion sensors experienced rapid development. With the maturity of manufacturing processes, improvement of structural design, and refinement of data processing, the cost of MEMS motion sensors is gradually decreasing. The low cost and miniaturization have enabled MEMS motion sensors to replace traditional sensors and quickly cover various emerging intelligent mobile devices.
- (4) It is expected that by 2030, the cumulative number of patent applications related to MEMS motion sensors will reach 90%. After that, the technology will enter a mature stage, during which the production and research and development entities in the field of MEMS motion sensors will be relatively fixed, and the activity of patent applications will decrease.

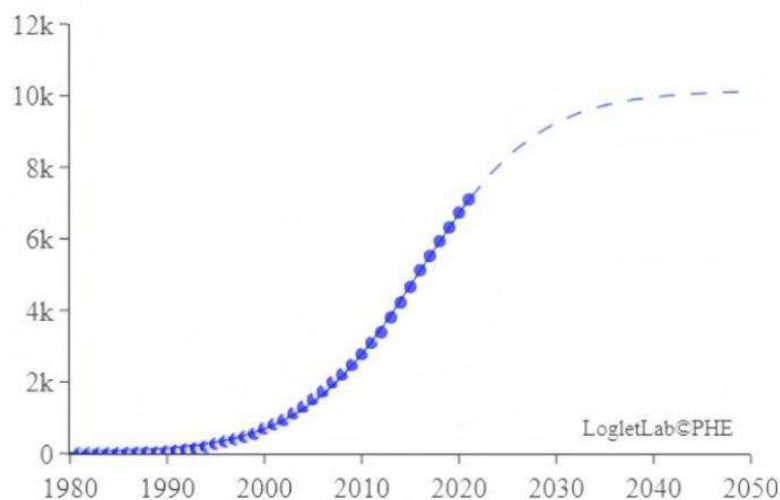


Fig. 3 S-curve of motion sensor

Table 2. Logistic Model Parameter Calculation

Logistic						
Application Trends of Motion Sensor Patents from 1980 to 2021						Phase1
d	K	a	tm	r	SSE	
0	10149	26.6	2016	0.165	100292	
RMS	MAD	MAPE	SE	Ln[MLE]	AICc	
55.1	45.8	0.114	57.8	-179	365	
R2	p	0.01	10%	50%	90%	99%
0.982	1.22E-28	1988	2002	2016	2030	2044

From this, it can be seen that since the 1980s, MEMS motion sensors have gone through a 10-year technological germination period, a 10-year low-speed growth period, and entered a high-speed growth period in the early 21st century. It is expected that the high-speed growth period will last for 30 years, and then enter a technological maturity period. Technology is often dominated by a small number of research and development entities during its infancy or low-speed growth period. In patent applications and information disclosure, research and development entities will take certain confidentiality measures for the technology. Therefore, countries that started late find it difficult to gain a competitive advantage during these two periods. With the continuous disclosure of technology information and the launch of related products, competition entities have the opportunity to join the competition and make full use of existing technology information to conduct intelligence analysis, which can enable weak competition entities to catch up with technology during the high-speed development period.

3.2 Patent Overview Analysis

According to the global patent data of MEMS motion sensors (Fig 4), the United States and China are the two most active regions for MEMS motion sensor technology research and development, with over 50% of global applications originating from these two countries. In addition, Japan, Germany, and Europe also play an important role in MEMS motion sensor technology research and development, with nearly 25% of applications coming from these three regions.

