TUT Research
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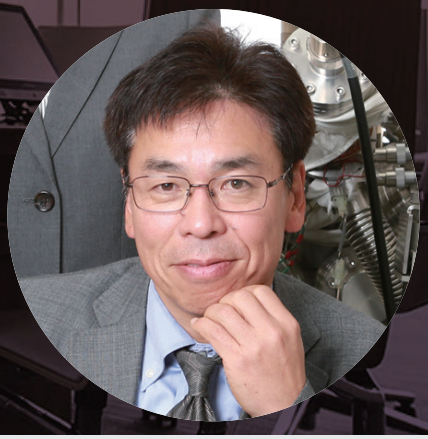
FEATURE STORY

Charmed by Plasma

Developing carbon film with the properties of a diamond



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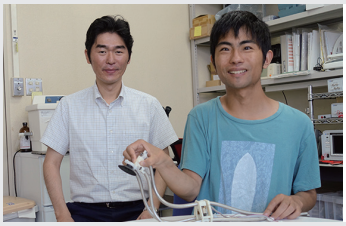
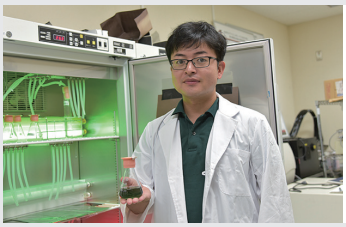
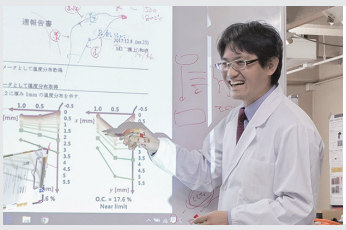
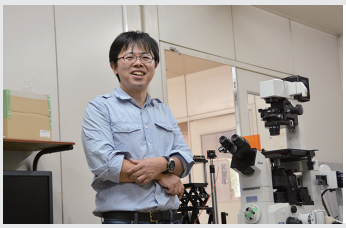
Research Highlights







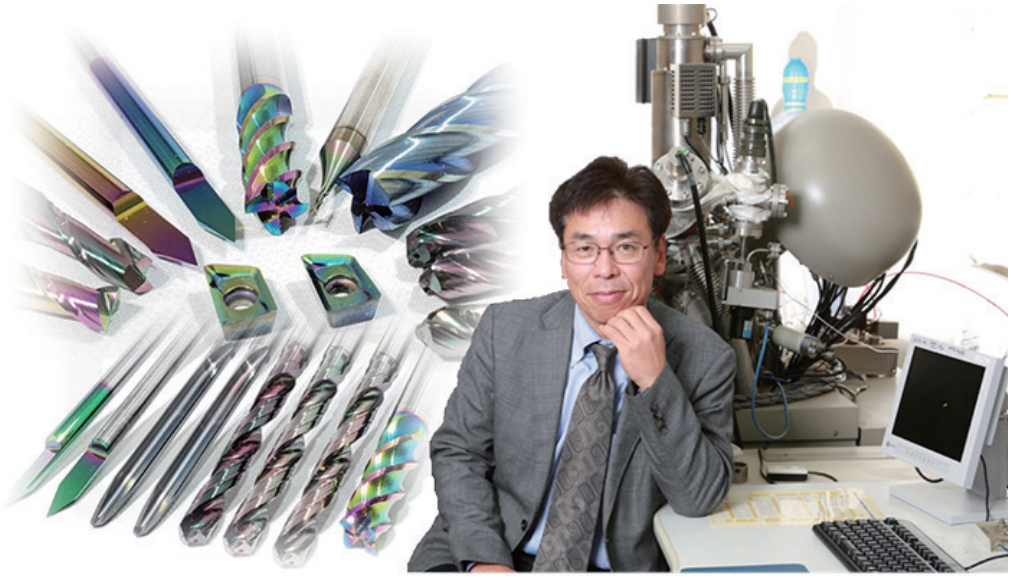


Pick Up

Charmed by Plasma

Developing carbon film with the properties of a diamond

Hirofumi Takikawa



At present, Professor Hirofumi Takikawa has his eyes set on a carbon thin film that has properties similar to that of a diamond (commonly referred to as a "diamond-like carbon (DLC) film") and on developing a device that will synthesize this material. The DLC developed by Professor Takikawa does not contain hydrogen and is a hard and smooth film. Because of the absence of hydrogen, the film does not chemically react with metal or glass and exhibits superior characteristics for a DLC. Industry-academia collaboration has already seen the application of DLC for various purposes, such as a coating film for cutting tools and lens molds. Further application of this product is expected.

