TECHNOLOGIES TO WATCH IN 2022

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INTRODUCTION

Each year, MGSSI's Technology Foresight Center identifies technologies that deserve particular attention, and provides a forward-looking overview of those technologies and insights. This year, we will look at (1) 6G, (2) molecular machines, (3) self-developing robots, (4) chemical looping combustion, and (5) living sensor plants.

(1) 6G is a wireless communication infrastructure and the successor to 5G, which was made commercially available in 2020. It is a technology that is currently under development by various organizations and global companies in order to achieve international standardization.

(2) Molecular machines are nanoscale machines, for which the Nobel Prize in Chemistry was awarded in 2016. This is a fundamental technology that is expected to be used in a wide range of fields, including drug delivery systems and other medicine and healthcare, as well as in the chemical and robotics industries.

(3) A self-developing robot is a robot that can make decisions and take actions autonomously without human programming or presentation of learning results. This technology will be used in complex environments including scientific experiments on animals and plants, disaster relief, and the like.

(4) Chemical looping combustion is a technology in which the oxygen required for the combustion reaction is supplied not from the air, but through an oxygen carrier such as iron. By increasing the concentration of CO_2 in the exhaust gas and facilitating its recovery, it enables decarbonization during power generation and hydrogen production.

(5) Living sensor plants utilize the characteristics of living plants as sensors. This technology is expected to be developed not only in agriculture, but also in the environmental and energy fields.

As in last year, we also analyze global patent application trends for each of the five themes covered in this report.

6G

— MOVES TO SEIZE THE INITIATIVE GAINING MOMENTUM —

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ABOUT 6G

(1) PROGRESS OF MOBILE COMMUNICATIONS AND 6G

Mobile communications have undergone a significant development about every decade since the introduction of the 1G, first generation mobile communication system in the 1980s. 1G was mainly used for car phones and shoulder phones. 2G enabled the first data communications. 3G saw an increase in standardization activities to make it a common specification worldwide. 4G was a response to the significant increase in the need for high-speed communications with the spread of smartphones. 5G is equipped with features such as low latency and multiple connections, and is expected to be used in IoT. In this way, each generation of mobile communications has become the foundation for creating new services and meeting the needs of society. Since 3G, which became a worldwide standard, the question of whether or not one's own proposed technology will be adopted as standard has become a key factor that impacts business thereafter for mobile communication providers, equipment manufacturers, and other related companies, and competition in technology development and standardization activities have intensified. Based on the issues that arose in the case of 5G, which adopted millimeter-wave communication for the first time, this report will explain the moves of relevant organizations toward 6G, the features and technologies of 6G, and give the big picture of 6G when it is realized along with the issues to be solved for its realization.

(2) STATUS OF 6G STUDIES

Normally, when standardizing mobile communication systems, the required performance, technologies, and frequency bands are determined by the ITU Radiocommunication Sector (ITU-R), a sector of a specialized agency of the United Nations, and 3GPP, a project of national standardization organizations. However, as the introduction of 5G has only just begun, there are as yet no confirmed standards for 6G from these organizations. Still, some telecommunications operators, manufacturers, and universities started discussing basic concepts for 6G even before the introduction of 5G, and some people believe that the launch of 6G is three to four years earlier in comparison to 5G, for which discussions are said to have started after the introduction of 4G. In other words, the speed of standardization is increasing along with its importance to the companies involved. The technologies used in mobile communications are becoming increasingly complex, and it is becoming more difficult for a single country or company to take the lead, making strategies for forming alliances even more important in the future.

Finland was one of the first countries to start studying 6G, with Oulu University leading the study in 2018. This later evolved into the 6G Flagship project (Figure 1). In Europe, Hexa-X has been launched with a budget of EUR 12 million over two and a half years from December 2020. Companies such as Huawei from China and Intel from the US are also participating in this initiative. In the US, then-President Trump made clear in 2019 that efforts would be stepped up, and research centers led by the Defense Advanced Research Projects Agency (DARPA) and New York University have been set up. US telecommunications operators have launched the Next G Alliance and many companies that has been involved in the telecommunication industries joined the project, but Huawei and other organizations included in the entity list[1] are not eligible to participate. The US is trying to recover ground lost to China for its presence in 5G standardization, and is expected to continue its efforts to bar China from 6G. Since the inauguration of the Biden administration, the government has also strengthened cooperation with its allies, and has announced a policy of investing JPY 490 billion in 6G-related research and development in collaboration with Japan. China, on the other hand, started research and development as a national project in 2019. While its strategy for 5G was to sell communications equipment such as base stations, some say that the China is aiming to build the system itself for 6G. South Korea is aiming to be the first country in the world to commercialize 6G, and it is also believed that South Korea will be the beneficiary of the US' exclusion of China. Reflecting on its failure to establish a presence in the development of 5G, Japan launched the Beyond 5G Promotion Consortium in 2020 as an industry-government-academia collaborative project. It is expected that related parties will conduct joint research and identify issues using a testbed. Japan has concluded an agreement with the aforementioned 6G Flagship in Finland as well as with the relevant organizations in Japan. Discussions on collaboration with organizations in the US has been also proceeding. The Ministry of Internal Affairs and Communications (MIC) has set the goal for Japanese companies to have a 10% or greater share of 6G-related patents, or 30% or more if equipment and software are included, but given the current situation, further measures may be required (see " Patent Application Trends Regarding 6G").

Figure 1: 6G status in each country

Country	Overview
Finland	• 6G Flagship: a planned budget of €250 million from 2019 to 2026. Members include Oulu University, Aalto University, Nokia, and VTT Technical Research Centre of Finland.
Europe	• Hexa-X: a planned budget of €120 billion in 2.5 years from December 2020. Members include 6G Flagship members such as Ericsson, Siemens, major European research institutes, Huawei and ZTE from China, and Intel from the US.
US	• A $200 million budget for five years is planned for DARPA's communications technology research projects, including 6G. • Next G Alliance: Members are mainly U.S. carriers, and Ericsson, Nokia and Samsung also join the project. Organizations that are included in the Entity List published by the US Department of Commerce are not eligible to participate.The US and Japan plans to jointly invest ¥490 billion in R&D.
China	• In 2019, Huawei announced its policy of commercializing 6G within a decade. • China Unicom and ZTE signed a 6G joint strategic agreement in 2020. • At the same time, the government announced the establishment of a subcommittee including 37 organizations from industry, government and academia to conduct research and development. • Huawei and other companies are actively participating in European projects.
South Korea	• Samsung, LG, and other companies started 6G research and development from 2019. • In 2020, the government announced a strategy to launch a 6G pilot project (with a budget of ₩200 billion from 2021 to 2026). The goal is to be the first country which commercialize 6G network. It will be around 2028 to 2030.
Japan	• NICT, NTT, NTT Docomo, and others started developing 6G around 2019. • Beyond 5G Promotion Consortium, a collaboration between industry, government and academia,was launched in 2020. The budget for research related to Beyond 5G by the Ministry of Internal Affairs and Communications is ¥50 billion.

Source: Compiled by MGSSI from websites of each organization.

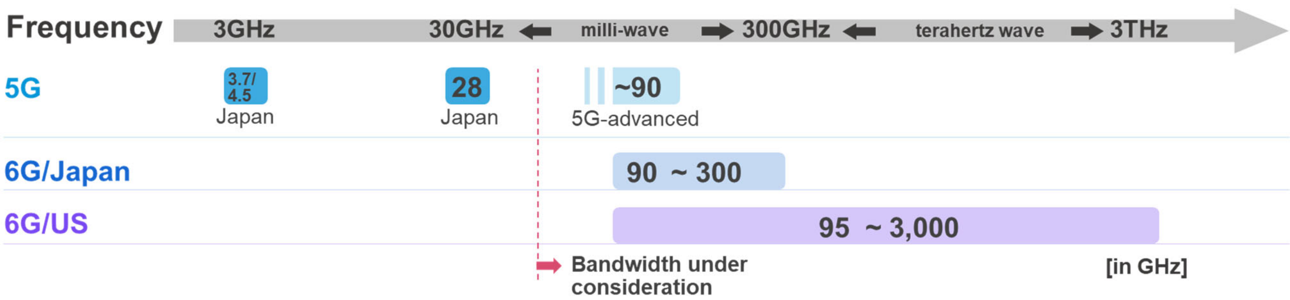
(3) FEATURES OF 6G

With several white papers proposed by various study groups on the features of 6G, the big picture is starting to take shape. First, let's look at the frequency bands used. Choosing the right band is important because the

[1]A list of companies designated by the US Department of Commerce as being a national security concern. A license is required to export goods, software, or technology to companies on the list.

characteristics of the radio waves are different depending on which band is used. Basically, communication speed depends on the width of the band, so the policy is to secure a wide bandwidth. The lower the frequency, the easier it is for radio waves to cover a wider area of communications, but these frequencies are already in use in existing systems such as television and public radio, making it difficult to secure a wide bandwidth. This is why high frequency bands that have not yet been utilized in existing systems, such as millimeter waves, are attracting attention. 5G uses Sub 6 (3.7/4.5 GHz band in Japan), which is a slightly higher frequency than 4G, and millimeter wave (28 GHz band in Japan), which was introduced for the first time. Up to 90 GHz is being considered for use in the upcoming 5G-Advanced (Figure 2). The use of even higher frequency bands is being considered for 6G, and frequencies between 90 GHz and 300 GHz are likely to be the main targets for inspection in Japan. The US Federal Communications Commission has called for even higher frequency waves in the terahertz range (95 GHz to 3 THz). These bands are expected to provide more than 10 times the bandwidth of 5G, and if realized, the communication speed can be more than 10 times faster than 5G. However, as mentioned above, disadvantages such as narrower coverage exist, and technology to compensate for this is required.

Figure 2: 5G and 6G Frequencies



Source: Compiled by MGSSI

Next, let's take a look at the performance of 6G. Looking at the white papers of the various study groups, there are five major 6G functions that are being considered by all organizations (Figure 3). Three of these are positioned as enhancements to 5G functions, and are ultra-high data rate (100 Gbps to 1 Tbps), ultra-low latency (0.1 to 1 ms), and ultra-massive connectivity (10 million to 100 million units/km^2), which are 10 to 100 times more advanced than the features that 5G promises. In addition to these, the trend is to add functions that take into account the use of higher frequency bands, changes in social patterns, and the development of technology in other fields. The remaining two of the five functions are ultra-low energy (functions to cope with the increase in power consumption against the backdrop of estimates that IT-related power consumption in 2030 will be 36 times that of 2016), and ultra-high reliability (functions to provide stable services and instantaneous recovery in the event of a disaster or failure).

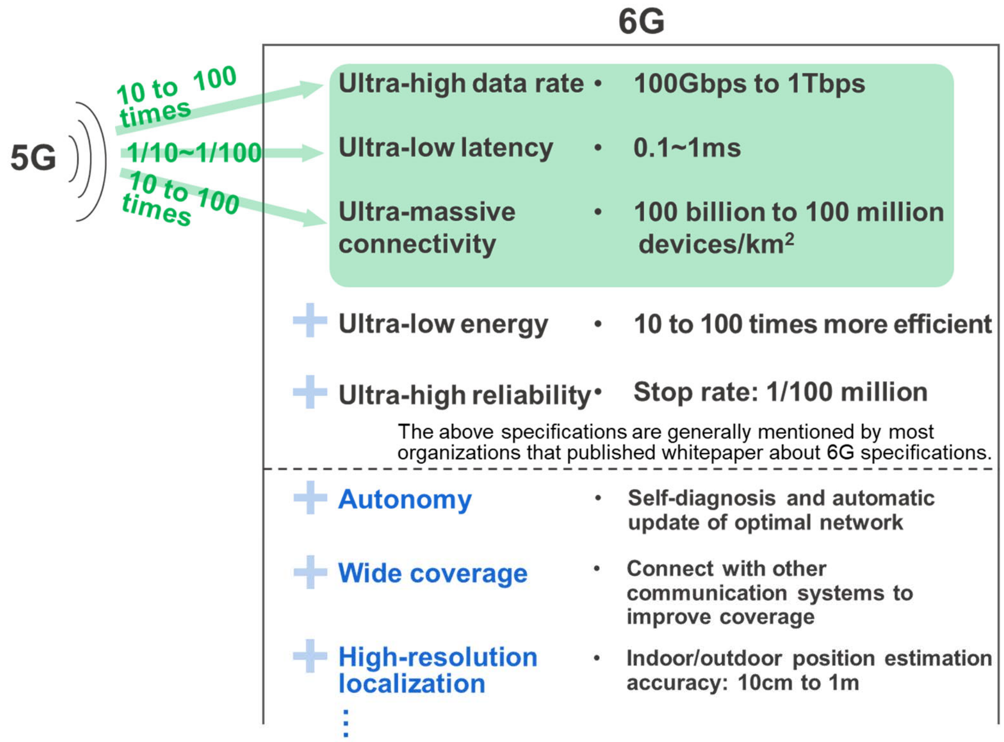
In addition, the following are being considered, although the details vary depending on the study group.

Autonomy: The ability of communication devices, etc. to work together autonomously and build the optimal network according to requirements by utilizing AI technology, etc.

Wide coverage: The ability of terminals and base stations to seamlessly connect to other communications systems, enabling communications anywhere on land, in air (space), and at sea.

High-resolution localization: A feature that enables highly accurate position estimation (10 cm indoors, 1 m outdoors).

Figure 3: Characteristics of 6G



Source: Compiled by MGSSI based on white papers by Ministry of Internal Affairs and Communications, DOCOMO, Hexa-X and 6G Flagship

(4) 6G TO BE REALIZED BY COMBINING MULTIPLE TECHNOLOGIES

A wide range of technologies are needed to realize 6G with the functions described above. Up to 3G, it was possible to name one symbolic technology that represented the generation, but since 4G, the situation has become more complex and involves multiple technologies. It is difficult to narrow down 6G to specific technologies at this point, but some examples of technological fields that can be considered are as follows.

Cell-free configuration: In order to make effective use of millimeter waves, 5G utilizes Massive MIMO technology with more than 100 antenna elements. With 6G, where terahertz waves are expected to be used, more than 10,000 antenna elements may hypothetically be utilized, and in such a case, a conventional cellular configuration in which one antenna covers one zone will increase interference at the edge of each cell. Therefore, 6G may adopt a cell-free configuration where a large number of antennas make up a single zone.

A new form of antenna: High frequency radio waves tend to diffract less than lower frequency waves. In other words, they are easily reflected and scattered. This is where the use of multipath propagation paths (reflected radio waves, etc.) becomes important. Technology has been developed to reflect radio waves in any direction, as well as materials to control the direction of radio wave radiation, such as glass substrates that transmit radio waves and focus them at a single point. In addition, the development of transmission cables that act as an antenna to emit radio waves from the surrounding area simply by pinching an arbitrary location is also being considered. This will make it possible to build a communication area at will by compensating for the problem of millimeter waves, whereby coverage tends to decrease.

A wide range of other technologies are also being studied, including a review of network architecture with a view to making base station and other equipment multipurpose, the sophistication of distributed networks, the use of satellite communications and High Altitude Platform Stations (HAPS) for expansion of coverage, and the use of AI technology in multifunctional communication systems.

PROMISING FIELDS OF APPLICATION

ANTICIPATED STATE OF 6G

As mentioned in the previous section, given that some of 6G's features are built on those of 5G, and that 5G will also be further developed with 5G-Advanced, the transition from 5G to 6G may not be as dramatic as in the case of from 1G to 2G, for example, when data communication became possible. However, the following section presents the author's view of the world that 6G will realize, based on the predictions of various organizations and the impact of future changes in social patterns.

The first point to look at is the major advancement in telepresence, where people feel as if they are right next to each other even when separated by distance. While the human visual perception time is said to be 20 ms, and the auditory perception time to be 2 ms, 6G is expected to have a communication speed 10 to 100 times faster than 5G, with an end-to-end delay time of 0.1 to 1 ms, which will almost eliminate the experience of lag that arises in communication. In particular, the need to be physically present in the same place is diminishing as teleworking and other forms of work are adopted due to the COVID-19 pandemic. Momentum is also building toward the Metaverse[2], as illustrated by the former Facebook changing its name to Meta. In combination with these factors, changes in the environment, such as the evolution of the hardware required for VR, etc., will make virtual space more familiar and its adoption will spread rapidly. Not only that, but the world may become more familiar with the introduction of telemedicine, which cannot tolerate communication lag, and remote AI-controlled robots may replace human labor.

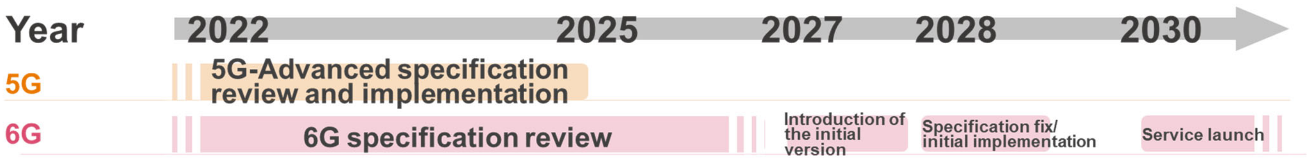
In addition, since it will be possible to connect 10 times as many devices as 5G, the world of real-world sensing and digital twins will advance if the issues of cost on the device can be cleared. It will also enable communication in the air, at sea, and in space, which are not yet covered by mobile communication systems. This could lead to changes in logistics, such as drone delivery, and unmanned primary industries.