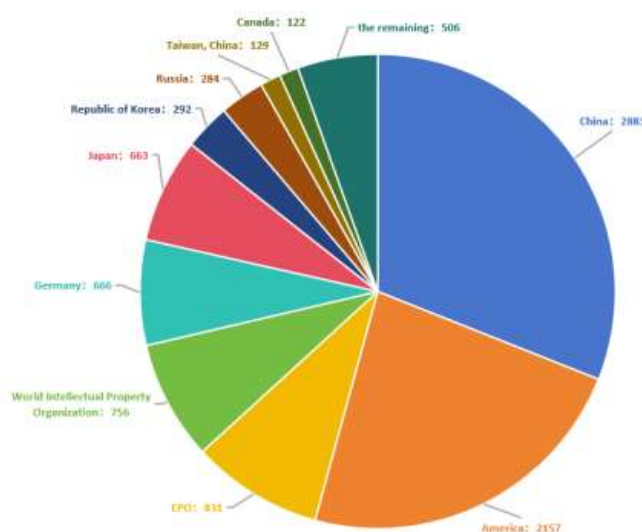


Fig. 4 Global Regional Ranking

Comparison between China and the United States reveals that all US patents are invention patents, with a total of 2159 patents; There are 2882 Chinese patents and 1308 authorized invention patents. In this field, the total number of patent applications in China is higher than that in the United States, but the number of invention patents accounts for only half of that in the United States. From the perspective of patent examination, it is believed that the quality of authorized invention patents is higher than that of utility model patents [14]. Therefore, in the field of MEMS motion sensors, although China has the largest number of patent applications, the number of high-quality patents is lower than that of the United States.

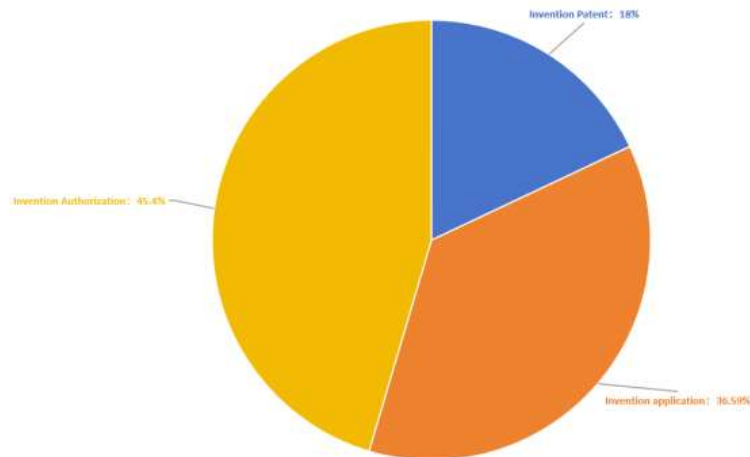


Fig. 5 Types of Chinese Patents

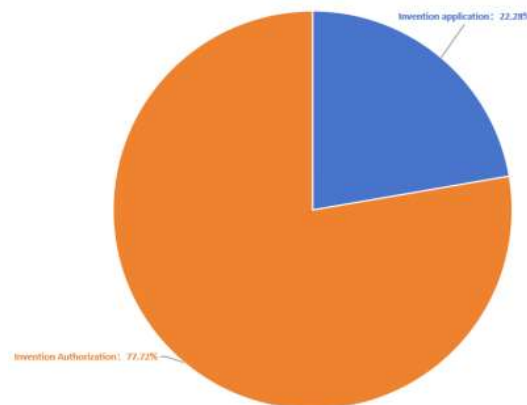


Fig. 6 Types of US Patents

The number of citations and value rating of a patent can be used to determine its value. The higher the number of citations and value rating of a patent, the higher its quality. According to the statistics of the number of patents with different value star ratings in China and the United States (Fig 7) and the number of cited patents in China and the United States (Fig 8), it can be seen that patents with a value star rating of 10 in the United States account for 70% of the total number of patents, exceeding 1500, while patents with a value star rating of 10 in China account for about 9% of the total number of patent applications, approximately 261; There are a total of 1974 patents with a value rating of 8 or above in the United States, and 1624 patents with a value rating of 8 or above in China; There are 327 patents cited more than 40 times in the United States, while there are no patents cited more than 40 times in China. From this, it can be seen that there is a certain gap in the quality of Chinese patents compared to American patents in this field, as evidenced by the number of citations and value ratings of patents.

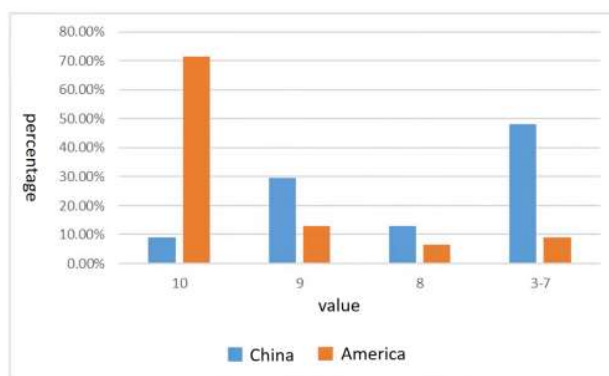


Fig. 7 Statistics of Patent Value and Patent Quantity in China and the United States