Interview and report by Madoka Tainaka

Creating a Hydrogen-free DLC Using Vacuum Arc Deposition

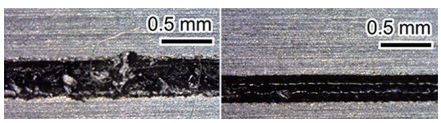
Diamond-like carbon (DLC) is a hard, amorphous carbon with desirable properties such as low friction and low wear. It is now gaining ground as a coating film for cutting tools and molds in place of hard nitride films.

DLCs can be divided into two categories – those which are purely composed of carbon and those which contain additional elements. The properties of each type of DLC depend on its composition and the way it was synthesized. DLC development researcher Professor Hirofumi Takikawa outlined the reasons for this as follows:

"What's really important is whether a DLC contains hydrogen. Any DLC that doesn't contain hydrogen will display superior hardness, density, heat resistance and refractive index. However, current popular methods of synthesizing DLC films, such as plasma CVD and ion vapor deposition use hydrocarbon gas or hydrocarbon vapor, which means that the resulting DLC will always contain hydrogen.

In order to develop a hydrogen-free DLC film, researchers have developed methods that use solid carbon (graphite), which does not contain hydrogen, as a raw material. There are four synthesizing methods that use graphite as a vapor source: vacuum deposition, electron beam deposition, sputtering deposition and vacuum arc deposition. Ions are required to make DLC films, which limits us to sputtering deposition or vacuum arc deposition, although sputtering deposition has low ion energy which results in a softer DLC. This is why I use vacuum arc deposition for synthesizing hydrogen-free DLC films."

Vacuum arc deposition is a method that uses arc discharge, that is, plasma (ionized gas), in a vacuum. In this method, a cathode spot is formed on a cathode solid surface, from which the cathode material (graphite) rapidly evaporates. At the same time, a large number of thermions are emitted and the evaporated graphite is ionized. When this occurs, a high ion energy is obtained and a super DLC (tetrahedral amorphous carbon (ta-C)), which has properties like a diamond, can be synthesized.



Photographs of grooves carved with cutters into an aluminum alloy plaque.
Left: Uncoated Cutter (with burr), Right: Super DLC-coated Cutter (no burr)

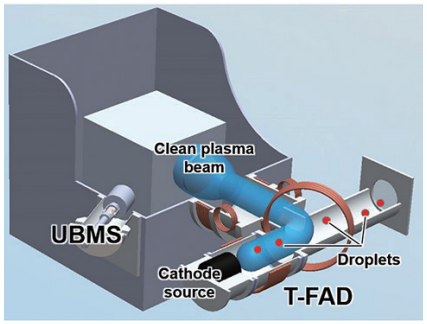
Professor Takikawa says that, "A cutting tool coated with a super DLC that has been synthesized using this method does not chemically react with metal or glass during cutting because it does not contain hydrogen.

This means that it can make clean cuts without leaving a burr. Also, it won't cause an unnecessary reaction and stick to materials when used in molds, which makes it suited for manufacturing high-precision camera lenses that need to be pressed at a high temperature, for instance.

Using a pure diamond as a cutting tool would obviously result in clean cuts, but diamonds are too expensive to be used for such applications. Diamonds are also crystals, which means that it's impossible to form an even thin film. The properties of an amorphous (non-crystalline) DLC makes it able to produce an even and smooth film."

T-shaped Device to Prevent Adherence of Microparticles

Vacuum arc deposition is required to make hydrogen-free DLC, but this method has its drawbacks. When microparticles called droplets are emitted from the cathode spot, these droplets adhere to the film and cause the film to lose uniformity or peel off. Films in such conditions cannot be used in cutting tools for micromachining and molds for camera lenses that require precision. Torus-shaped (that is, donut-like 3D-shaped) filters have been developed to prevent droplets from adhering to the film, but these filters cannot remove all droplets and require much effort to maintain.



Structure of T-shaped Filtered Arc Deposition (T-FAD),Unbalanced Magnetron Sputtering(UBMS)

"Facing this problem, we developed a device that has a T-shaped filter. The main advantage of this device is in transferring vacuum arc plasma generated from the cathode to a film-forming chamber with a magnetic field generated using an electromagnet and an electric field applied to the filter duct. Because the filter has a T-shape, the plasma bends 90° while the droplets proceed in a straight line. In other words, the plasma and the droplets can be separated from each other, which results in a clean film. The duct also has a simple straight shape, making it easy to maintain."

Using carbon which is a burnable substance enables the film that covers the surface of the tool or mold to be separated and removed in the gaseous phase of oxygen plasma, making maintenance simple. That is, the DLC film can be easily removed, meaning that expensive tools and molds can be reused even if the thin film coating them is damaged.

Expanding Scope of Research to Meet Corporate and Social Needs

Development of this device first began decades ago as a joint research project with Itoh Optical Industrial Co., Ltd., a local manufacturer of lenses.