FUTURE PROSPECTS

(1) TIMELINE

The first step will be the introduction of 5G-Advanced commercial networks by around 2025. At the same time, the requirements and standards for 6G will be developed, and an initial version of 6G is expected to be introduced around 2027. Thereafter, introduction of the first commercial version of 6G will start in some countries in 2028, and practical introduction is expected in 2030 (Figure 4).

Figure 4: 6G development timeline



Source: Compiled by MGSSI

[2]Metaverse is a generic term for a virtual three-dimensional space where people are constantly logged in and never log off. Within this space, events and economic activities such as real estate, gaming, e-commerce, and social networking are constantly synchronized in real time.

(2) ISSUES AND SUMMARY

Since 6G is expected to use even higher frequency bands compared to 5G and older systems, it will be necessary to expand coverage and stabilize communications. In terms of equipment, the higher the frequency band used, and the more compact and denser the antennas will need to be, the more serious the issue of heat generation will likely become. In order to solve this issue, it will be necessary to improve materials such as compound semiconductors. In addition, the use of high-frequency bands is expected to increase the numbers of antennas and base stations, and it will be necessary to optimize antenna placement in order to make distributed networks more sophisticated. If the network configuration changes to link with satellite communications and HAPS to extend coverage, the equipment configuration of base stations may also change, and it will be necessary to pay attention to cost issues. Several companies are currently working on network and base station virtualization technology. The advancement of this field may mean that less hardware is replaced than the previous generation, and it will be interesting to see how virtualization technology develops. There are many other hardware and software issues to be addressed, such as power consumption and the protection of the large amount of data that 6G will generate.

So far, this report has looked at the state of 6G studies in each country, the expected features and the technologies that will support them, a picture of the world in which 6G is realized, and the challenges. It seems that the interval between communication generations, which used to be every 10 years, is gradually getting shorter, and that the speed of change in the world of communication infrastructure is also accelerating. While new services have been created with each generation, 6G will dramatically expand the possibilities of service development through combination with other advanced technologies (AI, virtual space technologies, etc.). On the other hand, leading a discussion on the specifications and standards of 6G themselves has become a key national strategic matter, and the formulation of the specifications will require not only technology but also political aspects, such as with whom and how to form alliances. Now that Japan has decided to cooperate with the US, the question is how to build a good partnership with other countries and related organizations. In addition to the core technologies, each organization should also exercise wisdom on the development of services in anticipation of 6G.

Patent Application Trends Regarding 6G

MOLECULAR MACHINES

— TOWARD INDUSTRIALIZATION OF THE NANO WORLD —

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ABOUT MOLECULAR MACHINES

A molecular machine is a collection of molecules for which the rotation, extension, contraction, and other forms of motion are controlled. Molecular machines are of nanometer scale (one billionth of a meter), which is as small as a virus. They are a nanotechnology technology[3] that enables molecules to perform mechanical actions by leveraging chemical knowledge accumulated over many years. The early 20th century heralded the appearance of quantum theory. Quantum chemistry, which was derived from quantum theory, then advanced the understanding of the shapes and properties of molecules. The advancement of analytical technologies that enable precise analysis of the molecular structure of materials has also led to dramatic progress in the elucidation of the structure and chemical behavior of various molecules. Concurrently, research was also conducted on the manipulation of molecules, and in 1979, Professor Seiji Shinkai (now Professor Emeritus) of Kyushu University published his work on light-responsive molecular structures, which would become pioneering research on molecular machines[4]. Inspired by this research, advanced nations began to study how to make molecules work like machines by assembling them as parts. A number of research results were produced thereafter, and in 2016, the Nobel Prize in Chemistry was awarded[5] to three scientists for their research on the design and synthesis of molecular machines. This report gives an overview of molecular machines by tracing the achievements of Nobel laureates, and discusses the expected fields of application, future prospects and issues.

(1) MOLECULAR COMPONENTS (CATENANE AND ROTAXANE)

A molecule is a substance made up of several atoms bonded together. For example, methane (the main component of natural gas) is a molecule consisting of four hydrogen atoms bonded to one carbon atom. After hydrogen and helium, the methane molecule is the smallest and lightest of all molecules. In order to make these molecules behave like a machine, they need to have a certain size and a stable shape. A wide variety of molecules can combine in various ways to form molecular aggregates, such as a large number of methane molecules and water molecules (two hydrogen atoms and one oxygen atom) combining to form methane hydrate, which is a giant molecule. Molecular machines are a technology that stabilizes such molecular assemblies into a specific shape and skillfully combines them into a molecular component with a specific function.

Typical molecular components include catenane and rotaxane (Figure 1). Catenane is a molecular component consisting of two ring-shaped molecules joined in a chain by loose bonds. Jean-Pierre Sauvage, one of the 2016 Nobel laureates, was the first to successfully synthesize this in 1983. As the atoms that make up a molecule tend to share electrons with each other if they can, molecules may bond tightly together (covalent bonds are the strongest of all chemical bonds). What makes catenane groundbreaking is that it takes advantage of the bonding

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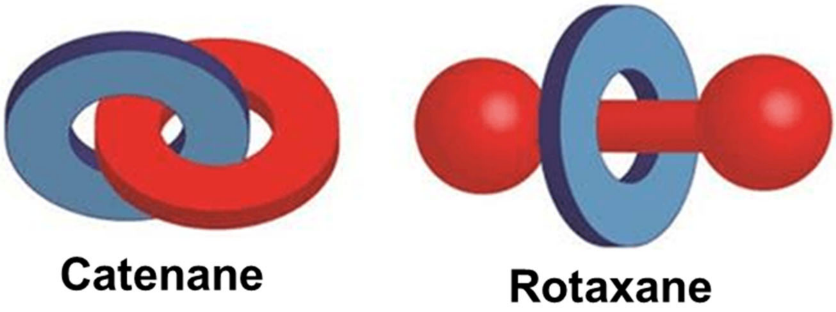
[3]The term nanomachines, as commonly used, refers to machines at the nanoscale, such as computational circuits, which do not necessarily involve mechanical operations. This report focuses on molecular machines, the subject of the 2016 Nobel Prize in Chemistry.

[4]The molecule (photoresponsive crown ether) developed by Professor Shinkai has a molecular structure known as trans type in its normal state before being exposed to light, and has the function of capturing sodium. When irradiated with UV light, however, the structure of the molecule changes to cis type, which is a molecular structure that captures potassium. The molecular structure is changed by irradiation with light.

[5] Royal Swedish Academy of Sciences press release: The Nobel Prize in Chemistry 2016 *for the design and synthesis of molecular machines* https://www.nobelprize.org/prizes/chemistry/2016/press-release/

properties of the molecule to create a create a loose enough bond between two ring-shaped molecules that they can move around each other.

Figure 1: Catenane and rotaxane



Source: Fuji Film
(https://sp-jp.fujifilm.com/finechemical_news/news/cs1610_nobel2016/index.html)

Catenanes normally have rigid, non-deformable crystal structures, but by arranging catenane molecules in three dimensions, the latest research has succeeded in developing crystals with flexible structures that can be deformed by external forces[6]. This catenane crystal, which has rubber-like properties, shows promise as a new material that will contribute to decarbonization by absorbing and releasing greenhouse gases such as carbon dioxide and methane.

Rotaxane is a molecular component that was developed by J. Fraser Stoddart in 1991. It is shaped like a molecular ring with a molecular wire passing through the middle. The ring can be moved along the wire, which acts like an axle. Since the rotaxane ring can be intentionally moved in either direction, it is currently being used as a molecular switch that turns on and off. Polyrotaxane is a molecular component that connects a string of rotaxane molecular rings (the blue part on the right of Figure 1). Nissan Motor has developed and put this into practical use as Scratch Shield, a coating that self-repairs scratches.

(2) FUNCTIONAL ENHANCEMENT OF MOLECULAR MACHINES

The third of the scientists to win the Nobel Prize in Chemistry was Bernard L. Feringa, who developed molecular motors in 1999, enhancing the functions of molecular components to enable them to move like machines. As a motor, the functions of rotation (clockwise and counterclockwise) and stopping of the molecules are necessary. However, in the nano world, the slightest energy change can cause fluctuations that greatly impede the rotation of molecules. For this reason, controlling the rotation of molecules is an extremely difficult task. Dr. Feringa's great achievement was in realizing a molecular motor that can withstand these fluctuations. Subsequent research has led to the development of a molecular motor that rotates a 0.028 mm glass cylinder, about 10,000 times larger than the molecular motor itself. Another research team has devised and implemented a mechanism for attaching a long, twistable rope-like molecule to a molecular motor, and releasing the twisted molecule by exposing the rope to ultraviolet light. This gave the molecular motor the ability to move through micro-space like a paper airplane with a propeller powered by an elastic band. This twistable rope-like molecular component is a technology that can also act as a kind of battery, storing the energy in the twist. In addition, the aforementioned catenane has been enhanced from a simple molecular component and given a function whereby its elongation and contraction can be controlled by applying an oxidation-reduction reaction, and rotaxane has also been enhanced to realize a molecular machine that can move up and down, which can be called a molecular elevator (2004).

Such research and development into functional enhancements of molecular machines has produced unique

[6] An Elastic Metal–Organic Crystal with a Densely Catenated Backbone, October 14, 2021 (RIKEN, The University of Tokyo, JST) https://www.riken.jp/press/2021/20211014_1/

molecular machines such as molecular switches, propellers, and rockets that can be controlled by light. Of particular interest is a technology in which the computational circuitry of a computer is composed of a large number of molecular switches protected by catenane crystals or the like. This has the potential to become a microscopic computing element that surpasses silicon transistors, and it is expected that molecular-machine-based computers will replace digital computers, which currently consume enormous amounts of electricity. Molecular machines are indeed a technology that shows great potential to expand from the nano to the digital world.

PROMISING FIELDS OF APPLICATION

The field in which molecular machines are most expected to play an active role is medicine. The aforementioned polyrotaxane has been attracting attention as a material that can perform functions unachievable with conventional pharmaceutical molecules, because the molecular ring can move on an axis, unlike the molecules with fixed shapes that are used in conventional pharmaceuticals. For example, research is being conducted on the use of biomaterials that self-repair in vivo, similar to the coating developed by Nissan Motor, and drug delivery systems (DDS) to intracellularly introduce drugs that are difficult to penetrate into cells. Some studies have shown that it is possible to introduce nucleic acids (RNA and DNA) into cells in the same way as RNA drugs that are used to combat COVID-19, and their use as anti-infective drugs may expand in the future.

Also attracting attention is the "in-body hospital," where molecular machines move autonomously through the body, diagnose abnormalities when they are detected, and provide treatment as necessary. The in-body hospital is a concept being pursued by the Innovation Center of NanoMedicine[7] of the Kawasaki Institute of Industrial Promotion, with the aim of realizing it by 2045. The molecular machines used in in-body hospitals are about 50 nanometers in diameter. If the human body were the size of the earth, molecular machines would be about the size of a ping-pong ball or about the same size as a virus. The molecular machine has the ability to move around the body and to detect abnormalities. If it finds something suspicious, it will decide on the spot whether treatment is necessary or not. If treatment is necessary, it will either take care of the problem itself by releasing drugs or call in another molecular machine that can provide the necessary treatment. The molecular machines are also expected to notify the person to introduce supporting molecular machines into the body if those in the body are insufficient. In this way, molecular machines that are capable of autonomous movement, cognition, and action are called molecular robots. If the concept of an in-body hospital is realized by integrating various technologies centered on molecular robots, it will be possible to take preventive measures against diseases before they manifest themselves, and may herald a disease-free society.

FUTURE PROSPECTS

Some scientists predict that molecular machines will become intelligent and evolve into molecular robots, while others predict that molecular machines will collectively grow into thousands, millions, and then trillions of macroscopic machines visible to the human eye, becoming able to move objects and create real components and chemical products like engineering machines. Research is also being considered to enable molecular machines themselves to assemble biological supramolecules and biomolecular robots using biological materials such as DNA, RNA, and proteins.

Although molecular machines are still in their infancy from a technological perspective, they are being researched and developed in many countries for both civilian and military applications. As they could become invisible nano-size weapons just like viruses, there are concerns about their impact on human society and the global environment. In the near future, the emergence of molecular machines/robots with lethal capabilities comparable to those of biological and chemical weapons are expected to appear, and a global consensus deterring their development, and monitoring and warning measures are necessary, before they have a catastrophic effect on

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7 Kawasaki Institute of Industrial Promotion, Innovation Center of NanoMedicine https://iconm.kawasaki-net.ne.jp/

humanity, such as through fully autonomous weapons[8]. The hope is for molecular machines to be implemented in society as technologies that contribute to the peace and tranquility of human society by improving health and welfare, just like in-body hospitals.

Patent Application Trends Regarding Molecular Machines

[8] Recent technological innovations have transformed the spatial perception of security, and space (inner and outer space), cyberspace (including the electromagnetic spectrum region), and the nano-space described in this report have emerged as new domains in addition to the traditional land, sea, and air. In particular, artificial life technology, which is making great strides combining synthetic biology and nano-technology, could revolutionize the concept of warfare.

SELF-LEARNING ROBOTS

— ROBOTS THAT THINK AND ACT AUTONOMOUSLY IN COLLABORATION WITH HUMANS, ANIMALS AND PLANTS —

Akira Yoshimoto
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ABOUT SELF-LEARNING ROBOTS

(1) EXPECTATIONS FOR SELF-LEARNING ROBOTS

Self-learning robots can seek out solutions and respond on their own. Conventionally, humans prepare instructions for robots, which then perform routine tasks according to them, contributing greatly to industry in saving labor and improving efficiency. However, such robots cannot respond in ways other than according to pre-programmed instructions. For example, it was previously difficult for robots to pick up screws that are messily piled in a box, making it necessary to prepare screws one by one on a separate device in an orientation and position that is easy for the robot to hold. In other words, humans had to set things up in advance to eliminate individual differences or the effects of environmental changes. The advancement of AI has made it possible to calculate the point where the screw should be grasped, even in the midst of a pile, and to grasp it accurately according to the situation without human assistance. On the other hand, it took a long time of trial and error and study by humans to make AI learn such functions. It was difficult for robots to respond immediately like humans when parts change one after another, as in high-mix low-volume production. In order to acquire the advanced judgment and responsiveness to solve such problems on their own, there are high expectations for the development of robots that can understand the goal, search for work techniques, and formulate an approach on their own without relying on instructions or data from humans, and that can also flexibly create tools and change their own shape as needed. This report defines such robots as “self-learning robots.”

There are three reasons why attention should be paid to self-learning robots as follows:

- The COVID-19 pandemic has led to a shift to digitalization and teleworking in many industries, but at the same time, bottlenecks in operational efficiency due to tasks that cannot be replaced, such as on-site inspections, have become apparent and have been highlighted as issues for operational reform.
- The fusion of AI and robotics is developing technologies that will lead to the realization of self-learning robots.
- For Japan, which has strengths in robotics and manufacturing, self-learning robots represent a great opportunity to create a new industrial pillar. As an example, one of the goals of the Moonshot Research & Development Program led by the Cabinet Office is to support research aimed at “realization of AI robots that autonomously learn, adapt to their environment, evolve in intelligence and act alongside human beings by 2050”. (Figure 1)

Figure 1: Moonshot Goal #3

Realization of AI robots that autonomously learn, adapt to their environment, evolve in intelligence and act alongside human beings by 2050

Target of Moonshot Goal

- Development of AI robots that humans feel comfortable with, have physical abilities equivalent to or greater than humans, and grow in harmony with human life, by 2050.
- Development of AI robots that behave well with humans under certain conditions, and allow over 90% of people to feel comfortable with them, by 2030.
- Development of an automated AI robot system that aims to discover impactful scientific principles and solutions, by thinking and acting in the field of natural science, by 2050.
- Development of an automated AI robot system that aims to support the process of discovery for scientific principles and solutions to specific problems by 2030.
- Development of AI robots that autonomously make judgements and act in environments where it is difficult for humans to act by 2050.
- Development of AI robots that operate unattended under human supervision in specific circumstances by 2030.

Source: Japan Cabinet Office website （https://www8.cao.go.jp/cstp/english/moonshot/sub3_en.html）

(2) CURRENT STATUS AND TECHNOLOGICAL DEVELOPMENT TOWARD THE REALIZATION OF SELF-LEARNING ROBOTS

Self-learning requires the evolution of two aspects: 1) the software side, where the AI, which corresponds to the brain, flexibly makes situational decisions like a human, and 2) the hardware side, where the robot creates tools and changes its own form as appropriate. When combined, these have the potential to adaptably solve problems that have not been addressed by conventional technologies, and will further promote labor-saving and automation of workplaces. Similar to how humans have applied fire in multiple ways such as for lighting, heating, and cooking, such robots may not only expand what is possible, but also create solutions using counterintuitive but rational methods and tools that humans never considered, in the same way that AI makes completely unconventional moves in the game of shogi.

・ EVOLUTION OF AI (STRONG AI)

With the dramatic evolution of AI, known as the third AI boom, it is no longer necessary to use human judgment to extract features, which was necessary for rule-based AI. AI can now extract features by learning from data obtained in the past. This evolution has made it possible for AI to make decisions when there are individual differences or changes in the environment, and to respond when the target is a natural object.

