ACTUATOR DEVELOPMENT PROJECTS IN FY2017 IN THE SPACE EXPLORATION INNOVATION HUB CENTER

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ABSTRACT

Based on the Japanese government policy "Comprehensive Strategy on Science, Technology, and Innovation 2014", JAXA established the Space Exploration Innovation Hub Center in April 2015.

Through this Innovation Hub Center, JAXA has created a new research team for their activities.

As the actuator is the basic components of the space exploration equipment such as rover, drone, airplane, and so on, the Innovation Hub Center has started the actuator research challenge, which goal is to realize the actuator having a power density of 1 kw/kg or more as the world's best performance actuator.

This paper reports the goals and the research results of selected five actuator projects in FY2017.

1 INTRODUCTION

Expanding humanosphere and the domain of human activity through the development of space exploration will directly link to creating values for new space development application. In the next 10 to 20 years, space exploration will be mainly led by activities for exploration of the Moon and the Mars through international collaboration and competition with the involvement of various players including private companies.

Therefore, JAXA established the Space Exploration Innovation Hub Center in April 2015, which is based on the Japanese government policy "Comprehensive Strategy on Science, Technology, and Innovation 2014 -A Challenge for Creating Japan in a New Dimension- (approved by the Cabinet on June 24, 2014)".

This Innovation Hub will set up a system for new industries to participate in space exploration, and aim at achieving new technological innovation by challenging innovative space exploration technology to non-continuously expand humanosphere and the domain of human activities.

By the way, actuator technology, which "moves and manipulates things", is the technology that forms the foundation of all modern science and industry.

Actuators with excellent performance are expected from a wide range of fields such as basic science, industry, medical welfare, etc. The emergence of such actuators is expected to greatly contribute to the protection of the global environment and improvement of the standard of living, including the development of the economy.

Actuator is also the basic components of the space exploration equipment such as rover, drone, airplane, and so on. Therefore, five actuator projects are selected as the "Solution Creating Research" of the Innovation Hub Center projects.

At first, this paper introduces the establishment reason and the objective of the Space Exploration Innovation Hub Center.

Then, the research goals and the research results in FY2017 are briefly presented.

2 WHAT IS "SPACE EXPLORATION INNOVATION HUB CENTER?

2.1 Beginning

Since the Japanese government announced their policy titled "Comprehensive Strategy on Science, Technology, and Innovation 2014 - A Challenge for Creating Japan in a New Dimension - (approved by the Cabinet on June 24, 2014)," public research institutions and agencies have been expected to perform strongly and contribute to innovation. Based on this strategy, the Japan Aerospace Exploration Agency (JAXA) was re-organized in April 2015 and the Space Exploration Innovation Hub Center was established [1].

A new research team was organized for gathering knowledge and specialists from various fields and creating new research areas. The center is located on the JAXA Sagamihara Campus. As of April 2015, the center has approximately 30 staffs who have undertaken new activities, and are working in three research areas as followings:

1) exploration technology in a wide range of unexplored areas

Target: By using multiple small probes rather than a single unit, the cooperation of the distributed exploration function achieves extensive and detailed exploration of the non-prospecting area. This strategy will innovate the exploration method.

Challenges: Development of small and lightweight probes, including insect-type movers, which have self-organizing mechanisms for distributed cooperation.

Approach: Creating distributed cooperative exploration systems based on knowledge of the group intelligence and group behavior of insects and animals.

2) automatic and autonomous exploration technology

Target: Development of an automatic and autonomous exploration technology that overcomes the weaknesses of the "Earth's command-based exploration". In the future, this technology enables the automatic construction of the manned exploration bases built on the Moon.

Challenges: Innovate the space technology by making the automobile technology and construction technology smaller, lighter and space-applicable.

Approach: Based on unmanned and automated technologies that have already been realized on the ground, the technologies applicable to space (such as weight, power consumption, environment and so on) are developed. At first, the technologies will be demonstrated in the simulated field, and finally demonstrated in space.

3) In-situ resource utilization (ISRU) technology

Target: The paradigm shift from "carrying everything" to "sourcing in the field" and "reusing" allows for a more efficient transportation and sustainable exploration than ever before.