Professor Takikawa recalls, "Itoh Optical knew that using ions to form a film with vapor deposition resulted in a harder film. They came to us for technical consultancy on what was needed in order to effectively apply this knowledge. After some time, we developed a process of making high-precision lenses in a mold instead of polishing the lenses by hand, as was previously done. That was the first application of the results of our joint research."

Following this, Professor Takikawa and his team developed the device in collaboration with a manufacturer, was granted a patent and made many improvements to the device and manufacturing process. Currently, Professor Takikawa is looking into how to create laminated films by adding a sputtering vapor source to the device.

"By laminating many films together, we can add the functions of wear-resistance and toughness. We are now applying this technology to not just cutting tools and molds but also many other products in response to requests from various companies."

Professor Takikawa has also been working on a range of other projects. For instance, he has been developing self-supporting DLC films with no base, which are expected to be used in filters and laser-driven heavy ion targets for treating cancer. He has also developed a nano-powder called a "carbon nano-balloon," which is a type of nanocarbon used for electrode materials in electric vehicle capacitors and which increases electric capacitance. For all such endeavors, Professor Takikawa has searched for practical ways of applying the results of his research through joint research with companies.

While seemingly unrelated to the developments described above, Professor Takikawa has also branched out into research on spectroscopic pyranometers for agricultural use and has developed a method of more accurately obtaining information on solar irradiance. This method involves producing sensors at low cost with a simple system, using many of those sensors to detect abnormal values and cancelling out the influence of shadows. Professor Takikawa's pyranometer is already being sold by a manufacturer under a licensing agreement. The prolific inventor is also working on a device that can disperse light every 100 nm and aims to further develop his products in order to assess harvesting times in greenhouses and to achieve more efficient operation at plant factories.

"Technology is made to be used, so I want to keep monitoring the market and applying my findings in the fields that need them. Pyranometers and carbon film research may seem completely unrelated to each other, but heat and light energy emitted by the sun, which we need to live, are the result of a nuclear fusion reaction of hydrogen plasma. In other words, plasma is the source of all living things and materials. That is why our research lab's name bears the words 'Plasma Energy System.' We will continue to research plasma in ways that benefit society."

プラズマに魅せられて

ダイヤモンドの性能を備えたカーボン薄膜を開発

現在、滝川浩史教授が注力するのが、「ダイヤモンドライクカーボン（DLC：Diamond-Like Carbon）」と呼ばれるダイヤモンドのような性質を備えたカーボンの薄膜と、その合成装置の開発だ。滝川教授が開発するDLCの特長は、水素を含まず、硬く、滑らかなこと。水素を含まないことから金属やガラスと化学反応を起こすことがなく、DLCの中でもとりわけ優れた特性を発揮する。すでに産学連携により、切削工具やレンズの金型などへのコーティング膜として多方面で実用化されており、さらなる応用へ期待が高まる。

真空アーク蒸着により、水素フリーのDLC膜をつくる

硬質なアモルファスカーボンであるダイヤモンドライクカーボン（DLC）は、低摩擦・低磨耗といった優れた特性を持つことから、窒化物系の硬質な薄膜に代わって、現在、掘削工具や金型のコーティング膜として広く活用され始めている。

ただ、一口にDLCと言っても、カーボンのみからなるものと、他の元素を含むものに分かれ、その特性は組成や合成法に依存する。その理由を、DLCの開発を手がける滝川浩史教授は次のように説明する。

「とくに重要なのが水素含むかどうかです。硬さ、密度、耐熱性、屈折率、いずれにおいても、水素を含まないDLCのほうが優れているのです。しかし、現在のDLC膜合成法の主流であるプラズマCVD法やイオン化蒸着法では、炭素水素ガスや炭化水素蒸気を用いるため、必ず水素を含んでしまいます。

そこで、水素フリーのDLC膜を開発するために、水素を含まない固体カーボン（黒鉛）を原料に用いる方法が開発されています。黒鉛を蒸発源として用いる合成法には、真空蒸着、電子ビーム蒸着、スパッタリング蒸着、真空アーク蒸着の4つがありますが、DLC膜の形成にはイオンが必要なことから、ここで使えるのはスパッタリング蒸着と真空アーク蒸着に限られます。しかし、スパッタリング蒸着ではイオンエネルギーが低く、硬いDLCができません。そうしたことから、水素フリーのDLC膜の合成に、私は真空アーク蒸着を採用しています」

真空アーク蒸着とは、真空中でのアーク放電、すなわちプラズマ（電離した気体）を利用する方法だ。この方法を用いると、陰極固体表面に陰極点が形成され、そこから陰極材料（黒鉛）が激しく蒸発し、同時に大量の熱電子が放出されて、蒸発した黒鉛をイオン化する。その際に高エネルギーのイオンエネルギーが得られ、ダイヤモンドのような特性を持つスーパーDLC（テトラヘドラルアモルファスカーボン：ta-C）を合成することができるという。