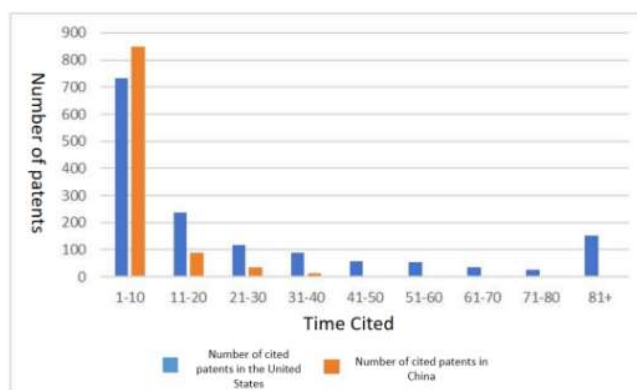


Fig. 8 Statistics of Cited Patents in China and the United States

3.3 Analysis of Technological Evolution between China and the United States

3.3.1 Analysis of Technological Evolution in the United States

The key patents and supplementary patents were sorted according to the timeline, and the development paths of MEMS motion sensor technology in the United States (Fig 9) and China (Fig 10) were drawn.

Since the 1980s, the United States has been researching MEMS motion sensors. In the early stages, the development of MEMS accelerometers was the main focus. After entering the growth stage, accelerometers, gyroscopes, magnetic sensors, and inertial sensors are in a state of simultaneous and mutually reinforcing development. Overall, MEMS motion sensors have evolved from measuring a single motion quantity to multi axis measurement integrating multiple motion quantities on a single chip. The overall trend is towards increasing integration, high precision, and high stability.

From 1979 to 1988, the development of MEMS accelerometers was promoted through the improvement of micro mechanical processing technology for silicon chips. In 1991, ADI (Analog Devices) in the United States commercially produced the world's first MEMS accelerometer, marking the official commercialization of MEMS accelerometers. In 1993, the Cornell University Foundation proposed a batch micro machining process, abbreviated as the SCREAM process, which further promoted the commercial application of MEMS accelerometers. Afterwards, the development of MEMS motion sensors entered the high-speed growth phase II. During this period, MEMS accelerometers developed from single axis measurement to multi axis measurement, with continuous improvements in structural design, micro machining processes, and materials. In 2004, patent US10760025 disclosed a capacitive lateral acceleration device for micro machining and a single-chip three-axis accelerometer with such a device. US10760025 proposes a single-chip three-axis accelerometer chip that includes three separate axis accelerometers. After 2010, single-chip integrated multi axis MEMS accelerometers became mainstream.

MEMS gyroscope technology has gone through single axis measurement to multi axis measurement of angular velocity. In 1995, Motorola proposed a MEMS gyroscope device . In 1996, the University of California proposed a Z-axis vibration rate gyroscope for measuring the rotation rate around an axis perpendicular to the substrate surface, which solved the difficulty of measuring the Z-axis rotation rate of three-axis MEMS gyroscopes . In 1999, the University of California further proposed a dual mass micro mechanical vibration rate gyroscope, which provided a more effective solution for measuring the rotational angular velocity of the Z-axis. In 2009, a single drive micro mechanical three-axis gyroscope containing a drive extension mode was proposed by Invensense, the current patent holder, in the name of an individual. In 2010, Apple first applied MEMS gyroscopes to smartphones, opening up a new application direction for MEMS gyroscopes in the consumer market. In 2011, Semiconductor Components Industries, LLC applied for US patent US13821842 for a single drive micro mechanical single-chip three-axis gyroscope, and in 2016, US patent US15005783 also proposed a single drive micro mechanical single-chip three-axis gyroscope.

The origin of MEMS magnetic sensors dates back to the 1980s, with the earliest appearance being Hall sensors . In the 1990s, the micro mechanical D'Arsonval magnetometer emerged, which does not rely on temperature sensitive semiconductor mobility effects or magnetic material properties and can operate and be used near the resonant frequency of micro mechanical structures . Between 1999 and 2005, flux gate magnetic sensors were developed. After 2010, integrated magnetic sensors became a focus of development. Movella proposed the process of integrating three-axis magnetic field sensors into a single chip, and the three-axis magnetic sensor can also be integrated with other MEMS sensors .