Challenges: Development of a system that enables efficient and unmanned production of necessary supplies by applying energy-saving, reuse and recycling technologies and resource refining technologies.

Approach: First, ground demonstration on the analog site, then aiming at the world's first space demonstration

2.2 Support of the JST Program

At June 11, 2015, the project "Open Innovation Hub for Expanding Humanosphere and Domain of Human Activity through Solar System Frontier Development" of the Space Exploration Hub Center was selected for the foundation of the "innovation hub construction support", an operation conducted by the Japan Science and Technology agency (JST).

After 2020, when funding is finished, the hub should be developed with its own funds.

2.3 Objective of the Innovation Hub Center

Through this innovation hub, an operation base was formed where new industries can participate for sustainable activities on planets with gravity including the Moon. More specifically, the examples of issues which should be tackled through this innovation hub are introduced, and an information exchange opportunity will be hold with companies and universities that are not necessarily related to the space field. The Space Exploration Innovative Hub Center always requests for the information (RFI) to attain innovative space probe technology to non-continuously expand humanosphere and the domain of human activities.

Based on the above information gathering and discussion, more concrete research issues are set up, then a research team for a specific activity will be established.

Technology that will be attained through this innovation hub will not only be utilized for future space development and utilization but also be targeted to be valuable for businesses of participating companies as feedback. Therefore, JAXA is organizing a new system by reviewing our conventional management method of intellectual property and personnel regulation so that new partners can easily join us.

3 RESEARCH AND DEVELOPMENT OF NEXT-GENERATION ACTUATORS

3.1 Background

Actuator is important as fundamental technology of the space exploration equipment such as planetary exploration base construction equipment, resource exploration equipment, and power assist of astronauts. It is one of the most important issue to make a high output, high efficiency, and high reliability actuators.

Japan's motor performance is the world's highest level. Small motors account for over half of world demand. On the other hand, in Europe, they are aiming at reversing the market share by formulating standards for high efficiency motors called IE 4, which should be against global warming. Whether to develop the motor clearing the IE 4 standard will affect the fate of the Japanese motor industry.

The power/mass ratio of the motor has greatly improved in the last 30 years and it is reaching a level that can be applied to the high-power mechanisms such as automobiles and construction machines. Moreover, the airplane driven by electric motors is proposed one after another from NASA and other industries.

Figure 1 shows the power/mass ratio of the commercialized AC and DC motors. The power/mass ratio of the motor has been improved more than 10 times in recent 30 years.

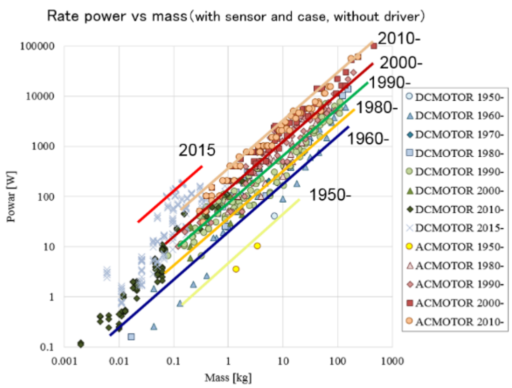

Figure 1. Power/mass ratio of the commercialized motors.

Especially, the power/mass ratio has been improved drastically from FY2010 to FY2015. This means that innovation is happening even in motor technology.

Under such circumstances, "Research and development of next-generation actuators" was launched as one of the research themes of the research area of "exploration technology in a wide range of unexplored areas".

This project aims to develop actuators to be mounted on planetary exploration equipment, but at the same time aims to commercialize the research results.

3.2 How to Set the Goals of the Project

In JAXA, we have developed an environmental robust motor unit that can withstand the environment on the surface of the Moon and planet, consisting of DC brushless motor, gear (planet gear and harmonic drive), angle sensor, bearing and case as shown in Figure 2.

The motor unit clear the following environmental testing [2]:

Operating temperature: -130 to + 220 degrees Celsius at degree of vacuum 1×10^{-4} Pa.

Non-operating temperature: -200 to + 220 degrees Celsius at degree of vacuum 1×10^{-4} Pa.