「この方法で合成されたスーパーDLCを施した切削工具は、水素を含まないことから切削の際に金属やガラスと化学反応を起こさず、バリの出ないきれいな断面が得られます。また、金型に用いても不要な反応で材料にくっつかないため、高温でプレスする必要のある高精細なカメラレンズなどの製造に適しています。

もちろん、ピュアなダイヤモンドを切削工具に用いれば、きれいに切ることはできますが、高価ですから気軽には使えません。しかも、ダイヤモンドは結晶なので均一の薄膜にすることができません。アモルファス（非晶質）のDLCだからこそ、均一かつ滑らかな膜として加工できるのです」と滝川教授は言う。

T字形状の装置で微粒子の付着を防ぐ

水素フリーのDLCの合成に欠かせない真空アーク蒸着法だが、じつは欠点もある。陰極点からドロップレットと呼ばれる微粒子が放出され、膜に付着して、均一性を損なったり、剥離したりしてしまうのだ。そのままでは、微細加工のための切削工具や精密さが求められるカメラレンズの金型に使うことができない。そのため、ドロップレットを膜に付着させないよう、トーラス状（ドーナツのような立体）のフィルタなどが開発されているが、完全な除去は難しいうえ、メンテナンスにも手間がかかる。

「そこで私たちが開発したのが、T字形状のフィルタを持つ装置です。この装置のポイントは、陰極から発生した真空アークプラズマを、電磁石を用いて形成した磁界とフィルタダクトに印加した電界により成膜室へと輸送することです。その際、フィルタの形状がT字型なので、プラズマは90°屈曲して進むのに対して、ドロップレットはそのまま直進します。つまりプラズマとドロップレットを分離できることから、クリーンな膜を作ることができる。ダクトの形状がストレートでシンプルなため、メンテナンスも楽です」

さらにメンテナンスに関しては、材料がカーボンなので燃焼できるため、工具や金型の表面に覆う膜を酸素プラズマの気相中で分解・除去できる点も優れている。つまり、DLC膜を簡単に剥離できるため、たとえ薄膜が傷ついても、高価な工具や金型をリユースができるというわけだ。

企業や社会の要請に応えて研究の幅を広げる

実はこの装置開発は、十数年前に地元のレンズメーカーである伊藤工学工業株式会社と始めた共同研究に端を発する。

「蒸着による膜の形成にイオンを使うと、硬質なものができるという知見を先方が持っていて、それを積極的に使うにはどうすればいいか、という技術相談が発端でした。しばらくして、それまで手で磨いて作っていた高精細レンズを金型でつくるプロセスが開発されたことで、初めて共同研究の成果が生きることになったのです」と滝川教授。

その後、メーカーと共同で装置を開発し、特許を取得して、装置やプロセスの改良を重ねてきた。また最近は、この装置にスパッタリング蒸発源をつけて、積層膜の研究もしている。

「膜を多層にすることで、耐磨耗性や靭性といった機能を付加することができます。切削工具や金型だけでなく、さまざまな企業からのご提案を受けて、応用が広がっています」

滝川教授はそのほかにも、レーザー駆動重粒子線がん治療用ターゲットやろ過フィルタへの応用が期待される下地を持たない自立膜DLCの開発や、電気自動車のキャパシタの電極材に用いられるナノカーボンの一種で、電気容量を向上させるナノ粉体「カーボンナノバルーン」の開発など、いずれも企業との共同研究により実用化の道を探ってきた。

さらには、まったく畑違いにも思えるが、農業用の分光型日射計の開発にも手を広げる。簡易なシステムで安価にセンサをつくり、複数台を用いて異常値を検出、影による影響をキャンセルして、より正確な日射量を得る方法を開発した。この日射計はすでに、ライセンス契約をしたメーカーから販売も始めている。さらに、100nmごとに分光できるデバイスも開発中。ハウスでの収穫時期の見極めや、植物工場の効率的な稼働を想定して、さらなる展開を図っているところだ。

「やはり技術は使われてこそ意味がある。だからこそ、企業や社会の状況を見ながら、需要のある分野で自分たちの知見を生かしていきたいと考えています。

ちなみに、日射計はカーボン膜の研究とはまったく関係ないと思えるかもしれませんが、そもそも地球の生命の生存に欠かせない太陽が発する熱・光エネルギーは、水素プラズマの核融合反応によるものです。すなわちプラズマは生命や物質の源といってもいい。だからこそ、研究室に『プラズマエネルギーシステム』という言葉を冠しているのです。これからも、プラズマ研究を深めて、いっそう社会に貢献していきたいですね」