However, current AI is unable to respond without historical data. For example, AI and robots that pack the contents of a lunch box may be able to handle a certain dish or ingredient, but as soon as they are replaced by other side dishes and ingredients, they are unable to respond and will need a lot of time to learn how. In addition, if an earthquake occurs and houses collapse, the automatic delivery robot will not be able to respond to the different map data it holds. If we were to try to assume all special cases such as the event of an earthquake, the scale of the AI logic would become too large for the robot to implement. This means that AI can only be utilized in specific environments, domains, and situations. For this reason, automation and manpower savings have not progressed significantly at sites where economic rationality could not be realized between the cost required to create an environment suitable for robots and the benefits obtained from the use of the robots.

Accordingly, there are great expectations for AI that can judge situations on its own, prioritize and act flexibly. This is called “strong AI.” This concept was proposed by John Searle in 1980, and is defined as an AI that is self-conscious just like a human. A team from the University of California, Berkeley and the Technical University of Munich is conducting research on learning environmental prediction models with behavior conditions, which predict how objects of unknown shape and material will move, and then make execution plans according to these hypotheses (Figure 2). This is similar to the process by which a child who sees building blocks for the first time learns how to stack them. Using the memory of the feel, weight, and shape of objects encountered in the past and hypothesizing that similar objects can be handled in the same way can guide the direction of the AI trial and error process, and may find innovative solutions without being bound by the preconceived notion of a building block.

Figure 2: AI self-learning research by UC Berkeley/ Technical University of Munich

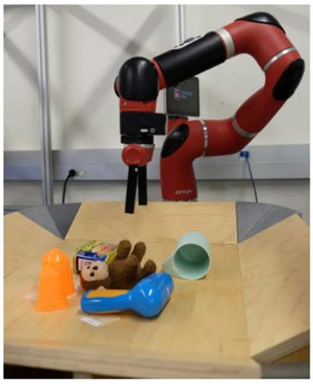


Figure 1: The robot learns to move new objects from self-supervised experience.

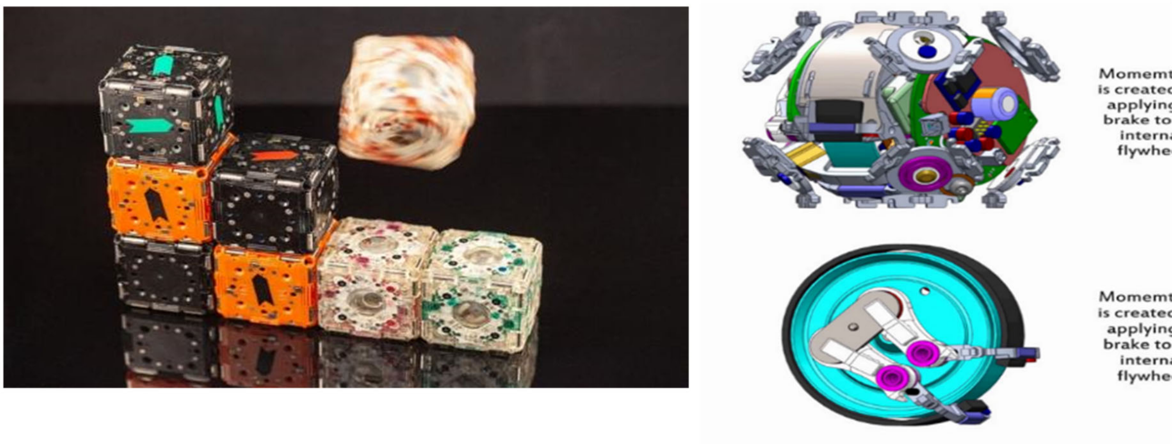
Source: UC Berkeley/ Technical University of Munich "Self-Supervised Visual Planning with Temporal Skip Connections"（https://arxiv.org/pdf/1710.05268.pdf）

・ DEVELOPMENT OF TOOLS AND SELF-TRANSFORMING ROBOTS

Even if strong AI is more flexible, it is difficult to achieve significant results because the range of search methods that can be tried is limited. Therefore, there is a growing interest in technologies that allow the robot to develop its own tools and change its shape, thereby increasing its options and expanding its range of applications. This is an equivalent approach to children using a platform or stretching higher when stacking blocks to a height greater than their own.

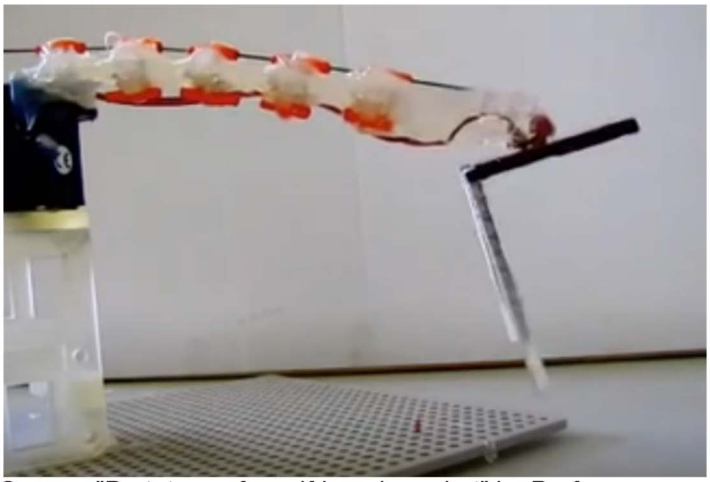
The M-Block (Figure 3) being developed at MIT moves itself with an internal flywheel, and can couple with other blocks using an electromagnet. This allows arbitrarily complex shapes to be built by combining multiple robot blocks, just like Lego. In addition, Professor Iida's team at the University of Cambridge has presented the idea of attaching a heater and a material called thermoplastic, which sticks at high temperatures and fixes at low temperatures, to the end of a robot arm. Tools can then be affixed to make them part of the arm, or removed and replaced with other tools by reheating the thermoplastic (Figure 4). In addition, they are also researching ideas such as robots operating 3D printers to make tools. Combining these technologies with the aforementioned trial and error by strong AI could solve problems that have been difficult to address in the past.

Figure 3: MIT's M-Block



Source: MIT News (https://news.mit.edu/2019/self-transforming-robot-blocks-jump-spin-flip-identify-each-other-1030)

Figure 4: Thermalplastic adhesive robot manipulator



Source: "Prototype of a self-learning robot" by Professor Fumiya Iida of Cambridge University
（https://www.youtube.com/watch?v=D7YhRVL8D90）

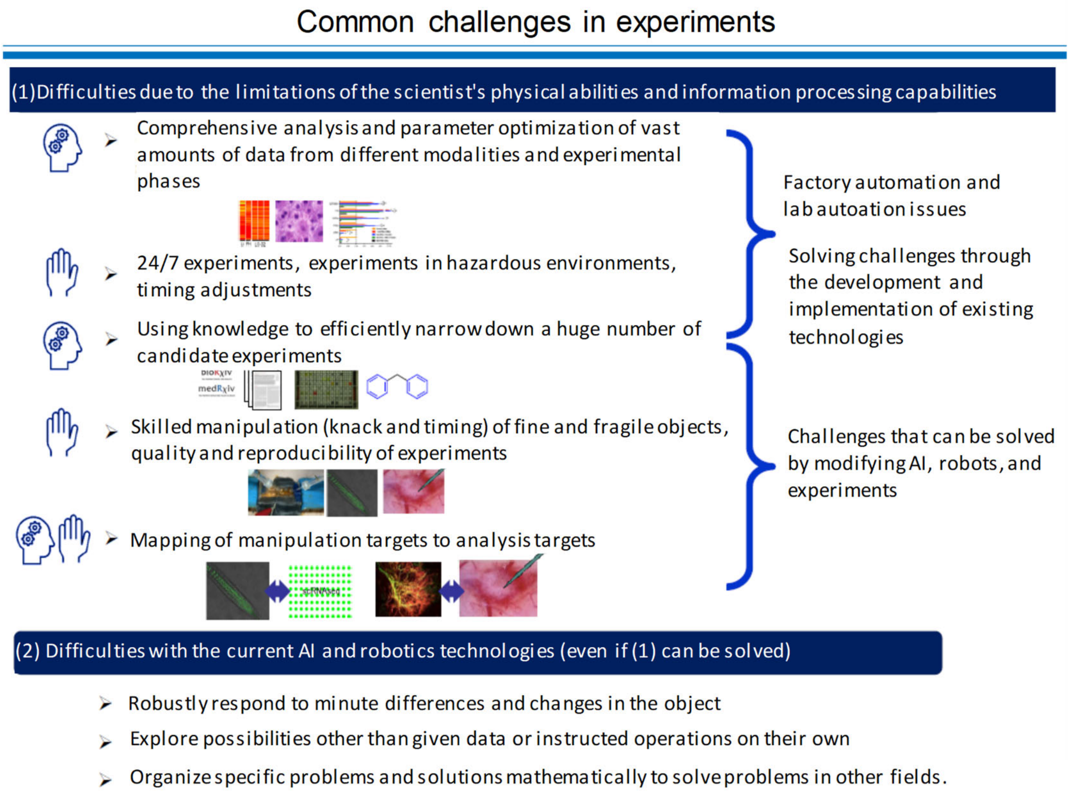
PROMISING FIELDS OF APPLICATION

(1) PHYSICAL AND CHEMICAL EXPERIMENTS ON ANIMALS AND PLANTS

In recent years, partly due to the growing interest in the SDGs, there has been a lot of research on personalized medicine and improving crop productivity. However, because of individual differences in the human body, animals and plants, it is currently difficult for robots to respond at the same level as humans, and researchers are sometimes forced to conduct experiments in hazardous environments or over long periods of time.

For example, biostimulant research aims to increase crop yields, improve crop quality, and increase tolerance to climate and other environmental factors by improving plant resistance to abiotic stress. Here, experiments are conducted to administer compounds that are candidate biostimulants to cells as small as 1 mm and measure their responses. Humans need to acquire proficiency to perform experiments on such small and flexible objects with high reproducibility, and it is difficult for conventional robots to respond to the individual differences of the target plants and animals. Self-learning robots are expected to contribute to the discovery of new substances, for example, by taking in the individual differences of the target and differences in skills to the extent possible and performing many verifications under the same conditions (Figure 5).

Figure 5: Application of robots to science and chemistry experiments, as targeted by the Moonshot-type R&D project Goal 3



Source: The 39th annual conference of the Robotics Society of Japan (RSJ2021) materials (https://www.youtube.com/watch?v=Ajo4CW2blQo)

Furthermore, by combining the traditional approach of analyzing past data with the new approach of strong AI, it will be possible to search for problems to solve and approaches to solve them, realize highly reproducible experiments by learning how to conduct experiments as expected, and gain insights based on a vast amount of experimental data, just like a human scientist. This will lead to the generalization of physical and chemical experiments, which had belonged to a few specialists, and the possibility of discovering better solutions without being bound by conventions or preconceived notions, which will further advance complementary cooperation between humans and robots.

(2) DISASTER RELIEF ROBOTS

When a house collapses due to a disaster, it is very difficult for a robot to traverse the area autonomously because data on the situation after the collapse is not available in advance. However, self-learning robots can be made into rescue robots that respond flexibly to unforeseen situations by assessing the surrounding environment and setting their own priorities, such as removing debris or lifting a fallen pillar blocking the way using a stick found on-site for leverage, just like a human. Eventually, they are also expected to be used in uncharted territories such as the surface of the moon, and in places where remote control is difficult due to poor communication conditions.

FUTURE PROSPECTS

(1) COMPANION ROBOTS

Smartphones are devices that can be tailored to the individual, with applications that can be selected to suit various situations in our lives and the human growth process, but they are nothing more than information projected on a display, and cannot go beyond adaptation from a software perspective. If we can develop a device that can change its shape according to the situation and can be customized in terms of hardware, we will be able to realize a robot like a partner that accompanies us throughout our lives, sometimes as a musical instrument, sometimes as a catching partner, and sometimes as a wheelchair that supports our weak legs and feet.

(2) Development into Self-Propagating and Self-Forming Robots

If self-development can be achieved, it will be possible to create robots that multiply themselves by creating copies of themselves like cell division, and then combine the multiplying blocks in complex ways to form themselves like living organisms. For example, hardware, including robots, can be produced anywhere if there are the necessary materials, energy, and blueprints, contributing to a local production, local consumption economy that does not require logistics.

(3) ETHICAL ISSUES

If robots, which do not tire like humans, have the same knowledge and creativity as humans, some are concerned that they will take away human jobs. If all work is performed by robots, we may be deprived of the opportunity to satisfy our higher needs, such as those for approval and self-realization. Rules that allow humans and robots to coexist while maintaining a balance in their work will probably be necessary. In addition, the first place that comes to mind for the use of self-learning robots is in the military field, but that would necessitate a worldwide discussion at least as diligent as that over nuclear weapons because of the possibility of robot armies and espionage activities. It would be too late for these matters to be addressed after the technology has been realized, and it will be necessary to create and study a system that transcends national boundaries, in which assessments are conducted in tandem with development while constantly predicting changes in the outcome.

➡ Patent Application Trends Related to Self-Learning Robots

CHEMICAL LOOPING COMBUSTION

— A NOTABLE COMBUSTION TECHNOLOGY FOR CO2 CAPTURE —

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WHAT IS CHEMICAL LOOPING COMBUSTION?

(1) CHEMICAL LOOPING COMBUSTION, AN EXCELLENT CO_2 SEPARATION AND RECOVERY TECHNOLOGY

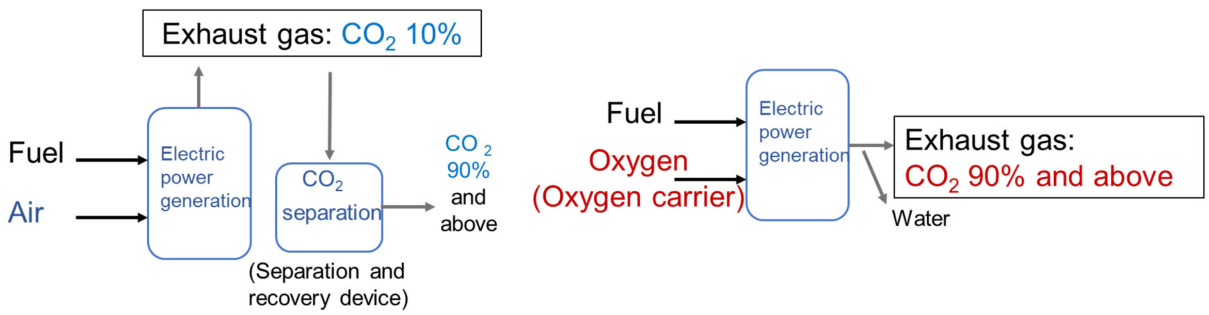
Chemical looping combustion (CLC) is a technology that does not use air to burn fuel (air combustion), but rather uses a reaction with oxygen adsorbed on metal particles. In recent years, from the viewpoint of decarbonization, there have been growing expectations for the realization of CO_2 capture and storage (CCS), in which carbon dioxide (CO_2) is separated and recovered from the exhaust gas of power plants and chemical plants and stored. Chemical looping combustion has been attracting attention as a technology for highly efficient CO_2 separation and recovery.

The concentration of CO_2 in the exhaust gas from oil- and natural gas-fired power generation by air combustion is 8-15%. In order to store CO_2 or use it in the manufacture of chemicals, it is necessary to increase its concentration, which requires equipment to separate and recover CO_2 from exhaust gas (Figure 1-a). On the other hand, in power generation by chemical looping combustion, since CO_2 accounts for more than 90% of the exhaust gas and the rest is water, a high concentration of CO_2 can be obtained simply by condensing and removing the water. There is no need to install a CO_2 separation and recovery device as in air combustion (Figure 1-b). In addition to reducing equipment costs, the energy required for CO_2 separation and recovery is small, so power generation efficiency is not drastically reduced. It is expected to be a technology to separate and recover CO_2 while maintaining the economic viability of power plants.