Machine vibration: H-2A launch environment equivalent (Sin, random, impact)

Radiation tolerance: (Angle sensor only) TID 20 M rad or more

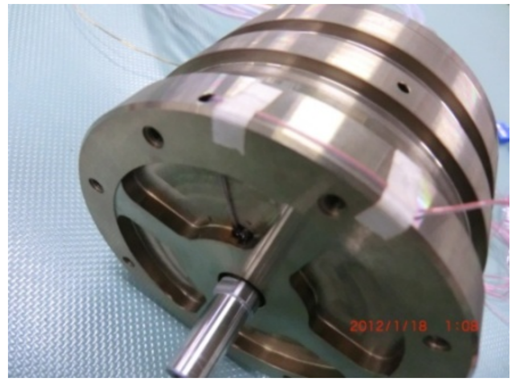

Figure 2. The DC brushless motor unit developed in JAXA.

The power density of the developed motor unit achieved 300 w/kg, but it is not enough when considering the payload for Mars' airplane or drone.

Therefore, the Innovation Hub Center requested for a project proposal (RFP) to realize an actuator having a power density of 1 kw/kg or more as the world's best performance actuator. Besides the electromagnetic motor, the scope of the project includes actuators with driving principles other than electromagnetic motors, and elemental technologies such as sensors.

Through the RFP process, the following five projects have been selected.

1) Development of the small actuator with the best power density in the world

2) Development of super small high accuracy absolute angular sensor modulated wave resolver for next generation actuator

3) Development of Small and High-Torque Actuator for Medical and Welfare field

4) Development of innovative soft actuator system and its application technology

5) Study of water/dust proof multi-stator electromagnetic motor

3.3 The Goals and the Research Results in FY2017 of Selected Five Actuator Projects

In this section, the goals and the research results in FY2017 of selected five actuator projects are described.

3.3.1 Development of the Small Actuator With the Best Power Density in the World

Project leader is Fumihiko Shinoda (ShinMaywa Industries, Ltd.) with project members from OITA UNIVERSITY, Ibaraki University, Shizuoka University and NIPPON BUNRI UNIVERSITY.

In the last 30 years, the improvement of the torque/mass ratio of the motor is largely due to the improvement of the maximum energy product of the permanent magnet as shown in Figure 3.

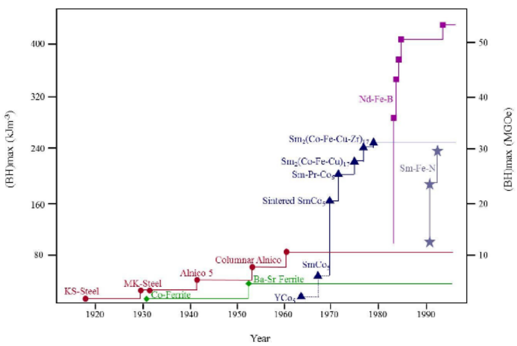

Figure 3. The development of permanent magnets in the 20th Century. BHmax has improved exponentially, doubling every 12 years [3].

In 1982 Mr. Masato Sagawa invented a neodymium magnet and the torque/mass ratio of the permanent magnet motor improved greatly. After that, the maximum energy product of the neodymium magnet reached 476 kJ/m^3 (60 MGOe) from 119kJ/m^3 (15 MGOe) at the time of invention due to the improvement of the material. Now, it is nearing the theoretical limit. Unless a new material is developed, further improvement of the permanent magnet's maximum energy product is not expected, and the improvement of the torque/mass ratio of the motor is not expected either.

To overcome this situation, several projects and organizations are established. The Elements Strategy Initiative Center for Magnetic Materials (ESICMM) [4] aims at laboratory-scale synthesis of mass-producible high-performance permanent magnets free of critical scarce elements for the next generation. "Construct guidelines for creation of innovative next-generation high-performance magnets" in JST Collaborative Research Based on Industrial Demand Program [5] aims at establishing guidelines for innovative next generation high performance magnets. "Development of magnetic material technology for high efficiency motors for next generation automobiles" in NEDO Project [6] aims at developing a high efficiency high power motor for automobiles.