With the development of MEMS accelerometers, gyroscopes, and magnetic sensors, micro inertial measurement units (MIMUs) that integrate multi axis and multi motion measurements have emerged. In 2000, GNC Corporation of the United States proposed a Micro Inertial Measurement Unit (MIMU) that integrates three-axis angular velocity sensors and three-axis acceleration sensors, forming a MEMS six axis inertial measurement unit. In 2006, a fully integrated IMU containing a magnetometer was proposed, which is lightweight and compact in size . In 2015, patent US15534702 proposed a nine axis inertial measurement unit that integrates three-axis accelerometers, three-axis gyroscopes, and three-axis magnetic sensors.

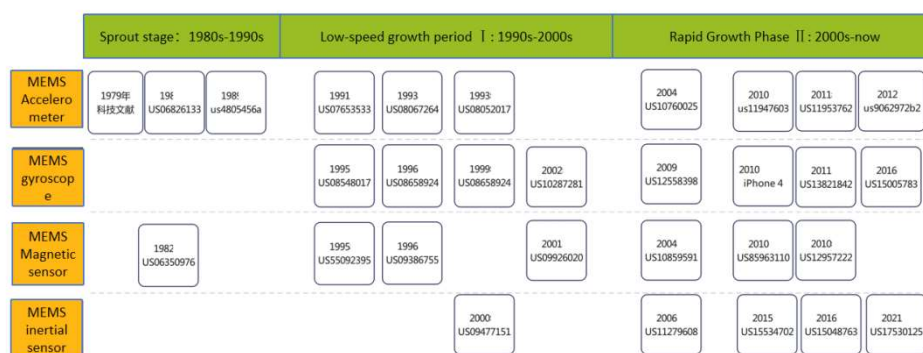


Fig. 9 Evolution of MEMS motion sensor technology in the United States

Through the above technical analysis, it can be seen that the United States has a long history of layout in this technology field, with basic technological research in manufacturing processes, structural design, and material research. Subsequent improvements in technology are also coherent, and commercial applications have also promoted technology. Overall, it is a virtuous cycle of "technology research - patent technology layout - commercial application - technology research", and the United States has strong technological competitiveness in this field.

3.3.2 Analysis of Technological Evolution in China

From the main technological roadmap of MEMS motion sensors in China (Fig 10), it can be seen that China's technology in this field started around 2005, 25-30 years later than the United States.

The research on MEMS accelerometer technology in China started with capacitive micro mechanical accelerometers, and in recent years, it has increasingly focused on optical accelerometers. Optical sensors have the advantages of high precision, high temperature characterization, and immunity to electromagnetic interference (EMI). In 2007, the Shanghai Institute of Microsystems and Information Technology, Chinese Academy of Sciences, proposed a capacitive micro acceleration sensor with symmetrical straight beam structure and its manufacturing method. In 2009, the Institute of Acoustics of the Chinese Academy of Sciences proposed a capacitive acceleration sensor with acoustic cavity based on micro machining technology. In 2015, North China University proposed a fiber optic MEMS Fabry Perot accelerometer and its manufacturing method. In 2019, Xi'an Jiaotong University proposed a Fabry Perot optical MEMS accelerometer with low lateral sensitivity. In 2022, Xi'an Jiaotong University proposed a chip level integrated Fabry Perot optical MEMS accelerometer.

The research on MEMS gyroscopes in China also started late, with a focus on the structure and preparation packaging methods of multi axis gyroscopes. In 2017, Southeast University proposed a single-chip resonant accelerometer gyroscope. In 2018, Sichuan Zhiwei Sensor Technology Co., Ltd. proposed a MEMS micro mechanical fully decoupled closed-loop gyroscope. In 2021, Wuhan University proposed two MEMS multi axis gyroscopes and their preparation and packaging methods. In 2023, Beijing Zhongke Haixin Technology Co., Ltd. proposed a resonant ring MEMS gyroscope and its manufacturing method.