Figure 1: Difference in CO_2capture methods depending on combustion method

1-a CO_2 separation and recovery system is required for air combustion

1-b Chemical looping combustion does not need a CO_2 separator

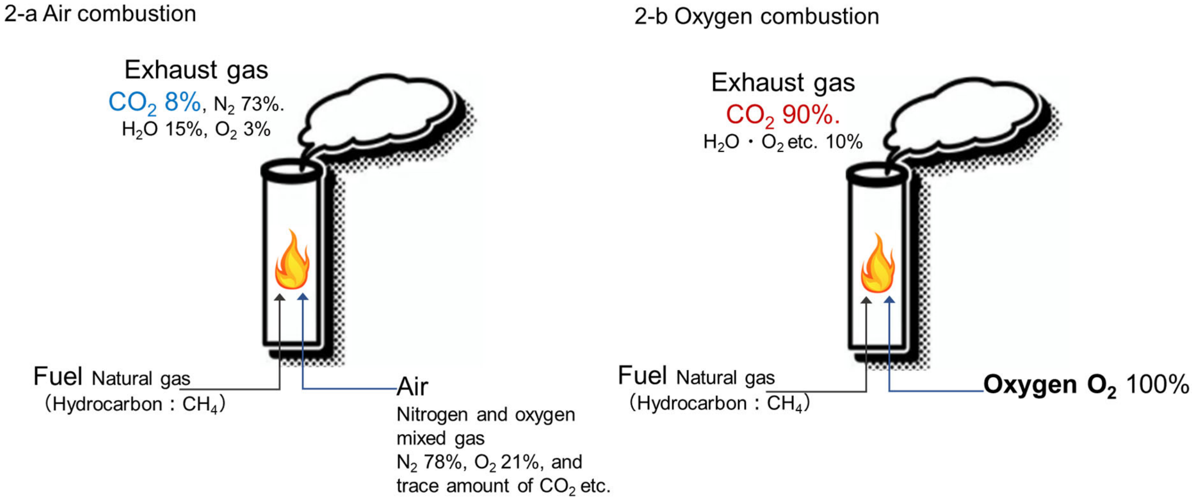


Source: Compiled by MGSSI

(2) MECHANISM OF CHEMICAL LOOPING COMBUSTION

Air is a mixture of 78% nitrogen (N_2), 21% oxygen (O_2), and other gases such as CO_2. For example, when natural gas is burned with air, the N_2 concentration in the exhaust gas exceeds 70%, and CO_2 is about 10% (Figure 2-a). On the other hand, when fuel is burned only with O_2, the exhaust gas contains no N_2, with CO_2 accounting for the majority (90%) and water and unburned O_2 remaining at about 10% (Figure 2-b). In addition, since only the O_2 required for combustion is supplied, the amount of exhaust gas itself is smaller than in air combustion.

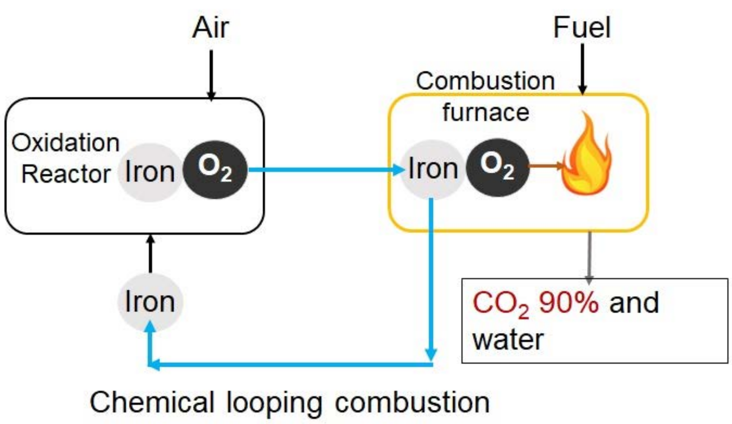
Figure 2: Difference between air combustion and oxygen combustion (for natural gas fuel)



Source: Compiled by MGSSI based on "Report on Research and Development of Carbon Dioxide Geological Storage Technology (March 2006)" by Research Institute of Innovative Technology for the Earth

The challenge here is how to make O_2 more efficiently. Although there have been demonstrative facilities for coal-fired power plants using oxyfuel combustion, most of them have used the cryogenic air separation method. The cryogenic air separation method consumes a large amount of energy because the air is cooled to nearly minus 200°C to separate O_2. Chemical looping combustion, on the other hand, is a method of oxidizing fine particles of minerals containing metals (such as iron and copper) that serve as "oxygen carriers," and then burning these particles by bringing them into contact with the fuel (Figure 3). The oxygen carrier first comes into contact with air in the oxidation reactor and is oxidized. The next step is to burn the oxygen carried by the oxygen carrier in contact with the fuel in the combustion furnace. The oxygen carriers that have lost O_2 are oxidized again in the oxidation reactor, fed into the combustion furnace, and the combustion cycle is repeated. It is called chemical looping combustion (CLC) because it uses a chemical reaction of oxidation and reduction with oxygen carriers, and because it involves repeated looping.

Figure 3: Mechanism of chemical looping combustion



Source: Compiled by MGSSI

In CLC, O_2 can be supplied to the combustion furnace without consuming a large amount of energy as in the cryogenic air separation method because it is easy to incorporate O_2 into the oxygen carrier in the oxidation reactor. Also, as mentioned above, only O_2 is supplied for combustion, so theoretically, the components in the exhaust gas are 90% CO_2 and the rest is water.

PROMISING FIELDS OF APPLICATION

(1) APPLICATION OF CHEMICAL LOOPING COMBUSTION TO THERMAL POWER GENERATION

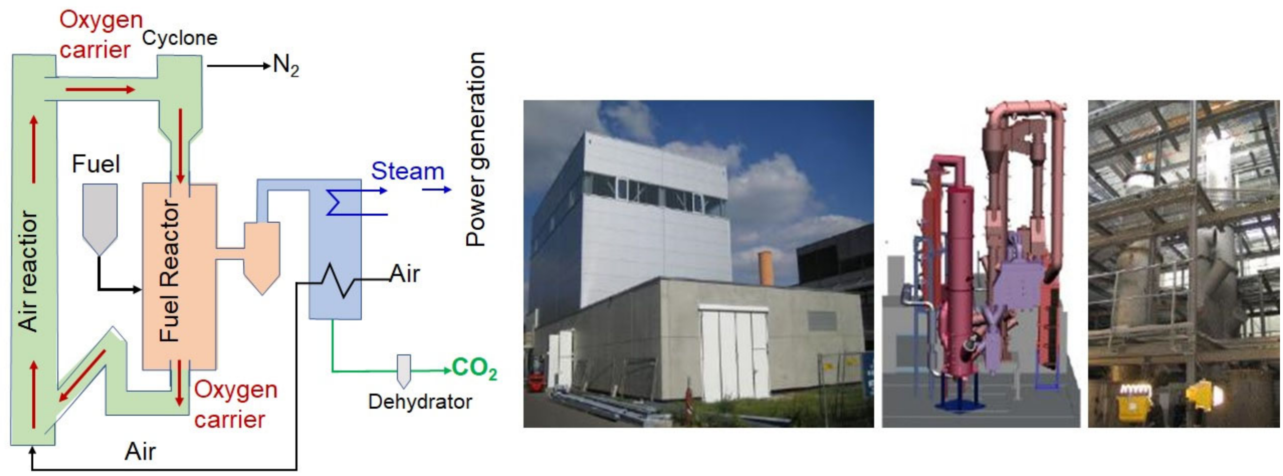
The mechanism of using oxygen carriers to burn fuel was invented in the United States, but it was Professor Emeritus Masaru Ishida of the Tokyo Institute of Technology who first adopted the name chemical looping combustion in the title of his paper. At the time the paper was published in 1994, the purpose of the research was to suppress the generation of nitrogen oxides (NOx) through oxygen combustion, and basic research was continuing mainly at universities.

Today, CCS is becoming increasingly important in achieving net zero emissions, and CLC is being developed mainly in Europe and the United States as one of the combustion technologies to recover CO_2 efficiently, as explained so far.

The actual CLC power generation system consists of an air reactor and a fuel reactor, with oxygen carriers circulating through the two reactors (Figure 4). The oxygen carrier is oxidized in the air reactor, separated from N_2 in a cyclone device that separates gas and solid, and only the oxygen carrier is sent to the fuel reactor where it contacts and burns the fuel. The heat from this combustion is used to produce steam, which is then used in a steam turbine to generate electricity in a CLC power plant.

Figure 4: Overview of equipment for chemical looping combustion

4-a Overview of a power generation plant 4-b Example of chemical looping combustion facility



Source: a: Compiled by MGSSI
b: Alstom (https://ieaghg.org/docs/General_Docs/OCC2/Abstracts/Abstract/occ2Final00050.pdf)

The core elemental technology of CLC is how to efficiently supply oxygen to the fuel reactor, and the selection of oxygen carriers is important. Metal oxides have shown promise, and the search for the optimal material in terms of both oxygen carrying capacity and cost is underway (Figure 5-a). Materials being studied include single metals such as iron-based (Fe_2O/Fe_3O_4 (name of the substance after/before oxidation)), copper-based (CuO/Cu), and manganese-based (Mn_3O_4/MnO), as well as composite oxides that combine multiple metals such as copper-manganese ($CuMnO_3$) (Figure 5-b). In both cases, alumina or titanium oxide is used as the carrier (base), and the particles are made by attaching a metal carrier to the surface.

Figure 5: Performance and examples of oxygen carriers

5-a Performance requirements for oxygen carriers	5-b Examples of oxygen carriers
• Highly reactive with oxygen and fuel • Ability to completely convert fuel into CO_2 and water • Withstand high temperature • Particles do not easily agglomerate and are resistant to grinding and abrasion. • Low production cost and low environmental impact	Synthetic particles • Fe_2O_3/Fe_3O_4, Mn_3O_4/MnO, CuO/Cu, composite oxides (e.g. $CuMnO_3$) :Use alumina or titanium dioxide as carrier Natural mineral • Iron ore, manganese ore, ilmenite

Source: Compiled by MGSSI from "Quarterly Report on Energy Engineering", Vol. 33 No. 1 (2010) by the Institute of Applied Energy

The use of iron-based oxygen carriers is in principle the same as the reaction used to reduce iron ore in steel mills. However, the steel mill continuously reuses the high temperature heat obtained for the reduction reaction and does not generate electricity. The challenge in CLC is how to use carriers to provide oxygen continuously. Iron and manganese are low cost, but have low reactivity with oxygen, and therefore low oxygen carrying capacity. Copper, on the other hand, is more expensive, but its high reactivity makes it a good oxygen carrier.

In addition to artificial synthetic particles, the use of powdered natural ores such as iron ore, manganese ore, and ilmenite themselves as oxygen carriers is also being studied. One promising candidate is ilmenite (a mixed ore of iron and titanium), where the iron component acts as an oxygen carrier. Since ilmenite is a raw material for titanium and its resources are large and can be procured at low cost, it is being considered for use in commercial plants for CLC.

Currently, CLC demonstration tests are being conducted mainly in Europe and the United States on scales ranging from 120 kWth[9] to 3 MWth (Figure 6), with the "CHEERS" project, a joint development between Europe and China, planning to install a 3 MWth test unit with the goal of starting operation in 2022. In the US, Babcock & Wilcox and Ohio State University are collaborating to commercialize the "Bright Loop," a proprietary process that uses CLC to produce hydrogen and syngas from a variety of fuels**.**

Figure 6: Example of technological development for chemical looping combustion

Research institution and company	Development Overview
(Europe) SINTEF, (France) Energies Nouvelles (China) Dongfang Boiler, (China) Tsinghua University, etc.	Project name "CHEERS": Methane combustion test is underway using copper oxide as oxygen carrier in 150kWth test unit. Planning to install a 3 MWth test unit with the goal of starting operation in 2022.
(Germany) The Technical University of Darmstadt	Coal CLC is being developed in a 1MWth test unit. The air reactor has an inner diameter of 0.6 m and a height of 8.7 m. The fuel reactor has an inner diameter of 0.4 m and a height of 11.4 m. Propane gas is used for start-up.
(Austria) Vienna University of Technology	CLC verification was conducted using natural gas, synthetic gas, and other fuels with ilmenite and nickel-based oxygen carriers in a 120kWth test unit.
(US) GE/Alstom	US DOE project conducted 3MWth test with Ca oxygen carrier by 2017; working on scaling up to 10MWt.
(US) Babcock & Wilcox, Ohio State University	Partnered on the development of the Bright Loop, a proprietary process that uses CLC to produce hydrogen and syngas from a variety of fuels.
(Japan) NEDO project: Osaka Gas, Japan Coal Frontier Organization	By the end of fiscal year 2024, a CLC process demonstration will be conducted to produce electricity and hydrogen on a 300kWth scale using coal and biomass as fuel. The goal is to commercialize the plant in 2025 onwards.

Source: Compiled by MGSSI based on the website of each company

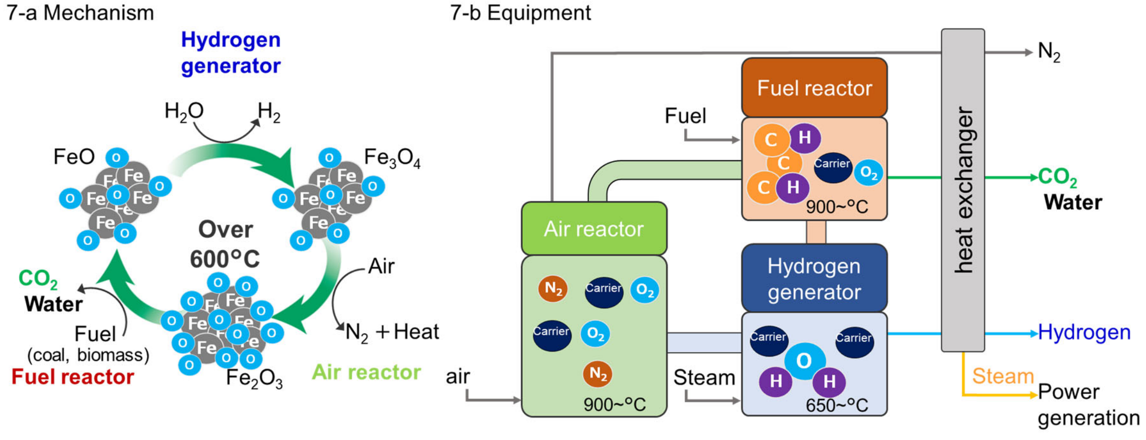
(2) INTEGRATION OF HYDROGEN PRODUCTION INTO CHEMICAL LOOPING COMBUSTION

Osaka Gas and the Coal Frontier Organization are working to develop technology for CLCs that incorporate hydrogen generation under a NEDO (New Energy and Industrial Technology Development Organization) project. It incorporates a hydrogen generator that generates hydrogen (H_2) from water through the oxidation reaction of iron oxide, and is a process that realizes power generation using high-temperature heat, hydrogen production, and the recovery of high concentrations of CO_2 (Figure 7). Iron oxide (FeO), which loses oxygen when fuel is

[9] kWth stands for kW-thermal, indicating a heat supply equivalent to 1 kW. It is used to distinguish from the electrical supply.

burned in the fuel reactor, takes O_2 from water vapor and produces H_2 when exposed to high temperature water vapor in the hydrogen generator. After that, the iron oxide (Fe_3O_4), which is still in an oxygen-deficient state, is exposed to air in the air reactor to obtain O_2, and then returns to the state before the reaction with the fuel (Fe_2O_3), and the loop can be repeated starting from the fuel reactor again.

Figure 7: Mechanism of chemical looping combustion including hydrogen production



Source: Compiled by MGSSI based on data from Osaka Gas

The system consists of air and fuel reactors plus a hydrogen generator, where the waste heat from them is used to produce steam for power generation, the fuel reactor emits high levels of CO_2, and the hydrogen generator produces H_2. The NEDO project will use coal or biomass as fuel, and a test device with an input energy of about 300 kW will be built. The device will be capable of producing about 35 m^3 of H_2 per hour, and development is currently under way with the goal of commercialization in 2025 or later. In December 2021, a 10-meter-high acrylic resin plant (cold model) will be installed to verify the circulation of iron oxide between the reactors. The plan is to select fuels and metal oxides, develop elemental technologies such as reaction conditions, and design a 300-kW test equipment by the end of FY2022.

FUTURE PROSPECTS

(1) CHALLENGES FOR PRACTICAL APPLICATION

CLC has challenges such as the performance and degradation of oxygen carrier particles, damage caused by the particles to the equipment, and scale-up. Various materials are being tested to improve the performance of oxygen carriers, and the search for materials with high oxygen supply, long life and low cost is ongoing. In terms of facilities, there is a search for operational measures such as designing pipes to prevent wear and replacing damaged parts at the appropriate time. Demonstration tests are being conducted by research institutes and private companies in various countries, and it is expected that the technical issues will be resolved as soon as possible.

(2) PROSPECTS FOR COMMERCIALIZATION

In addition to its advantage in CO_2 recovery, CLC is also being developed as a technology to produce hydrogen while generating electricity. Depending on the progress of technological development, it could replace conventional power generation systems that require CO_2 capture facilities. However, at present, demonstration tests are being conducted in pilot plants on a scale of several hundred kW, and it is estimated that only a few MW will be possible to scale up in the next five to ten years. Therefore, after the cost advantage of not needing a CO_2 capture facility is clarified, technologies that are expected to be closest to commercialization may be biomass power generation on a scale of several MW and distributed small thermal power generation using fossil fuels.