The goal of this project is different from the above projects. This project aims to improve the performance of the motor by analyzing the loss of the motor, and designing to minimize each loss as much as possible. High efficiency motors generate less heat, making heat dissipation easier in outer space. In addition, it is possible to reduce the size of the power source.

Using the power density ((output power)/mass) instead of the torque/mass ratio as the performance index of the motor, realize the world's highest performance motor with power density. Specifically, the target of this project is to develop a very small, high efficiency motor with a mass of 25 g and a rated output of 50 w. The output power is the product of output torque and rotational speed. As the output torque is limited, high rate rotational speed is necessary for high power output. Therefore, the high rate rotational speed of the developed motor is set over 1,048rad/s (10,000rpm).

Motor losses are classified as iron loss, copper loss, mechanical loss, and loss of control equipment as shown in Figure 4.

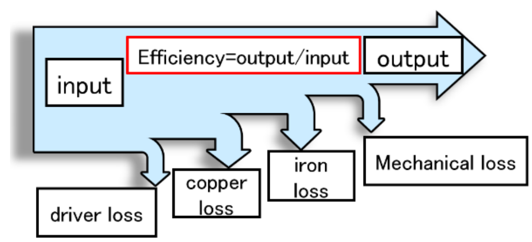

Figure 4: Classification of the motor loss.

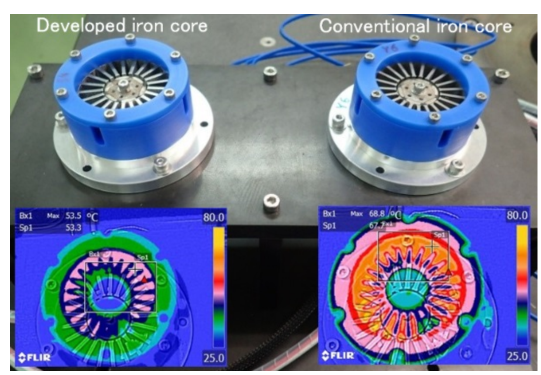

Figure 5. Heat characteristics of the commercialized motor of ShinMaywa (right) and a stator core replaced motor (left).

Usually, the loss in Figure 4 increases under high speed rotation.

Therefore, this project aims to reduce above loss at high frequency region.

In FY2016, for reducing iron loss, a stator core of a conventional motor (right in Figure 5) is replaced to a core made of new material (left in Figure 5) and measures the thermal gradient. From the thermal gradient data, the heat loss of the motor decreases about 45% at 1,048rad/s[7].

In FY2017, first prototype motor shown in Figure 6 is developed. The mass of the motor is 41g, and the rated output power is 50w at 838rad/s (8,000rpm). The first prototype motor clears the power/mass ratio of 1kw/kg.

The first prototype motor uses the new material optimized for motor core to reduce iron loss furthermore by decreasing the hysteresis loss.

For designing the final prototype motor, which mass is 25g and the rated output power aims at 50w, following technological research and development is ongoing:

1) Optimize the shape of the stator core for less iron loss.

2) Develop new coil winding method to reduce the copper loss.

3) Develop new support system for high-speed motor to reduce the mechanical loss.

4) Develop high efficiency small motor driver for high-speed motor to reduce the loss of controller.

Figure 6. Rotor and the stator of the first prototype motor.

3.3.2 Development of Super Small High Accuracy Absolute Angular Sensor Modulated Wave Resolver for Next Generation Actuator

Project leader is Tadao Chino (EXTCOM Inc.).

The EXTCOM Inc. have already developed a small absolute angular sensor by modulated wave resolver shown in Figure.7. The size of the resolver is 25mm square and the thickness is only 6.3mm. The resolution is 1/8192.

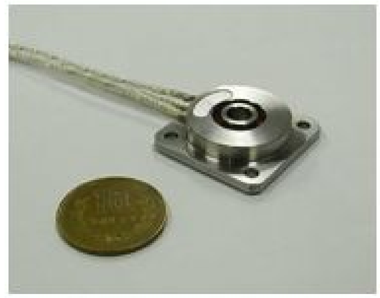

Figure 7. Modulated wave resolver developed in FY2012.