China's research on MEMS magnetic sensors mainly proposes error correction systems and methods based on foreign patents, and there are relatively few patents on the hardware structure of MEMS magnetic sensors. In 2012, Wuxi Hanhe Aviation Technology Co., Ltd. proposed an electronic compass calibration method for unmanned aerial vehicles in magnetic environments. In 2014, Wenzhou University proposed a zero point and proportional coefficient kernel correction method for a three-dimensional solid-state electronic compass and its sensor. In 2015, Gaoxin Technology Group Co., Ltd. proposed a calibration and compensation method for electronic compasses in cylindrical cameras. In 2022, the Southwest Institute of Applied Magnetism proposed a fast calibration and compensation method for electronic compass sensor errors and installation errors.

In the field of MEMS inertial measurement units, Fast Semiconductor Company proposed two six degree of freedom inertial measurement systems integrating three-axis gyroscopes and three-axis accelerometers in 2010 and 2011, respectively.

In addition to the above research focuses, China has also invested heavily in the comprehensive application of MEMS motion sensors, such as the construction of navigation systems, position positioning systems, attitude measurement systems, and algorithm optimization, which have shown good performance.

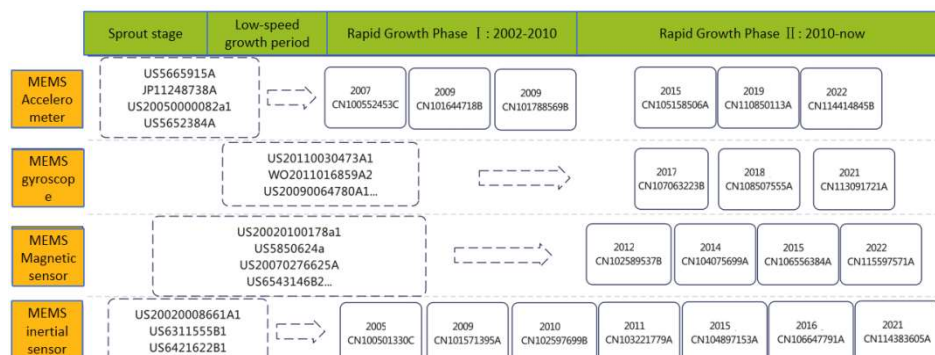


Fig. 10 Evolution of MEMS motion sensor technology in China

Through a comprehensive comparison of the evolution process of MEMS motion sensor technology between China and the United States, it can be seen that there is still a certain gap between China and the United States in this field. Compared with the continuity and completeness of technological development in the United States, China has had many technological gaps in the early stage. In recent years, China has started to closely follow the key and concentrate its efforts, and has achieved certain results in both basic technology research and application in this field, increasingly aligning with the world's advanced technologies.

4. Conclusion and Recommendation

This study comprehensively compares the current status, key areas, and gaps in the development of MEMS motion sensor technology between China and the United States from both macro data and micro technical perspectives. Based on the research results, from the perspective of information assisted scientific research, some opinions and suggestions are proposed for innovative entities such as universities and enterprises in China.

- (1) Strengthen the connection between universities, enterprises, and intellectual property intelligence departments to guide the technological research and development work of universities and enterprises. We can establish connections with our existing intellectual property department or have third-party intellectual property departments provide navigation and other services to keep track of the direction of technology research and development and ensure the linkage between technology and the market.
- (2) Strengthen research investment in micro mechanical processing technology, MEMS sensor structures, and advanced materials in universities, fill in technological gaps, enhance school enterprise cooperation, industry university research integration, and technology incubation and transformation work, invest the latest scientific research achievements into enterprise production, promote breakthroughs in key technologies, and help China gain an advantageous position in international competition.
- (3) Increase the research investment of enterprises in this field, based on multidimensional information analysis such as patents, scientific literature, industries, and markets, formulate enterprise development strategies, determine the research direction of technology departments, and find the optimal path for technological innovation of enterprises.

This study conducted effective patent information analysis, but there are still some shortcomings: (1) the patent analysis work at the micro technical level can be more detailed. In future research on patent information analysis, more analysis methods and tools will be utilized to focus on the specific technical analysis of MEMS motion sensors, striving to provide the most targeted opinions and suggestions for specific scientific research work. (2) This study only utilized partial statistical data and citation data of patents, lacking the utilization of information from dimensions such as industry and market. In future research, we will combine as much multidimensional information as possible to carry out analysis work, and extract more valuable and instructive intelligence information for universities and enterprises.

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