➡ Patent Application Trends Related to Chemical Looping Combustion

LIVING SENSOR PLANTS

— NEW DEVICES CREATED BY DIGITAL TECHNOLOGY —

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ABOUT LIVING SENSOR PLANTS

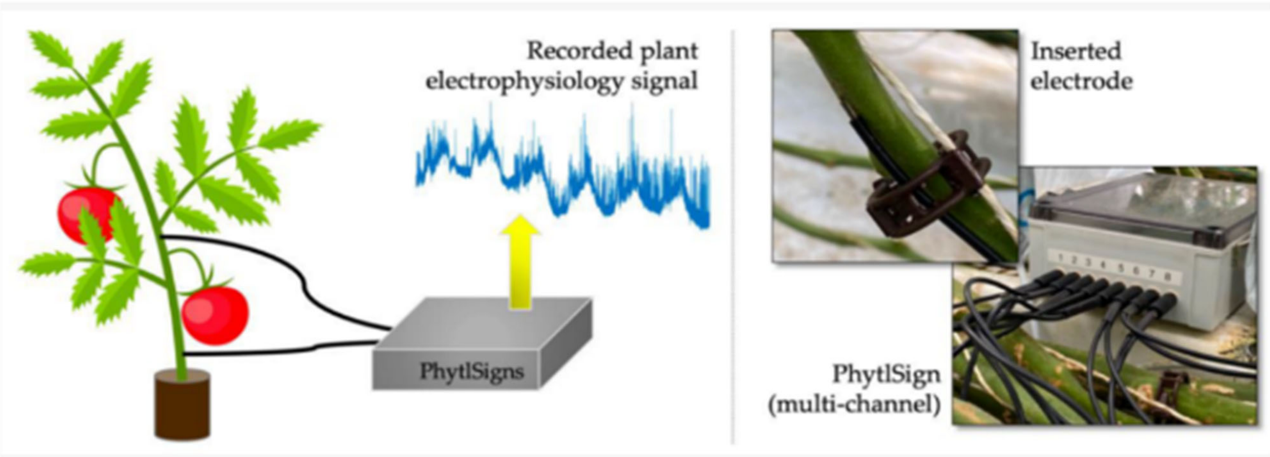
A living sensor plant is a plant that has been given a sensor function. Recent advances in plant physiological sciences, combined with technologies such as genetic engineering, nanotechnology, and AI, are making it possible to sense and detect plant responses to changes in the external environment as information. By modifying plants in a variety of ways and expanding the scope of their functions, we can expect to see this technology spreading to industries other than agriculture.

(1) SPEAKING PLANT APPROACH

Plants are known to change their biopotential when they are stressed by pests, drought, or the like. If we can measure this response in real time, like an electrocardiogram for humans, we can understand the state of activity of plants. The application of this concept, called the Speaking Plant Approach (SPA), to the agricultural sector has been advocated for several decades. SPA uses various sensors to understand and diagnose the growth status of crops and control the cultivation environment appropriately. It has recently become a reality with the development of sensors, robot technology, and AI. SPA is beginning to be used in controlled-environment agriculture because its prerequisites is that the growing environment can be properly controlled.

In Japan, Plant Data provides a system that measures the degree of photosynthetic activity and feeds it back to the cultivation environment. Swiss startup Vivent also offers a sensing system called PhytlSigns, which it describes as a ‘Fitbit for plants’ (Figure 1). Most of the technologies used in smart agriculture measure the condition of crops indirectly based on data such as soil moisture content and fertilizer application rate, and any feedback is given to growing conditions only after the appearance of the crop has deteriorated. However, this system allows farmers to know directly when their crops are under stress, so they can take immediate action.

Figure 1: Overview of PhytlSigns, Vivent (Switzerland)



Source: Applied Sciences Volume 11 Issue 4, Classification of Plant Electrophysiology Signals for Detection of Spider Mites Infestation in Tomatoes （https://www.mdpi.com/2076-3417/11/4/1414/htm）

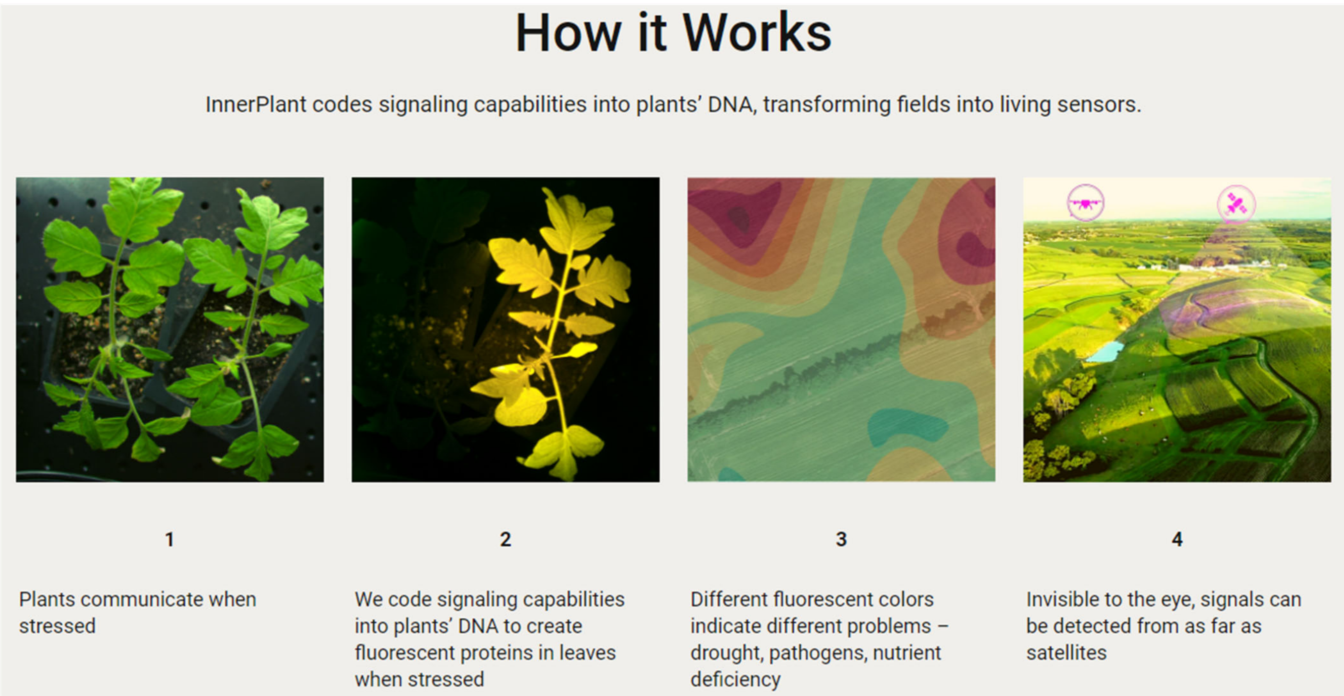
(2) LIVING SENSOR PLANTS THROUGH BIOLOGICAL MODIFICATION

Biological modifications, such as the incorporation into plants of genes that express fluorescent proteins under stress, are being considered in order to use plants as sensors. This makes it possible to visualize when a plant is in an unusual state due to stress caused by pests or other factors. The technology of incorporating fluorescent protein genes into plants is not new, but it is important to combine it with digital technology. Recently, devices such as smartphones and drones have started to spread, lowering the cost of photography. This is one of the factors that the technology could be put to practical use in society. A typical example of this is the work of InnerPlant in the US. This company aims to use the above genetic technology in crops such as tomatoes and soybeans to develop sensor technology for agriculture (Figure 2). The technology was featured in Time magazine's The Best Inventions of 2021.

On the other hand, since the varieties developed by InnerPlant are considered to be genetically modified crops, regulatory approval would be required for commercialization. In addition, sufficient protein must be accumulated in the crop to be detected using remote sensing technology for observation by video, smartphone, or satellite.

Despite these challenges, if stress-detectable crops can be planted in the field, it will be possible to precisely map stress and optimize the amount and timing of agrichemical applications.

Figure 2: Technology overview of InnerPlant (US)



Source: InnerPlant website（https://innerplant.com/products/）

(3) LIVING SENSOR PLANTS THROUGH MECHANICAL MODIFICATION

Mechanical modification is the incorporation of highly functional materials, such as conductive polymers and carbon nanotubes, into plants to turn them into devices. This gives the plant functions that it previously did not have. However, many technologies to create living sensor plants through mechanical modification are still in the research stage. For practical use in society, it will be important to combine mechanical modification with nanotechnology that does not cause significant damage to the plant itself. Nanotechnology controls the structure of materials at a very fine level, on the order of nanometers (billionths of a meter), which is invisible to the naked eye.

In a paper entitled Electronic Plant, Linköping University in Sweden succeeded in embedding conductive polymers in the leaves and stems of a plant to conduct electricity throughout the plant, indicating the possibility of creating an electronic circuit inside the plant. Triggered by the results of this study, the investigation of creating living sensor plants through mechanical modification has accelerated. Professor Strano's group at MIT in the US is actively researching a field of study called Plant Nanobionics, which combines nanotechnology to give new functions to plants.

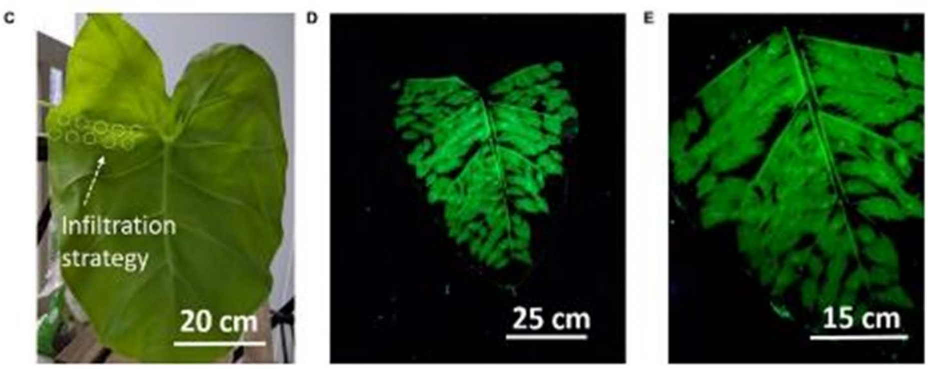
In 2021, the Singapore-MIT Alliance for Research and Technology (SMART) announced the results of a study to detect arsenic in soil using the technology. SMART has incorporated carbon nanotubes modified to react with arsenic into plants that act as sensors. Arsenic in the soil has a significant adverse effect on the crops themselves, and also poses a health risk to people who eat the contaminated crops. Using the results of SMART's research makes it possible to detect arsenic in real time by capturing by smartphone camera the signal emitted by the living sensor plants when they absorb arsenic from the soil (Figure 3).

Figure 3: Image of arsenic detection by a plant-based sensor

Source: MIT News
（https://news.mit.edu/2020/plant-nanobionic-sensor-monitor-arsenic-levels-soil-1213）

MIT has also realized a technology to make plants emit light by incorporating nanoparticles of a light-storing inorganic compound called strontium aluminate into them (Figure 4). Nanoparticles are injected through the pores of the leaf and accumulate inside to function as a capacitor (an electronic component that can store and release electricity). It has been demonstrated that after shining LED lighting on a modified plant for 10 seconds, it will then emit light for an hour, and can do so repeatedly for at least two weeks. If this research advances, it may be possible to use plants that are exposed to sunlight during the day as lighting during the night.

Figure 4: Light-emitting plants with fluorescent nanoparticles



Source: Science Advances Vol.7, No.37 Augmenting the living plant mesophyll into a photonic capacitor
（https://www.science.org/doi/10.1126/sciadv.abe9733#）

Figure 5: Examples of living sensor plants

Category	Technology	Overview	Company/Institute	Application example
1) Speaking Plant Approach	Machine learning, AI	Real-time measurement of photosynthesis by measuring fluorescent chlorophy	PLANT DATA(JPN)	Environmentally controlled agriculture
		• FitBit for plants: PhytlSigns • Detecting stress by measuring biopotential in plants • Announced a partnership with Bayer and raised €1.8 million in 2021.	Vivent (Switzerland)	Agriculture
(2) Living sensor plant through biological modification	Genetic engineering	• Genetically modified to produce a fluorescent signal upon stress • Announced that the company raised $5.7 million in 2021.	InnerPlant (US)	Agriculture (tomatoes, soybeans)
(3) Living sensor plant through mechanical modification	Conductive polymer	Controlling discoloration by incorporating conductive polymers into the leaves and stems of plants and applying electricity to the entire plant	Linköping University (Sweden)	Electronics
	Carbon nanotube	Carbon nanotubes can be embedded in plants to detect arsenic in soil	Singapore-MIT Alliance for Research and Technology	Soil sensor
	Nanoparticle	Fluorescent nanoparticles are embedded in plant leaves and illuminated by LED for 10 seconds to emit light for an hour.	MIT	Lighting

Source: Compiled by MGSSI based on the websites of each company/institute and academic papers

PROMISING FIELDS OF APPLICATION

(1) AGRICULTURE

One promising area of application for living sensor plants is smart agriculture. This field combines IoT and other sensors, information obtained from drones and satellite imagery, and machine learning technology to analyze these data. The combination with smart agriculture is attracting a lot of attention, as exemplified by the case of InnerPlant. One feature of SPA and living sensor plants through biological modification is the ability to directly measure the response of crops to growing conditions and reflect the information in cultivation in real time. Therefore, technological development will first be focused on fields that can leverage this feature. For example, companies may aim to further improve production efficiency centered on environmentally-controlled agriculture, where the cultivation environment and conditions can be actively controlled. Although it is difficult to control the growing environment of crops in outdoor agriculture, it is still possible to catch signs of deteriorating crop conditions at an earlier stage than with conventional techniques, which is expected to prevent reduced yields and excessive application of agrichemicals.

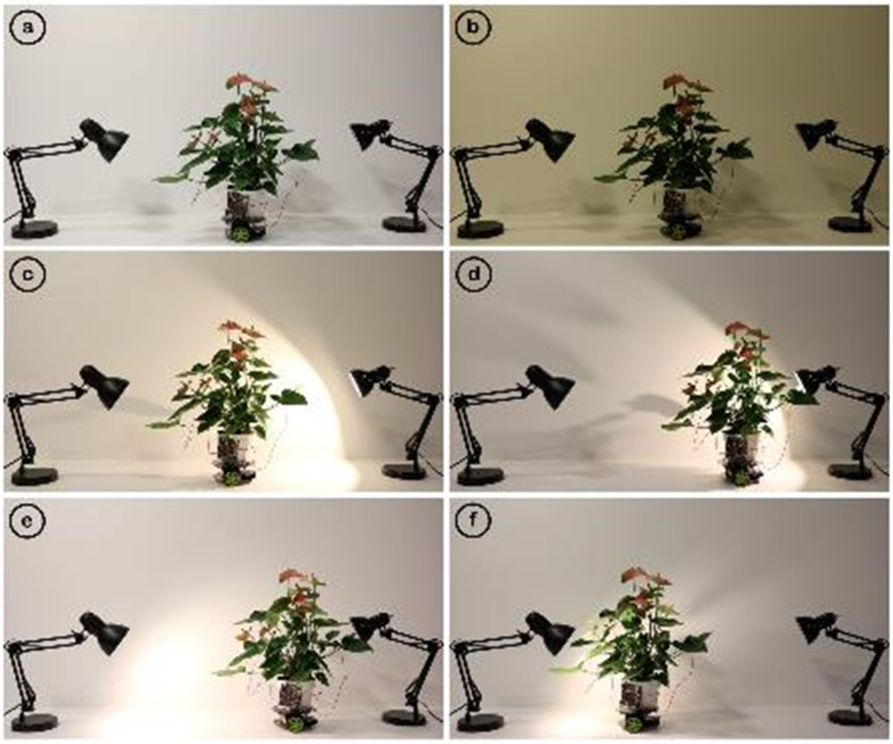
In addition, the ability to directly detect stress in crops could contribute to the development of stress-resistant crop varieties, or to the development of new agricultural materials if the effects of agrichemicals can be quantitatively demonstrated.

(2) ENVIRONMENT AND ENERGY

At the research level, it is becoming clear that plants can be used as environmental sensors and lighting through mechanical modifications that combine plants with nanotechnology and electronics to create living sensors. Plants store and regenerate energy through photosynthesis. If these features can be utilized together, sensing technology with low environmental impact can be developed.

Combinations with robots are also being explored, and MIT has experimentally created a plant that moves autonomously toward light (Figure 6). The robot reads the electrical signals generated by the stems and leaves of plants when light hits them, determines the direction of the light, and moves toward it. This demonstrates that it is possible to move plants according to external stimuli.

Figure 6: Elowan, a plant-robot hybrid that knows where the light is



Source: MIT Media Lab website
（https://www.media.mit.edu/projects/elowan-a-plant-robot-hybrid/overview/）

FUTURE PROSPECTS

Research on making plants function as sensors has been progressing, and promising results are beginning to emerge. Companies are now at the stage of implementing the technology in society. It will first be applied to controlled-environment agriculture and smart agriculture, and business based on data obtained directly from plants is also expected to emerge.

In the medium to long term, studies are underway to utilize mechanically-modified plants as environmental sensors and lighting, which is expected to contribute to the areas of environment and energy.

However, the following issues remain to be addressed in the lead up to practical application.

(1) SPA is mainly being considered for controlled-environment agriculture, such as vertical farming, but it is questionable whether it can produce results commensurate with the cost of implementation.

(2) Living sensor plants created through biological modification will require partnerships with seed companies that support the technology and approval from the authorities as it falls under the category of genetically modified crops. Technically, it remains to be seen whether the sensor output will be sufficient enough to be identified by drone or satellite images.

(3) The challenges of living sensor plants created through mechanical modification are the durability of the electronic device combined with the plant, and the fact that it may become a source of environmental pollution when the plant dies.

➡ Patent Application Trends Regarding Sensor Plants

INTELLECTUAL PROPERTY REPORT ON TECHNOLOGIES TO WATCH IN 2022

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This report examines and analyzes the international trends of patents regarding the five themes discussed in Technologies to Watch in 2022. The survey and analysis were conducted using PatSnap Analytics, a global patent search and analysis platform provided by PatSnap.

In principle, a patent application is published 18 months from the filing date. Therefore, as of January 2022, some of the patent applications submitted in 2020 and later have not been published. However, due to the nature of the Technologies to Watch in 2022 report, we believe it is preferable to note the latest state of patent applications, and so the number of patent applications from 2020 onward is included as a predicted or reference value.