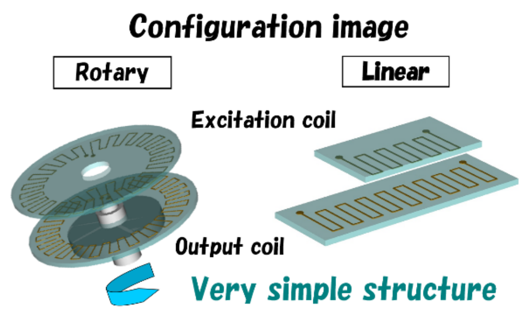

Figure 8: Configuration images of the resolvers.

The principle of the modulated wave resolver is very simple. Just place the coils on two sheets in face. The output signal from the output coil changes by the absolute position of the excitation coil. Therefore, it is very easy to make small, high-resolution absolute position sensor. The resolver is very robust in space environment. The operating temperature is from -100 Celsius to 220 Celsius.

The goal of this project is to develop several very small resolvers with higher resolution. The main target is to develop the 20mm square and 19bit (1/524288) resolution resolver.

In FY 2017, following technological research and development is ongoing.

1) Develop thin flexible lead wire.

Figure 9 shows the super small resolver with thin flexible lead wire. Six wires are put together in one thin flexible lead wire. The diameter of the resolver is 6mm and the height is 4.2mm.

2) Develop small data processor.

According to the processing data bits, the size of the developed data processor is from 20mm by 25mm to 45mm by 55mm.

Figure 9: Super small resolver with thin flexible lead wire.

Figure 10: High resolution resolver.

3) Develop high resolution small resolver

A 20bit (1/1,000,000) absolute resolver shown in Figure 10 is developed. The base is 20mm square and the height is 7.5mm.

This resolver clears the final goal of the resolution.

In FY2018, development of the motor integrated type resolver is scheduled.

3.3.3 Development of Small and High-Torque Actuator for Medical and Welfare Field

Project leader is Toru Shikayama (YASKAWA Electric Corporation).

While ShinMaywa group is aiming to develop a high-power density motor, this group is aiming to develop a high-torque motor.

As the developed motor is expected to be applied to the robot arm of the Mars explorer and the Power assisted space suit used for the activity in gravity planets such as Moon and Mars, YASKAWA Electric Corporation is aiming to use the developed motor for the power assist suit.

Power assist suit is classified into two groups: one assists the joint power partially for rehabilitation and the other generate the full joint power for assist hard-worker and/or paralysis person.

This project is aiming to develop the full power assist equipment indicated by the arrows in Figure 11. YASKAWA Electric Corporation has commercialized power assist equipment, but the torque/weight ratio is around 50Nm/kg. It is not enough for the full power assist. For example, full power assist of knee joint needs over 100Nm. Then, the weight of the full power assist equipment nowadays is over 2kg, and it is impossible to put several equipment on the body.

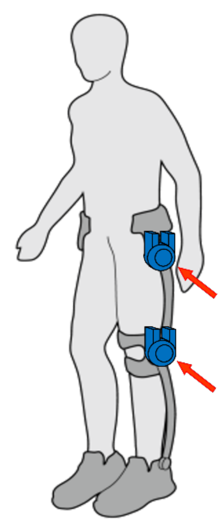

Figure 11: Full support system.

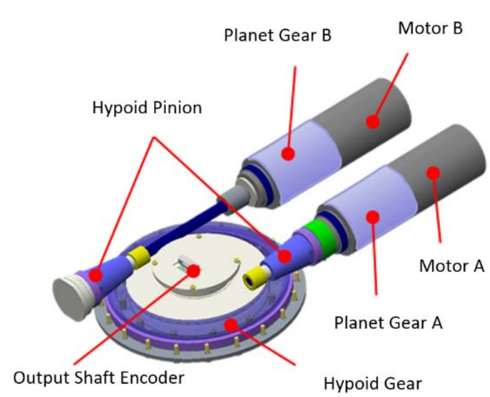

Figure 12: Basic structure of the power assist unit.

Therefore, the goal of this project is to develop high torque density full power assist equipment. The target torque/weight ratio is 110Nm/kg.