（取材・文＝田井中麻都佳）

取材後記

滝川教授がプラズマ研究と出合ったのは、豊橋技術科学大学の修士課程のとき、所属していた研究室で電力ケーブルの事故時に発生するアーク放電の研究に携わったのが最初だった。以来、プラズマの面白さに魅せられてきた。

「昔から、雷の多い地域でキノコがよく育つという言い伝えがありますが、迷信というわけでなく、現在では、プラズマ照射で植物の成長を促進させる、傷口を塞ぐなど、食品や医療分野などに役立てる研究が進んでいます。プラズマはまだまだ奥が深く、多様な活用法があるはず。そこに切り込んでいきたいですね」と滝川教授。

一方で最近は、先の日射計を使って、太陽光発電の運転予測技術の開発も手がける。センサで雲の動きを捉え、リアルタイムで発電量を予測しながら、太陽光発電の最適な稼働に役立てる構想だ。滝川教授の研究は、まださらに広がりを見せることになりそうだ。

Researcher Profile

Hirofumi Takikawa

Dr. Hirofumi Takikawa received his M.S. and PhD degree in engineering in 1986 and 1992 respectively from Toyohashi University of Technology, Japan. Since he started his career at Toyohashi University of Technology, had been involved in arc plasma applications, cathodic arc deposition, and plasma ion process. He is currently a professor at the Department of Electrical and Electronic Information Engineering, Toyohashi University of Technology

Reporter Profile

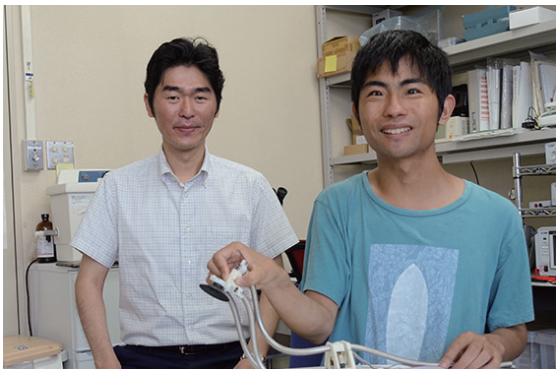
Madoka Tainaka is a freelance editor, writer and interpreter. She graduated in Law from Chuo University, Japan. She served as a chief editor of "Nature Interface" magazine, a committee for the promotion of Information and Science Technology at MEXT (Ministry of Education, Culture, Sports, Science and Technology).

A wall-climbing robot – inspired by the soft body of a leech

180 degree rotation from one side of the wall to the other

by Tomoaki Mashimo

A research team led by Associate Professor Tomoaki Mashimo of the Department of Mechanical Engineering at Toyohashi University of Technology, in collaboration with Dr. Fumiya Iida, Reader in Robotics at the department of Engineering at the University of Cambridge, has successfully developed a leech-shaped robot, "LEeCH" (Longitudinally Extensible Continuum-robot inspired by Hirudinea), which can climb vertical wall. LEeCH is capable of elongating and bending its body without any constraints; just like a leech. Thanks to its flexible body structure and the suction cups, the robot has successfully climbed a vertical wall and even reached the other side of the wall. The study was published in Soft Robotics, an American scientific journal, on March 27, 2019.

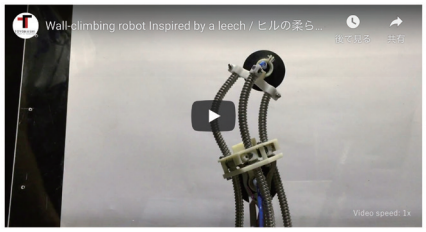


Tomoaki Mashimo (left) with Ph.D candidate, Ayato Kanada

Wall climbing robots have a wide range of potential applications, including building inspections and maintenance, and search and rescue duties at disaster sites. For robots, climbing straight up vertical walls is a fairly easy goal to accomplish. In the real world however, the robot may have to navigate over obstacles on the wall, such as steps, and transition to walls with different facings. Even if it can reach the top, the robot then faces the most challenging task, which is to traverse the summit over to the other side.

The research team has developed a robot inspired by land leeches, which are excellent climbers in nature. The land leeches, usually found in forests or mountains, can move around complex terrain and walls using two suction cups on each end of their soft extensible bodies. Their bodies are so light and soft that they are relatively shock resistant should they fall from height.

The team designed a new motion mechanism using the tubular structure of a shower hose to mimic the useful qualities of leeches, namely, to be lightweight, flexible and extendable. The flexible tube with a metal plate with an S shaped profile spirally wound is the same kind as found in household use. A gear engages with the helical groove on the surface of the tube. The flexible tube moves back and forth by rotational motion. The robot has a body composed of three flexible tubes that are connected in parallel. The body can bend or elongate by controlling the length of each flexible tube fed by the gear.