PATENT APPLICATION TRENDS REGARDING 6G

In order to investigate and analyze the international trends in 6G-related patents, we created a population of global patent information.

In this case, the following search formula was used.

Search formula:

IPC (International Patent Classification) = H04W (Wireless Communication Networks)
AND Year of application = 2018 or later

As of December 28, 2021

This search formula created a population consisting of 147,594 patent families (345,577 patents in total).

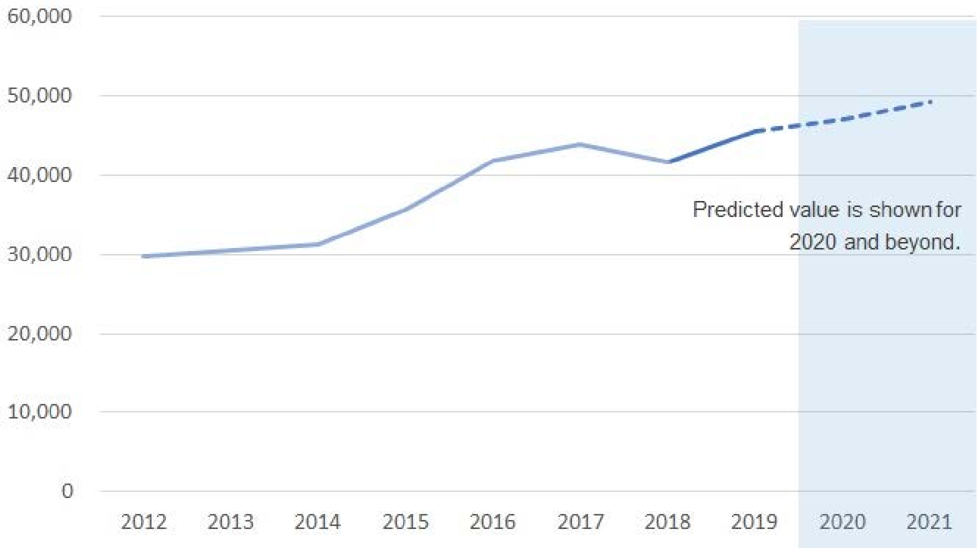
The International Patent Classification (IPC) is a symbol assigned by the Patent Office to all patent applications. Considering the timing of the transition to beyond-5G technologies, patent applications that were filed in 2018 and later from among those granted IPC: H04W (wireless communication networks) were included in the survey. Note that not all patent applications granted IPC: H04W in 2018 and later are related to 6G, but this search formula was adopted because it is difficult to clearly separate 6G-related patents.

First, the global trend in 6G-related patent applications is shown in Figure 1.

As shown in the figure, the number of patent applications granted IPC: H04W (wireless communication networks) is on the rise, including the period when 5G was being studied. 6G-related patents are also on the rise, and the number of applications is expected to continue to increase in 2020 and beyond.

Figure 1: 6G-related patent applications

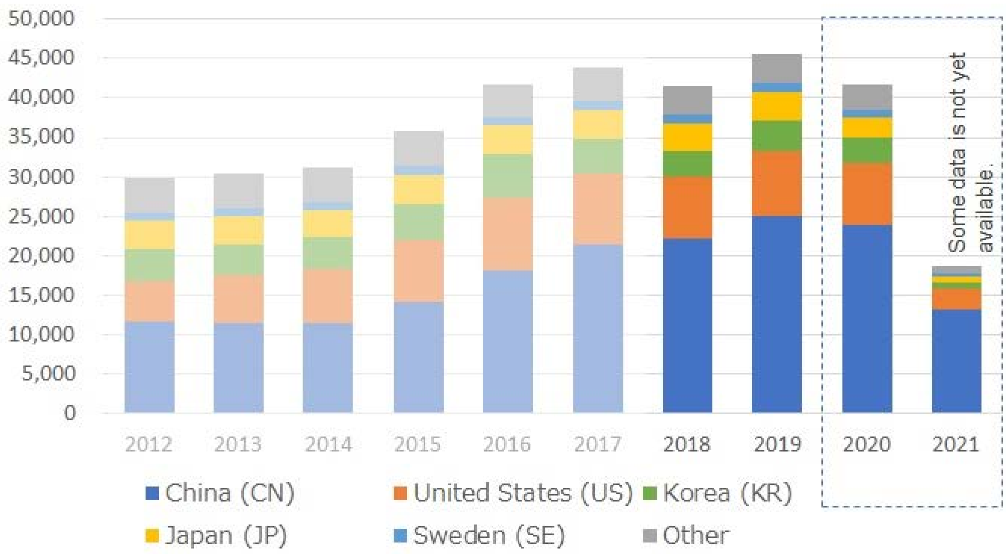
(Vertical axis: Number of patent families, Horizontal axis: Year of application)



Next, Figure 2 shows the trend in 6G-related patents by country/region. The name of the country in Figure 2 refers to the address of the current applicant (right holder). For example, Japan (JP) means an application by an applicant with an address in Japan, i.e., a Japanese company, etc. Although there are some applications from 2020 onward that have not yet been published, the current values are listed for reference.

Figure 2: 6G-related patent applications by country/region

(Vertical axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 2, the largest number of 6G-related patent applications are from China, followed by the US, South Korea, Japan, and Sweden. China accounts for about 57% of applications, the US for about 18%, South Korea for about 8%, Japan for about 7%, Sweden for about 2%, and other countries for about 8%.

Next, Figure 3 shows the top applicants by number of 6G-related patent applications.

Figure 3: Top applicants for 6G-related patents
(Vertical axis: Applicants, Horizontal axis: Number of patent families)

According to Figure 3, Qualcomm (US) and Huawei (CN) are the two leading companies, with the rest trailing them. Chinese companies accounted for five of the top 10 companies, indicating a battle for supremacy in 6G between China and other countries.

Next, Figure 4 shows the countries and regions in which 6G-related patent applications are filed (China/US/South Korea/Japan). For example, if a Chinese applicant files an application in China for one invention, they may use that application as the basis for filing an application in a different country. A patent family is a group of patent applications filed in multiple countries for a single invention.

Figure 4: Countries and regions where 6G-related patents are filed

Address of the applicant (right holder)	Country/Region of application	Number of patent families
China	China	79,092
	WIPO	20,127
	US	9,139
US	US	24,579
	WIPO	14,954
	China	7,240
South Korea	South Korea	7,788
	WIPO	5,978
	US	4,661
Japan	Japan	6,641
	WIPO	6,186
	US	4,837

WIPO in Figure 4 refers to international patent applications based on the Patent Cooperation Treaty (PCT) under the authority of the World Intellectual Property Organization (WIPO). The filing of a PCT international patent application indicates that the applicant is seeking international patent protection for their invention.

Taking US in Figure 4 as an example, applicants with addresses in the US have filed 24,579 6G-related patent applications in their home country. This is called a national application. On the basis of these national applications, 14,954 PCT international patent applications and 7,240 applications in China have been filed. These are referred to as foreign applications. It is possible to file multiple foreign applications on the basis of one national application. Based on the number of national applications and the number of applications to the second largest authority, the US foreign application rate is calculated to be about 61%.

In the same way, China's foreign application rate is about 25%, South Korea's is about 77%, and Japan's is about 93%. China has the highest number of applications, but its foreign application rate is lower than that of other countries. Foreign applications will be essential for the global deployment of 6G technology.

Next, Figure 5 shows the top applicants for 6G-related patents by top countries of application (China/US/South Korea/Japan).

Figure 5: Top applicants for 6G-related patents by country

Address of the applicant (right holder)	Top applicants	Number of patent families
China	HUAWEI	7,919
	OPPO	4,334
	ZTE	2,272
US	QUALCOMM	6,898
	APPLE	1,363
	INTEL	1,035
South Korea	LG	3,349
	SAMSUNG	2,877
	Electronics and Telecommunications Research Institute	514
Japan	NTT DOCOMO	1,962
	SONY	966
	SHARP	902

When calculated with just the top three Chinese applicants shown in Figure 5, the foreign application rate is about 97%, indicating that they are developing a patent strategy to gain 6G supremacy in the world.

PATENT APPLICATION TRENDS REGARDING MOLECULAR MACHINES

In order to investigate and analyze the international trends in molecular machine related patents, we created a population of global patent information.

In this case, the following search formula was used.

Search formula:

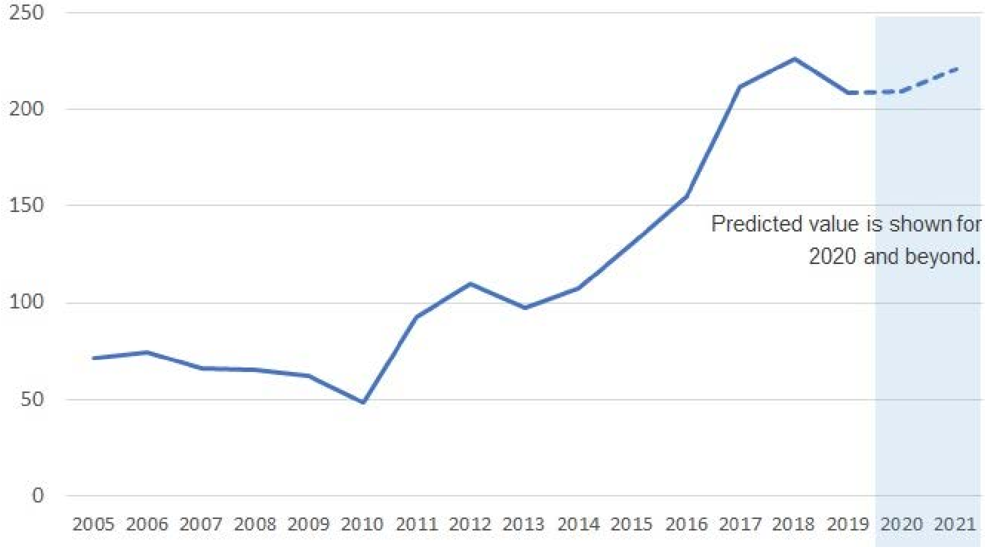
Text (title/abstract/claims) “Molecular Machine/ Motor/ Propeller/ Switch/ Shuttle/ Balance/ Tweezers/ Sensor/ Logic gate/ Assembler/ Hinge” OR “Nanocar”

As of December 28, 2021

This search formula created a population consisting of 2,511 patent families (5,861 patents in total).

First, the global trend in molecular machine related patent applications is shown in Figure 6.

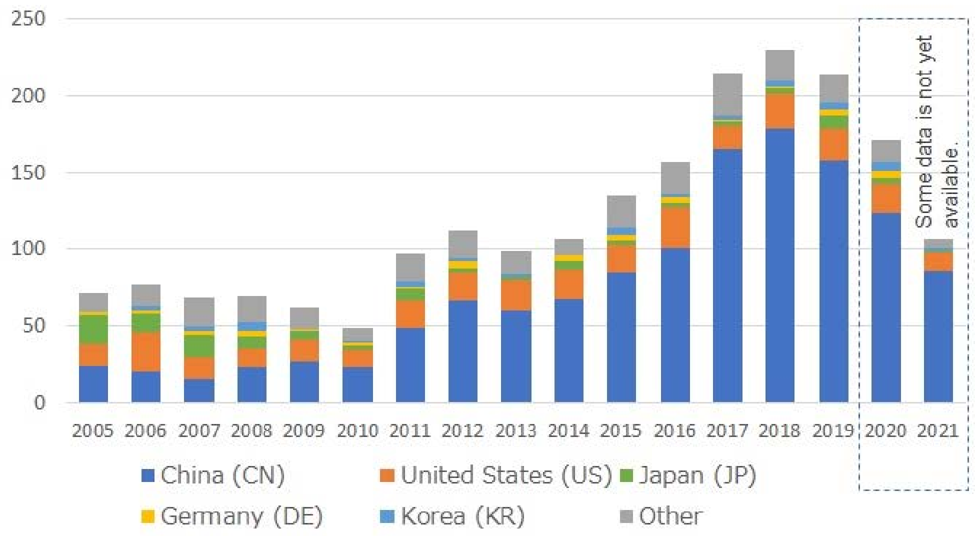
Figure 6: Molecular machinery-related patent applications
(Vertical axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 6, the number of patents related to molecular machines has been on the rise since 2010, and the number is not expected to drop significantly from 2020 onward.

Next, Figure 7 shows the trend in molecular machine related patent applications by country/region. The name of the country in Figure 7 refers to the address of the current applicant (right holder). For example, Japan (JP) means an application by an applicant with an address in Japan, i.e., a Japanese company, etc. Although there are some applications from 2020 onward that have not yet been published, the current values are listed for reference.

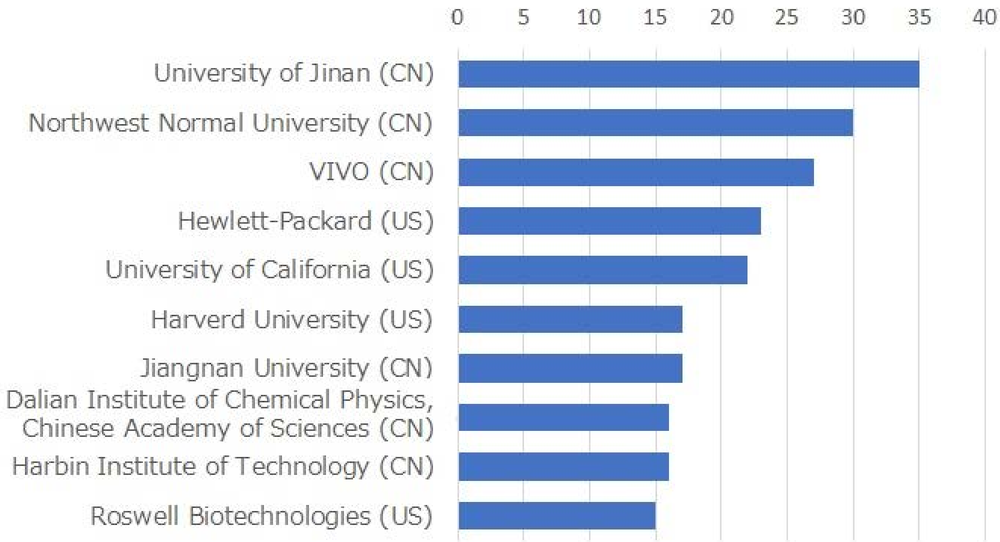
Figure 7 :Molecular machinery-related patent applications by country/region
(Vertical Axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 7, the largest number of molecular machine related patent applications are from China, followed by the US, Japan, Germany and South Korea. China accounts for about 59% of applications, the US for about 17%, Japan for about 6%, Germany for about 2%, South Korea for about 2%, and other countries for about 15%.

Next, Figure 8 shows the top applicants for molecular machines related patents.

Figure 8: Top applicants for molecular machines-related patents
(Vertical axis: Applicants, Horizontal axis: Number of patent families)



HP, which ranks fourth in Figure 8, applied for nine patents related to molecular machines in 2004, but filed no more applications after the last one in 2010. Therefore, in order to verify the recent state of research and development, we will limit our review to trends in patent applications filed since 2015.

Figure 9 shows the countries and regions in which molecular machine related patents are filed (China/US/South Korea) since 2015. For example, if a Chinese applicant files an application in China for one invention, they may use that application as the basis for filing an application in a different country. A patent family is a group of patent applications filed in multiple countries for a single invention.

Figure 9: Countries and regions where molecular machinery-related patents are filed

Address of the applicant (right holder)	Country/Region of application	Number of patent families
China	China	888
	WIPO	21
	US	20
US	US	132
	WIPO	114
	Europe	68
South Korea	South Korea	25
	US	9
	WIPO	9

WIPO in Figure 9 refers to international patent applications based on the Patent Cooperation Treaty (PCT) under the authority of the World Intellectual Property Organization (WIPO). The filing of a PCT international patent application indicates that the applicant is seeking international patent protection for their invention.

Taking US in Figure 9 as an example, applicants with addresses in the US have filed 132 molecular machine related patent applications in their home country. This is called a national application. On the basis of these national applications, 114 PCT international patent applications and 68 applications in Europe have been filed. These are referred to as foreign applications. It is possible to file multiple foreign applications on the basis of one national application. Based on the number of national applications and the number of applications to the second largest authority, the US foreign application rate is calculated to be about 86%.

In the same way, China's foreign application rate is about 2% and South Korea's is about 36%. China has the highest number of applications, but its foreign application rate is low, indicating that Chinese applicants may not be considering implementing or enforcing their patented inventions overseas.

Next, Figure 10 shows the top applicants for molecular machinery related patents by country (China/US/South Korea) since 2015.

Figure 10: Top applicants for molecular machinery-related patents by country

Address of the applicant (right holder)	Top applicants	Number of patent families
China	VIVO	28
	Jinan University	27
	Northwest Normal University	24
US	Roswell Biotechnologies	16
	MIT	8
	Harvard University	7
South Korea	Individuals	4
	INTOCELL	3
	Korea Advanced Institute of Science and Technology	2

As shown in Figure 10, the top applicant in South Korea is an individual with four applications. However, this applicant has not filed any foreign applications. Intocell, which ranked second, filed applications for all three of its patents in the most foreign countries, including China, Europe, India, Australia, Brazil, Canada, and the US. When assessing the trend of patent applications by country and company, it is important to consider not only the number of applications but also the coverage of the patents (where they are filed).