The basic structure of the developed power assist unit is shown in Figure 12.

The unit has a hypoid gear driven by two small motor units. Each motor has planet gear. This structure enables to make the power assist unit very thin and high torque. The thinner device allows the wearer to sit in a wheelchair.

For develop the equipment, following technological research and developments are necessary.

1) Develop a small, high efficiency electric motor.

Original high efficiency small motor is developed.

2) Develop a high efficiency, light weight gear system.

A steel and resin hybrid hypoid gear is made by using 3D printer.

3) Develop a twin-drive, less backlash control system.

A new control algorithm is developed.

In FY2016, YASKAWA Electric Corporation has developed full power assist equipment, which torque/weight ratio is 73Nm/kg (1.5kg for 110Nm).

In FY 2017, YASKAWA Electric Corporation has improved the equipment elements and has developed full power assist equipment, which torque/weight ratio is 110Nm/kg (1.0kg for 110Nm).

3.3.4 Development of Innovative Soft Actuator System and Its Application Technology

Project leaders are Takashi Terajima (MEIJI RUBBER & CHEMICAL CO., LTD) and Taro Nakamura (Chuo University).

The goal of this project is to develop an air-pressure driven rubber actuator with high force/pressure, which is triple of the conventional McKibben-type rubber actuator.

This group has already developed a rubber actuator named “Straight fibers type soft actuator” [8].

When several hard-rings are set on the rubber tube with carbon fiber layer, the rubber tube shrinks depending on the air pressure as shown in Figure 13.

In FY2016, developed soft actuator shown in Figure 14 achieved the goal characteristics and the project has finished.

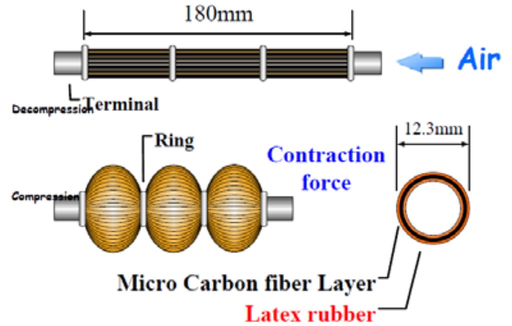

Figure 13: Structure and the driving principle of the straight fibers type soft actuator.

Figure 14: Developed soft actuator.

3.3.5 Study of Water/Dust Proof Multi-Stator Electromagnetic Motor

Project leader is Yuichi Narasaki (Namiki Precision Jewel Co., LTD)

The water/dust proof performance is very important not only for the space exploration equipment but also on-earth equipment such as the drone. On the other hand, the heat release is very difficult for the water/dust proof actuator by the sealing equipment.

Therefore, the goal of this project is to develop a water/dust proof high power density motor.

Figure 15: Final prototype water and dust proof actuator.

The water/dust proof aims to clear the IP56 standard. The output power aims at over 1kw at the peak for the 0.4kg mass.

For developing small, high power motor, this project adopts the multi stator structure.

In FY2016, first prototype motor was developed. The first prototype motor clears IP56 standard. But the output power of the motor is only 185w and the mass is 460g.

In FY2017, final prototype motor was developed to clear the final goals of this project. The final prototype motor also clear IP56 standard. The output power of the final prototype motor is 1.024kw and the mass is 415g.

The mass of the final prototype motor exceeds the target mass by 15g, and it can be reduced by sharpening the body.

The final prototype motor almost achieved the goal characteristics and the project has finished.

4 CONCLUSIONS

The establishment and the objective of the Space Exploration Innovation Hub Center is introduced.

The research goals and the research results of the project area “Research and Development of Next-generation Actuators” in FY2017 are presented.

Several new challenging results are found in the projects.

JAXA will improve the research results for applying space application. And the corporation aims at the commercialization of the developed technology.

The Space Exploration Innovation Hub Center requests for the information (RFI) at any time. We are looking forward to the information of the innovative study.

The Space Exploration Innovation Hub Center requested for new project proposals (RFP) based on the RFI on a regular basis that will accelerate the project to achieve the target and make use of the research results.

ACKNOWLEDGEMENTS

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