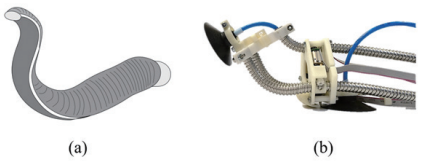


Movie of the wall-climbing robot experiment

The robot successfully achieved upward/downward climbing and horizontal transition on a vertical wall. By combining these two transitions, the robot is capable of moving freely on a two-dimensional wall surface. The robot's flexible body, with large deformation, enabled it to transition from one side of a vertical wall to the other side. Achieving this level of freedom of movement for a soft and flexible robot represents a world first.

The Ph.D candidate Ayato Kanada, who is in charge of the development and the lead author of the study, says, "I came up with the idea in the bathroom of my house. The shower hose went wild as if it was alive when I inadvertently turned on the faucet at maximum. Then an idea occurred to me that if I could manipulate a hose, I might be able to make a robot which mimics the dynamic movement of a living creature."

Making the most of the hollow structure of the shower hose, the team is considering the possibility of changing the stiffness of the tube by pouring fluid into the cavity. Robots with this kind of flexible body structure are not only highly adaptable to their environment, but also highly secure against collision. As such, they show promise in terms of their potential applications to labor in proximity to humans.



Schematic of proposed climbing robot. (a) Real leech. (b) LEeCH (Longitudinally Extensible Continuum-robot inspired by Hirudinea).

This work was supported by the Grant-in-Aid for JSPS Research Fellow (No. 17J04776), the United Kingdom's Engineering and Physical Science Research Council (EPSRC) DTP under Award 1476475 and RG92738, and Mathworks Ltd RG90950 378. Ayato Kanada, the first author, was supported by the Program for Leading Graduate Schools conducted by Japan Society for the Promotion of Science of the Ministry of Education, Culture, Sports, Science and Technology.

Reference

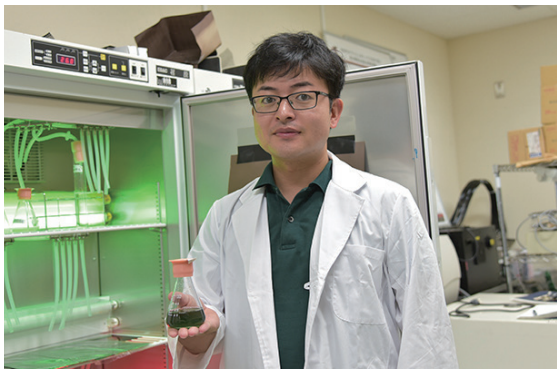
Ayato Kanada, Fabio Giardina, Toby Howison, Tomoaki Mashimo, Fumiya Iida, "Reachability Improvement of a Climbing Robot based on Large Deformations induced by Tri-Tube Soft Actuators," Soft Robotics.

https://doi.org/10.1089/soro.2018.0115

Discovery of the Photosensor for Yellow-Green Light-Driven Photosynthesis in Cyanobacteria

By Yu Hirose

Cyanobacteria are a type of bacteria that performs photosynthesis, utilizing a photosensor to maximize their light-harvesting capacity under different light environments. A joint research team lead by Toyohashi University of Technology, in cooperation with the University of Tokyo and the National Institute for Physiological Science, has found a new photosensor that regulates yellow-green light-harvesting antenna in cyanobacteria. Further analysis of the cyanobacterial genomes revealed that this photosensor emerged about 2.1 billion years ago or more and evolved through genetic exchange between cyanobacteria.



Photosynthesis is a reaction that converts light energy into chemical energy. It is a fundamental reaction that supports all organisms living on the earth. Cyanobacteria are prokaryotes that perform oxygenic photosynthesis and are found in all kinds of environments throughout the world. Cyanobacteria have three types of major antenna proteins for harvesting lights: phycocyanin (PC) for absorbing red light, phycoerythrin (PE) for absorbing green light, and phycoerythrocyanin (PEC) for absorbing yellow-green light. To date, it has been known that the amount of PC and PE are regulated by a photosensor of the phytochrome-class, but no research has been reported on the regulation of PEC.

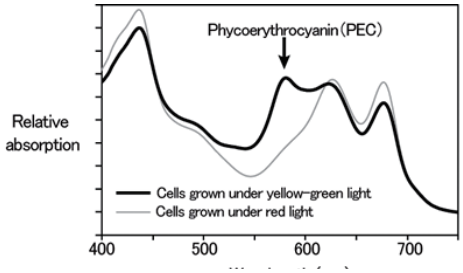


Fig.1 Absorption spectra of cyanobacteria cells cultured under yellow-green light or under red light. The increase in the amount of PEC was only seen in the cells cultured in yellow-green light.