PATENT APPLICATION TRENDS RELATED TO SELF-LEARNING ROBOTS

In order to investigate and analyze the international trends in self-learning robot related patents, we created a population of global patent information.

In this case, the following search formula was used.

Search formula:

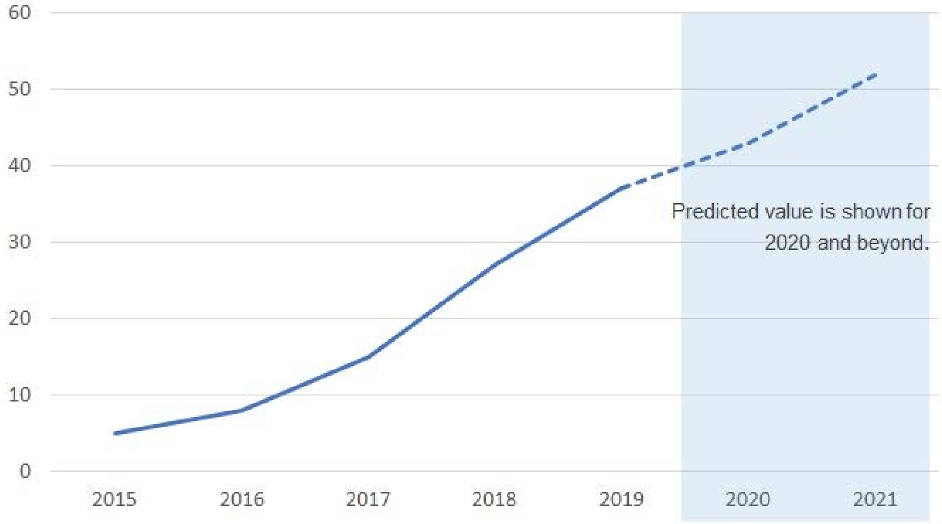
Text (title/abstract/claims)= “Learning” AND “self OR meta” AND
International Patent Classification= B25J9/16（Program control）AND
Year of application = 2015 or later

As of December 28, 2021

This search formula created a population consisting of 155 patent families (211 patents in total).The International Patent Classification (IPC) is a symbol assigned by the Patent Office to all patent applications.

First, the global trend in self-learning robot related patent applications is shown in Figure 11.

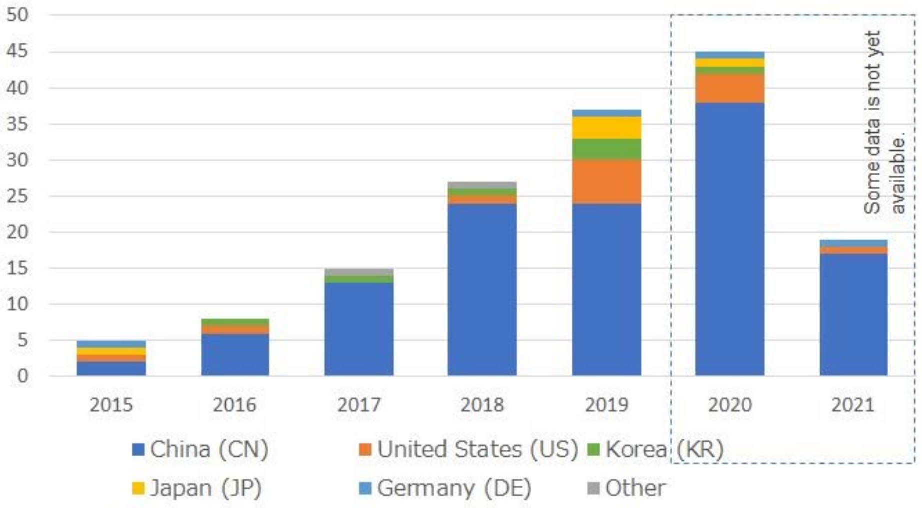
Figure 11: Self-learning robot-related patent applications
(Vertical axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 11, patent applications related to self-learning robots are on the rise, and the number of applications is expected to continue to increase from 2020 onward.

Next, Figure 12 shows the trend in self-learning robot related patents by country/region. The name of the country in Figure 12 refers to the address of the current applicant (right holder). For example, Japan (JP) means an application by an applicant with an address in Japan, i.e., a Japanese company, etc. Although there are some applications from 2020 onward that have not yet been published, the current values are listed for reference.

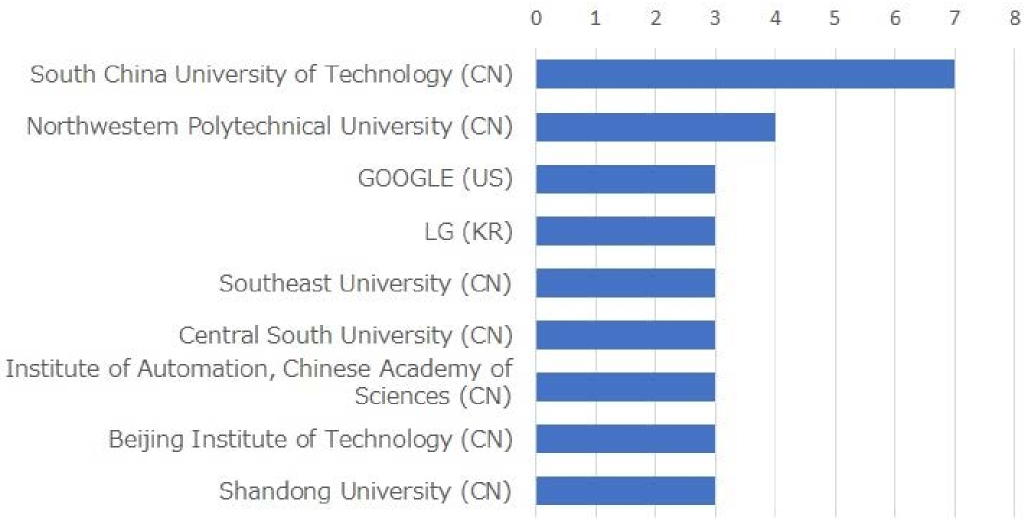
Figure 12: Self-learning robot-related patent application by country/region
(Vertical axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 12, the largest number of self-learning robot related patent applications are from China, followed by the US, South Korea, Japan, and Germany. China accounts for about 80% of applications, the US for about 9%, South Korea for about 5%, Japan for about 3%, Germany for about 3%, and other countries for about 1%.

Next, Figure 13 shows the top applicants by number of self-learning robot related patent applications.

Figure13: Top applicants for self-learning robot-related patents
(Vertical axis: Applicants, Horizontal axis: Number of patent families)



As shown in Figure 13, applications by Chinese academia occupy the top positions.

Next, Figure 14 shows the countries and regions in which self-learning robot related patents are filed (China/US/South Korea). For example, if a Chinese applicant files an application in China for one invention, they may use that application as the basis for filing an application in a different country. A patent family is a group of patent applications filed in multiple countries for a single invention.

Figure 14: Countries and regions where self-learning robot-related patents are filed

Address of the applicant (right holder)	Country/Region of application	Number of patent families
China	China	124
	WIPO	4
	US	3
US	US	13
	WIPO	10
	China	6
South Korea	South Korea	7
	WIPO	6
	US	4

WIPO in Figure 14 refers to international patent applications based on the Patent Cooperation Treaty (PCT) under the authority of the World Intellectual Property Organization (WIPO). The filing of a PCT international patent application indicates that the applicant is seeking international patent protection for their invention.

Taking the US in Figure 14 as an example, applicants with addresses in the US have filed 13 self-learning robot related patent applications in their home country. This is called a national application. On the basis of these national applications, 10 PCT international patent applications and 6 applications in China have been filed. These are referred to as foreign applications. It is possible to file multiple foreign applications on the basis of one national application. Based on the number of national applications and the number of applications to the second largest authority, the US foreign application rate is calculated to be about 77%.

In the same way, China's foreign application rate is about 4% and South Korea's is about 86%. China has the highest number of applications, but its foreign application rate is low, which can be read as indicating that Chinese applicants are not considering implementing or enforcing their patented inventions overseas.

Next, Figure 15 shows the top applicants for self-learning robot related patents by top countries of application (China/US/South Korea).

Figure 15: Top applicants for self-learning robot-related patents by country

Address of the applicant (right holder)	Top applicants	Number of patent families
China	South China University of Technology	7
	Northwestern Polytechnical University	4
	Institute of Automation Chinese Academy of Sciences	3
USA	GOOGLE	3
	NVIDIA	2
	-	1
South Korea	LG	4
	-	1

In Figure 15, third place is tied in the US with one application after NVIDIA in second place. Second place is tied at one application in South Korea after LG in first place.

PATENT APPLICATION TRENDS REGARDING CHEMICAL LOOPING

In order to investigate and analyze the international trends in chemical looping related patents, we created a population of global patent information.

In this case, the following search formula was used.

Search formula:

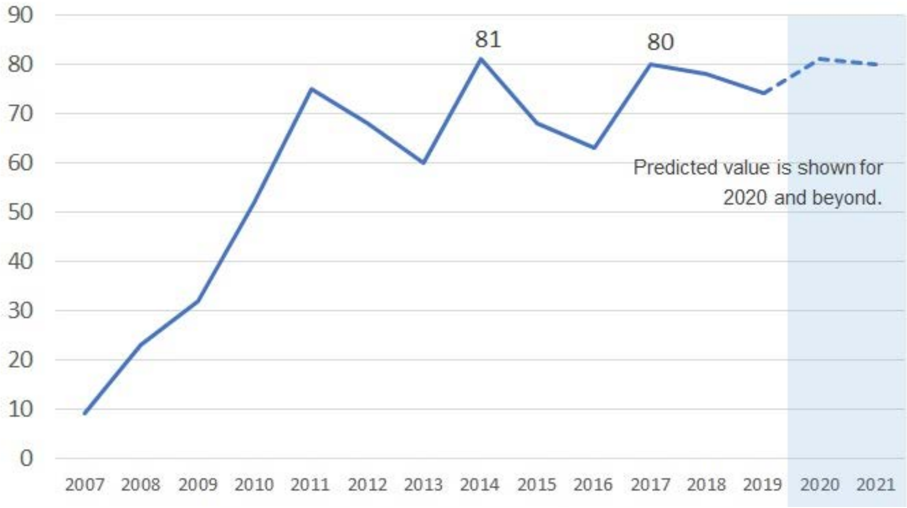
Text (title/abstract/claims/description) = “Chemical Looping”

As of December 28, 2021

This search formula created a population consisting of 940 patent families (3,433 patents in total).

First, the global trend in chemical looping related patent applications is shown in Figure 16.

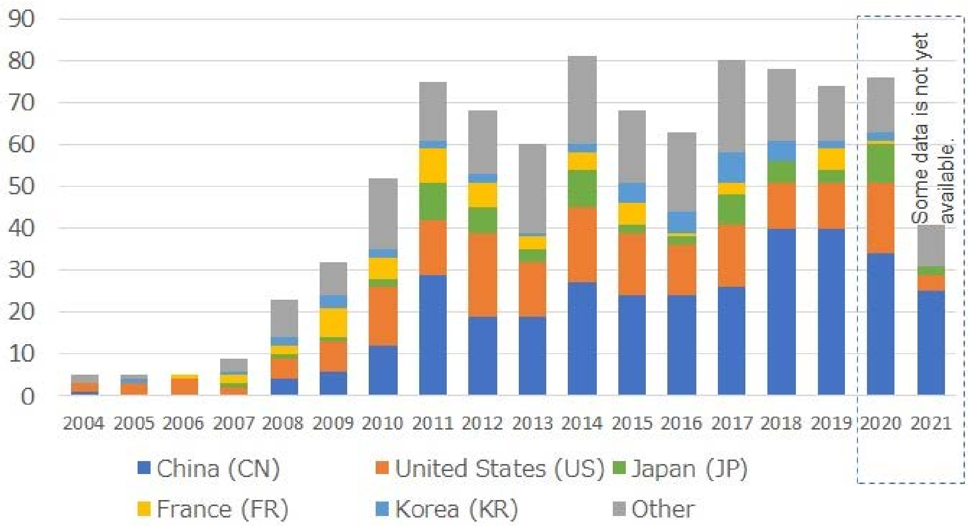
Figure 16: Chemical looping-related patent applications
(Vertical axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 16, the number of patent applications related to chemical looping increased since 2007, peaking at around 80 applications per year, and fluctuating thereafter. The number of applications is not expected to drop significantly from 2020. There has not been an explosive boom, but rather a continuous state of research and development.

Next, Figure 17 shows the trend in chemical looping related patents by country/region. The name of the country in Figure 17 refers to the address of the current applicant (right holder). For example, Japan (JP) means an application by an applicant with an address in Japan, i.e., a Japanese company, etc. Although there are some applications from 2020 onward that have not yet been published, the current values are listed for reference.

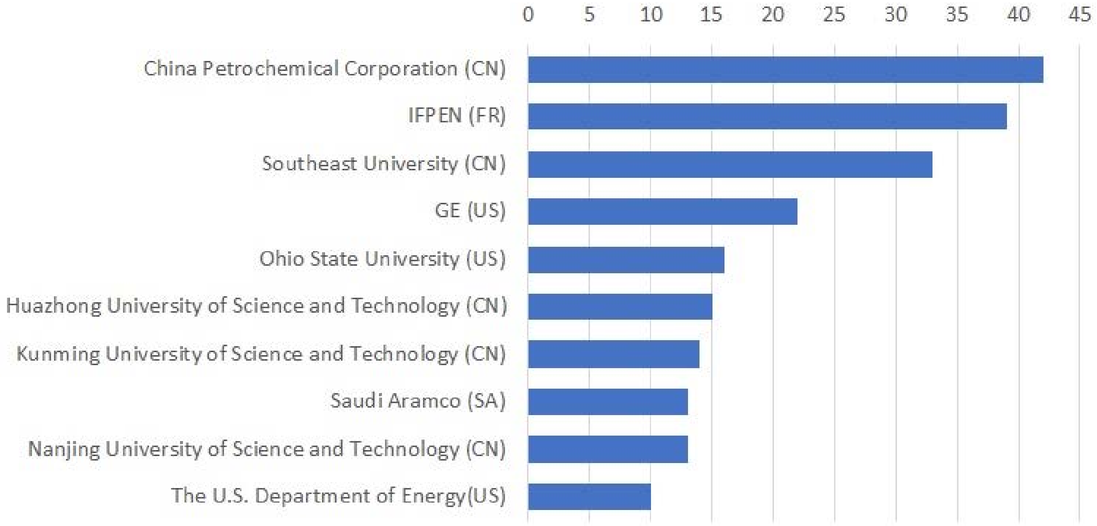
Figure 17: Chemical looping-related patent applications by country/region
(Vertical axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 17, the largest number of chemical looping related patent applications are from China, followed by the US, Japan, France, and South Korea. China accounts for about 37% of applications, the US for about 21%, Japan for about 7%, France for about 6%, South Korea for about 5% and other countries for about 25%.

Next, Figure 18 shows the top applicants by number of chemical looping related patent applications.

Figure 18: Top applicants for chemical looping-related patents
(Vertical axis: Applicants, Horizontal axis: Number of patent families)



In Figure 18, IFPEN (FR) stands for the French Institute of Petroleum. GE (US) applications include those filed by Alstom (FR) and later transferred to GE.

Next, Figure 19 shows the top applicants for chemical looping related patents by top countries of application (China/US/Japan). For example, if a Chinese applicant files an application in China for one invention, they may use that application as the basis for filing an application in a different country. A patent family is a group of patent applications filed in multiple countries for a single invention.

Figure 19: Countries and regions where chemical looping-related patents are filed

Address of the applicant (right holder)	Top applicants	Number of patent families
China	China	300
	Taiwan	24
	US	17
US	US	185
	WIPO	131
	Europe	70
Japan	Japan	66
	WIPO	19
	China	15

WIPO in Figure 19 refers to international patent applications based on the Patent Cooperation Treaty (PCT) under the authority of the World Intellectual Property Organization (WIPO). The filing of a PCT international patent application indicates that the applicant is seeking international patent protection for their invention.

Taking the US in Figure 19 as an example, applicants with addresses in the US have filed 185 chemical looping related patent applications in their home country. This is called a national application. On the basis of these national applications, 131 PCT international patent applications and 70 applications in Europe have been filed. These are referred to as foreign applications. It is possible to file multiple foreign applications on the basis of one national application. Based on the number of national applications and the number of applications to the second largest authority, the US foreign application rate is calculated to be about 71%.

In the same way, China's foreign application rate is about 7% and Japan's is about 29%. China has the highest number of applications, but its foreign application rate is low, indicating that Chinese applicants may not be considering implementing or enforcing their patented inventions overseas. A company that has been active in filing foreign applications is the French Institute of Petroleum, which filed about 79% of its 28 patent applications in France in foreign countries. The company has submitted applications to a wide range of authorities, including the US, Canada, China, Spain, Poland, Germany, Australia, and South Africa.

Next, Figure 20 shows the top applicants for chemical looping related patents by top countries of application (China/US/Japan).