Assistant Professor Yu Hirose at the Department of Applied Chemistry and Life Sciences, Toyohashi University of Technology, in a joint research project with the University of Tokyo and the National Institute for Physiological Science, discovered a new photosensor regulating the amount of PEC. By searching through the genome database, the research team identified several cyanobacteria strains that harbors both PEC and the photosensor genes. Furthermore, they cultured one of the cyanobacteria strains and showed that the amount of PEC depends on the color of the light (Fig.1).

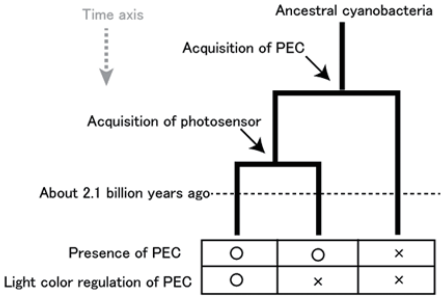


Fig.2 Phylogenic tree of cyanobacteria. Ancestral cyanobacteria acquired PEC and the photosensor, each only once, about 2.1 billion years ago or more.

Further analysis of about 450 cyanobacteria genomes revealed that this photosensor regulating PEC emerged only once about 2.1 billion years ago or more and evolved through a genetic exchange between cyanobacteria strains (Fig. 2 and 3), which is a process called horizontal gene transfer. The photosensor was preferentially distributed among filamentous and multicellular strains but not unicellular strains. These cyanobacteria strains may utilize different light colors for photosynthesis between cells and share limited light energy.

PC and PE are currently used as natural food color additives in some foods. The result of this research can be applied to the mass production of PEC and the development of new food products. This finding may also be applied to the improvement of light energy conversion of photosynthesis and applied to research fields for the regulation of genetic functions using light illumination.

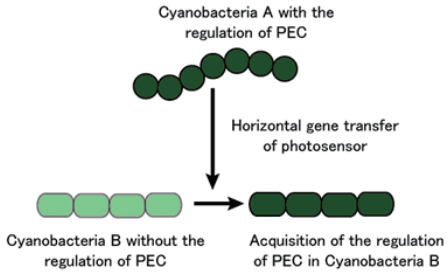


Fig.3 Acquisition of photosensor by genetic exchange

Reference

Hirose Y., Chihong S., Watanabe M., Yonekawa C., Murata K., Ikeuchi M., Eki T. Diverse Chromatic Acclimation Processes Regulating Phycoerythrocyanin and Rod-Shaped Phycobilisome in Cyanobacteria. Molecular Plant (2019) Feb 26. in press.

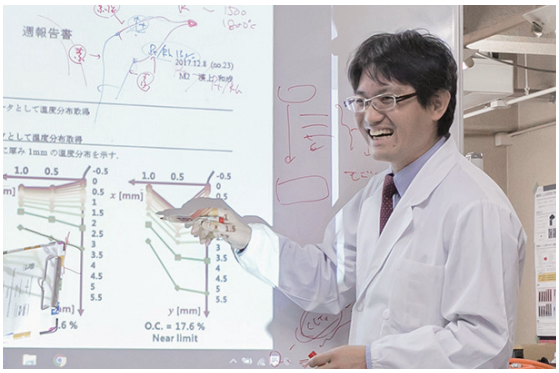
https://doi.org/10.1016/j.molp.2019.02.010

New concept for a fire extinguisher usable in space

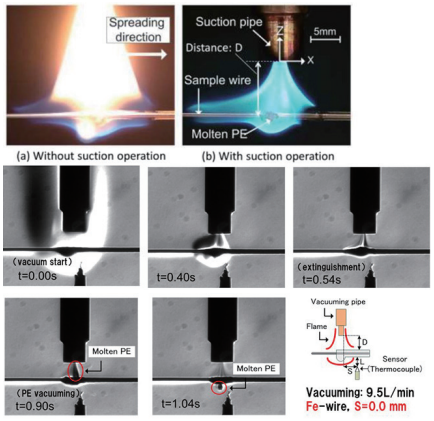
Vacuum Extinguishing Method – A Fire Extinguisher designed for use in space

By Yuji Nakamura

Professor Yuji Nakamura and his research team at the Department of Mechanical Engineering of Toyohashi University of Technology, in collaboration with the Hokkaido and Shinshu Universities, has developed a new concept of fire extinguishing, named the Vacuum Extinguishing Method (VEM). VEM is based on a complete "inverse" operation of the conventional fire extinguishing procedure; It neutralizes the combustion by sucking the combusting material, along with the flames and the source of the combustion, into a vacuum chamber. This concept is advantageous for use in space, as it prevents the spread of harmful combustible material within the enclosed cabin.