Figure 20: Top applicants for chemical looping-related patents by country

Address of the applicant (right holder)	Top applicants	Number of patent families
China	Petroleum and Chemical Corporation	42
	Southeast University	33
	Huazhong University of Science and Technology	15
US	GE	22
	Ohio Sate University	16
	US Department of Energy	12
Japan	Tokyo Gas	9
	Mitsubishi Heavy Industries	9
	Sekisui Chemical	9

As shown in Figure 20, academia ranks among the top applicants in China, and academia and government agencies also rank among the top applicants in the US.

PATENT APPLICATION TRENDS REGARDING SENSOR PLANTS

In order to investigate and analyze the international trends in living sensor plant related patents, we created a population of global patent information.

In this case, the following search formula was used.

Search formula:

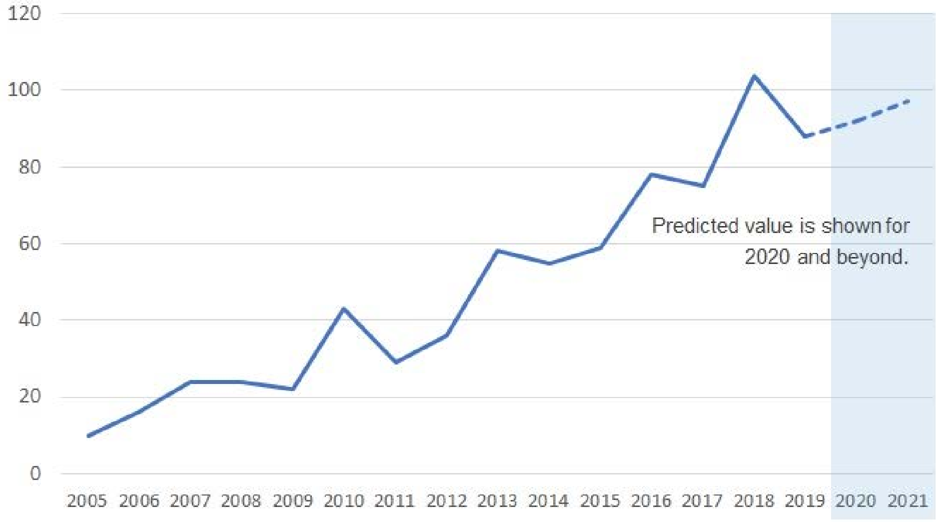
Text (title/abstract/claims) = "Sensor Plants" OR "Plant nanobionics" OR "Phytosensors" OR "Vascular Bundle" AND (Sensor OR Measurement) OR (Photosynthesis AND Rate) AND (Sensor OR Measurement) OR (Stress* AND (Plant OR Crop)) AND (Sensor OR Measurement) AND "Agriculture"

As of December 28, 2021

This search formula created a population consisting of 980 patent families (1,825 patents in total).

First, the global trend in living sensor plant related patent applications is shown in Figure 21.

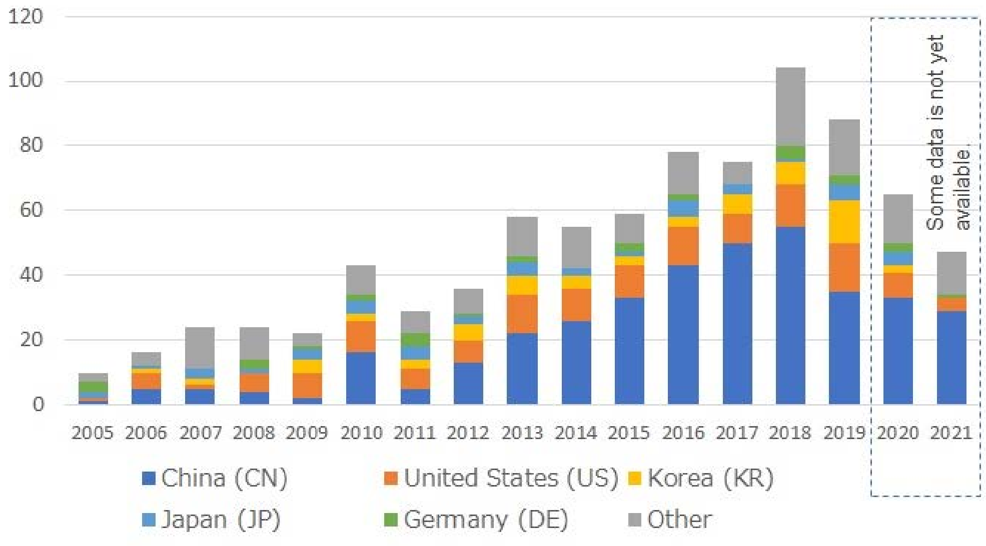
Figure 21: Sensor plant-related patent applications
(Vertical axis: Number of patent families, Horizontal axis: Year of application)



As shown in Figure 21, the number of sensor plant related patents has been increasing on the whole since 2005, although there have been fluctuations. The number of applications is not expected to drop significantly from 2020. Research and development are being conducted continuously, and has been especially active in recent years.

Next, Figure 22 shows the trend in sensor plant related patents by country/region. The name of the country in Figure 22 refers to the address of the current applicant (right holder). For example, Japan (JP) means an application by an applicant with an address in Japan, i.e., a Japanese company, etc. Although there are some applications from 2020 onward that have not yet been published, the current values are listed for reference.

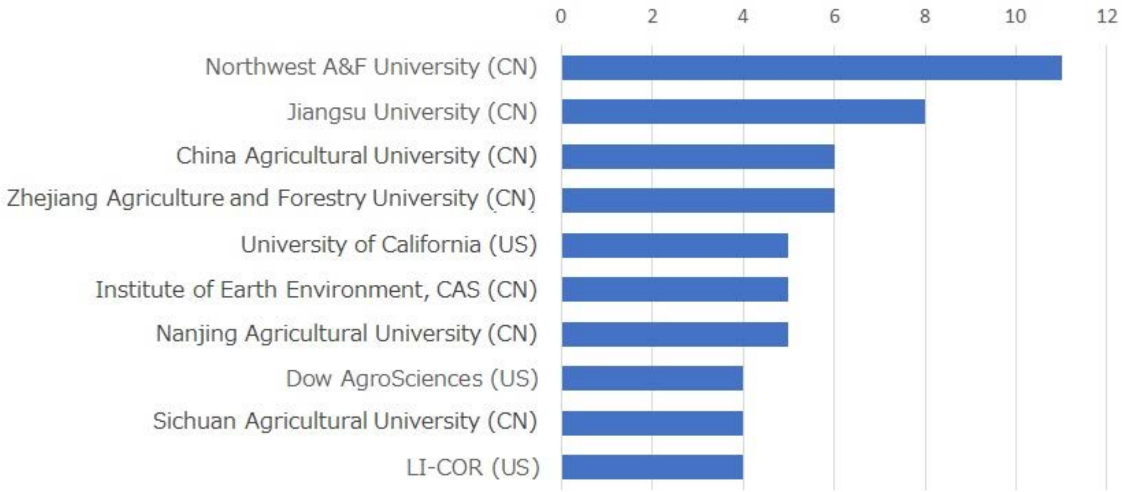
Figure 22: Sensor plant-related patent applications by country/region
(Vertical Axis: Number of patent families, Horizontal axis: Year of Application)



As shown in Figure 22, the largest number of sensor plant related patent applications are from China, followed by the US, South Korea, Japan, and Germany. China accounts for about 45% of applications, the US for about 16%, South Korea for about 7%, Japan for about 5%, Germany for about 4%, and other countries for about 22%.

Next, Figure 23 shows the top applicants by number sensor plant related patent applications.

Figure 23: Top applicants for sensor plant-related patents
(Vertical axis: applicants, Horizontal axis: number of patent families)



As shown in Figure 23, patent applications by universities and research institutions account for the largest share.

Next, Figure 24 shows the countries and regions in which sensor plant related patent applications are filed (China/US/South Korea). For example, if a Chinese applicant files an application in China for one invention, they may use that application as the basis for filing an application in a different country. A patent family is a group of patent applications filed in multiple countries for a single invention.

Figure 24: Countries and regions where sensor plant-related patents are filed

Address of the applicant (right holder)	Top applicants	Number of patent families
China	China	373
	WIPO	13
	US	9
US	US	132
	WIPO	98
	Europe	67
South Korea	South Korea	59
	WIPO	14
	US	5

WIPO in Figure 24 refers to international patent applications based on the Patent Cooperation Treaty (PCT) under the authority of the World Intellectual Property Organization (WIPO). The filing of a PCT international patent application indicates that the applicant is seeking international patent protection for their invention.

Taking the US in Figure 24 as an example, applicants with addresses in the US have filed 132 sensor plant related patent applications in their home country. This is called a national application. On the basis of these national applications, 98 PCT international patent applications and 67 applications in Europe have been filed. These are referred to as foreign applications. It is possible to file multiple foreign applications on the basis of one national application. Based on the number of national applications and the number of applications to the second largest authority, the US foreign application rate is calculated to be about 74%.

In the same way, China's foreign application rate is about 3% and South Korea's is about 24%. China has the highest number of applications, but its foreign application rate is low, indicating that Chinese applicants may not be considering implementing or enforcing their patented inventions overseas.

Next, Figure 25 shows the top applicants for sensor plant related patents by top countries of application (China/US/South Korea).

Figure 25: Top applicants for sensor plant-related patents by country

Address of the applicant (right holder)	Top applicants	Number of patent families
China	Northwest A&F University	11
	Jiangsu University	11
	China Agricultural University	6
USA	University of California	6
	LI-COR	5
	Dow AgroSciences	4
South Korea	Rural Development Administration	4
	Kunok	4
	Seoul National University	3

As shown in Figure 25, academia ranks in the top applicants in all three countries. The number of applications filed by companies is expected to increase as the technology moves from the stage of basic research to practical use.

SUMMARY OF TECHNOLOGIES TO WATCH IN 2021

(PRIME EDITING, SUPER CLOCKS, EUV LITHOGRAPHY, INVASIVE BMI)

Below is a brief summary of the subsequent trends in prime editing, super clocks, EUV lithography, and invasive BMI, which were discussed in Technologies to Watch in 2021, published in January 2021.

PRIME EDITING

> The previous report stated that prime editing is a genome editing technology that can reduce the risk of off-target editing and advance efforts to overcome genetic diseases.

One notable trend in prime editing in 2021 is the progress in developing technology that eliminates the risk of off-target editing, which is the accidental editing of unintended locations. In the case of genome editing by CRISPR, it is difficult to be sure that only the targeted area and no other is edited and after cutting the DNA double strand. With prime editing, the RNA with the changed gene sequence is transcribed by reverse transcriptase into the region to be edited once again after the genome is edited, enabling accurate gene editing. Improved prime editing[10], which minimizes off-target editing and increases efficiency by a factor of three or more, appeared in October 2021.

One of the drawbacks of prime editing is that it is considered to be less efficient than genome editing with CRISPR. However, the arrival of improved prime editing technology may enable use in industries such as agriculture, stock farming, and fisheries from 2022. The global genome editing market is expected to grow at an annual rate of 24.3% between 2021 and 2030[11], and prime editing in particular is expected to be widely trialed and validated in the medical field moving forward, increasing in technological maturity, and going on to be applied to the treatment of intractable diseases. (Yutaka Abe, Technology Foresight Center)

SUPER CLOCKS

> Super clocks are precision clocks that do not require correction for a long period. The previous report stated that as photonics technology permeates society, super clocks will be a core technology for controlling the future systems of society, which will process information at the speed of light.

In 2021, verification was completed of the accuracy of the Deep Space Atomic Clock (DSAC) mounted aboard an experimental satellite launched by NASA, confirming it to be at least 10 times more accurate than the current highest accuracy atomic clock[12]. The fact that the DSAC has been able to maintain stable operation and designated performance under the extreme environment of fluctuating radiation, magnetic fields, and temperatures in space indicates that a core technology for navigation in deep space has been established, such as for a crewed exploration of Mars, which is expected to become a full-scale endeavor in the future. The DSAC is expected to be mounted on GPS satellites from now on, and will enable ultra-precise positioning on the

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[10] Nature Biotechnology (October 4, 2021) Engineered pegRNAs Improve Prime Editing Efficiency
https://www.nature.com/articles/s41587-021-01039-7

[11] Allied Market Research, Prime Editing and CRISPR Market by Service, Application, and End User: Global Opportunity Analysis and Industry Forecast, 2021—2030
https://www.alliedmarketresearch.com/prime-editing-and-crispr-market-A11781

[12] Nature (June 30, 2021) Demonstration of a trapped-ion atomic clock in space
https://www.nature.com/articles/s41586-021-03571-7

ground in the order of centimeters, which is expected to dramatically increase the sophistication and safety of self-driving car navigation in particular.

The miniaturization of super clocks is also progressing steadily, and chip-based atomic clocks are becoming available for smartphones and watches in replacement of the current crystal oscillators. The DSAC is about the size of a toaster, and the optical lattice clock is small enough to be carried. In the future, atomic and other types of super clocks will be implemented in all kinds of devices, including sensors and control devices, and will steadily spread as a core technology that supports digital society, enabling the recording, analysis, and control of various social events in real time. (Yutaka Abe, Technology Foresight Center)

NEXT-GENERATION EUV LITHOGRAPHY

EUV lithography is a core technology for semiconductor miniaturization. The previous report stated that the technology to increase the density per wafer area will develop in pace with the progress of DX.

In November 2021, ASML (Netherlands), the world's only extreme ultraviolet (EUV) lithography equipment manufacturer, announced that it is on track to provide its customers with new EUV equipment with an NA (lens aperture) greater than 0.55 in the first half of 2023[13]. The combination of new and existing equipment has increased the probability of realizing a process that far exceeds 2 nm in the next decade.

A clear demarcation between winners and losers was seen among the three giants in the semiconductor market. TSMC (Taiwan), the first company to successfully mass-produce processors using EUV lithography and the leader in the industry, is realizing its planned roadmap. The company has announced that it will begin construction of a manufacturing plant using the 2 nm process in early 2022, and will be ready for mass-production in the second half of 2024[14]. On the other hand, Samsung (South Korea) has not been able to improve its yield with the 4 nm process, and has allowed TSMC to capture some of the contract manufacturing business outsourced by Qualcomm (US)[15]. In addition, in July 2021, the company announced[16] that it would push back the launch of the 3 nm process by one year, to 2023, from the previous plan as of 2020 to launch it in 2022. Intel (US) announced that it will invest about $20 billion to build two new factories in Arizona. The company has declared that it will build a line capable of introducing EUV lithography and manufacture the world's most advanced chips by 2024, intensifying its rivalry with TSMC[17].

In addition to the existing demand for servers and smartphones, advances in sensing and communication technologies have created constant demand for advanced semiconductor technologies. The fierce competition over development continues. (Reina Ogawa, Industry Innovation Dept.)

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[13] ASML's New EUV Device Could Extend Moore's Law for the Next 10 Years
https://eetimes.itmedia.co.jp/ee/articles/2111/01/news153.html

[14] TSMC to Build a Semiconductor Manufacturing Plant with 2 nm Process in 2022: Mass Production to Start in 2024
https://iphone-mania.jp/news-385645/

[15] TSMC's Entry into Snapdragon 8 Gen 1 Manufacturing Raises Concerns Over Performance Gap; Samsung's Manufacturing Capacity in Question
https://buzzap.jp/news/20211208-snapdragon-8-gen-1-tsmc-samsung/

[16] Samsung Foundry's 3 nm GAA Process May Be Pushed Back to Volume Production in 2023
https://news.mynavi.jp/techplus/article/20210713-1921142/

[17] Intel Announces Foundry Business: Major Investment in Factories
https://eetimes.itmedia.co.jp/ee/articles/2103/24/news060.html

INVASIVE BMI

Invasive BMI is an interface technology that physically exchanges information directly with the human brain. The previous report referred to the compatibility and integration of digital technology and the brain.

In July 2021, Neuralink, a BMI venture company led by Elon Musk, announced that it had received a total of about $200 million in investments from Google Ventures, Founders Fund, etc.[18], indicating that expectations in BMI are mounting. The company released a video of a macaque monkey with a Neuralink chip implanted in its brain controlling a tennis-like computer game called MindPong by brainwaves alone[19]. The success of the experiments on primates has brought us one step closer to practical applications for humans, such as prosthetic engineering for the disabled.

In addition, Synchron has developed a BMI called Stentrode, which accesses the brain through a vein, and the US FDA has approved a clinical trial in which ALS patients use it to operate a PC[20]. The fact that permits were granted despite the specified purpose can be called progress in terms of legislation and regulations.

On the other hand, the year was also marked by increased discussion of ethical issues, such as the early start of debate in Chile on the inclusion in the constitution of so-called neurorights, a human rights issue that may become relevant with the manipulation of brain activity[21]. (Akira Yoshimoto, Consumer Innovation Dept.)

18 https://www.cnbc.com/2021/07/30/elon-musks-neuralink-backed-by-google-ventures-peter-thiel-sam-altman.html

19 https://neuralink.com/blog/monkey-mindpong/

20 https://jp.techcrunch.com/2021/07/30/fda-clears-synchrons-brain-computer-interface-device-for-human-trials/

21 https://www.scientificamerican.com/article/the-rise-of-neurotechnology-calls-for-a-parallel-focus-on-neurorights/?fbclid=IwAR2IX_z112KweDiknic4DnEjbzInRtc9TvHaDLb3T4-CDM_BxLyxqnecx48