At present, fire extinguishers used in spacecraft or space stations are mainly CO_2-spraying gas extinguishers, although water mist was partially considered as an alternative. However, it must be noticed that the spraying type of extinguisher is not the best choice for the space-environment because of the limited volume of the cabin, resulting in the increase of CO_2 concentration. It is, therefore, necessary to wear an O_2 mask before actually being able to use the extinguisher, and the resulting delay allows the fire to grow. In addition, spraying CO_2 gas toward the fire causes the combusting material and CO_2 to scatter dangerously across the cabin. Cleaning up these emissions is very likely to cause considerable delay to the mission. Furthermore, the strain on the CO_2 filter would necessitate frequent replacement; thus creating a need to bring substantial stocks of filters for longer space missions. Since these factors are not critical on earth, the research team focused their attention on the discovering the best solutions for fires in space.



Fire extinguishing demonstration by vacuum-based suction operation. (a) Flame appearance with/without suction operation. (b) time-sequential Schlieren images during the suction extinguishment process. With the suction operation, the flame's color becomes blue, suggesting that the particulate matter generated by the flame (e.g. soot) is suppressed by the reduction of residence time and harmful product gas components as well as the burning source (molten polymer in this case) are effectively drained into the suction box connected to the suction pipe (where extreme vacuum condition is maintained).

VEM is a state-of-art concept newly proposed by the team lead by Professor Yuji Nakamura, which is basically a completely "inversion" of the standard procdeure for fighting fire. It basically uses a vacuum to suck the combusting material, along with the flames and the source of the combustion, into a vacuum container to be isolated, where it can be safely extinguished. Should this method be successful, it would negate the need for the time consuming step of putting on an an O_2 mask, and so respond quickly dealing with the fire. In addition, any gas emissions would be effectively removed from the cabin and so reduce damage to the filter. Though this method sounds odd on earth, it may turn out to be the best solution for space.

Taichi Usuki, Prof. Yuji Nakamura's former masters student from his time at Hokkaido University, investigated the feasibility of this concept and formulated the explanation of how it could be implemented. Three types of extinction modes were found and each extinction mode was controlled by a suction flow rate. The article summarizing this concept was accepted to be published in a special issue entitled "Spacecraft Fire Safety" in the prominent international journal Fire Technology.

The leader of the research team, Professor Yuji Nakamura, said, "The idea initially emerged through informal discussions with US researchers. Though it was simple enough to test and confirm the concept, it proved far more challenging to create a systematic study to demonstrate its performance and to formulate the performance based on a mathematical model. With the assistance of Mr. Usuki, and their collaborator Prof. Wakatsuki, the concept was confirmed and the complete testing device was successfully developed. Controlled vacuuming was introduced by an ejector system and all devices were activated with sensors in the test to substantially improve reproducibility. Fascinating flame suction images show the results and provide high quality images which show how the process should be modeled. At present, space agencies are wary of introducing this concept because a functioning device has yet to be developed and tested. However, we will continue to refine and share the concept".

The research team expects VEM to be adopted as a technique for future space missions. They note also that the technique would be applicable for extinguishing certain rare types of blaze, such as a metal powder fire, which can not easily be dealt with by the current generation of extinguishers. It is also expected to be useful for tackling fires in clean rooms, where the spray of fire-fighting agents could cause severe damage to the structure and equipment, and so render them unusable for a significant period.

In the future, if long-term space missions are to be viable, then fire safety strategy will require reconsideration. Moreover, because non-specialists such as newly recruited astronauts may in the future be involved in space travel, or even staying at a space hotel, the need for easy-to-use emergency devices becomes clear. This concept could eventually become the new standard for fire-fighting devices in space. Even for home use, a "new" vacuum cleaner may have special options with this kind of fire extinguisher. Sounds ridiculous? Maybe not.

This work was supported by Grants-in-Aid for Challenging Exploratory Research, The Ministry of Education, Science, Sports and Culture (No. 25560160).

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Yuji Nakamura, Taichi Usuki, Kaoru Wakatsuki (2019). Novel Fire Extinguisher Method using Vacuuming Force Applicable to Space habitats. Fire Technology (special issue: Spacecraft Fire Safety),

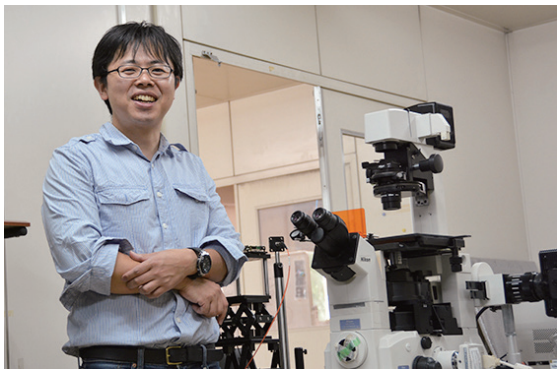
https://doi.org/10.1007/s10694-019-00854-4

Harnessing Microorganisms for Smart Microsystems

Vorticella autonomously converts its linear motion to rotation

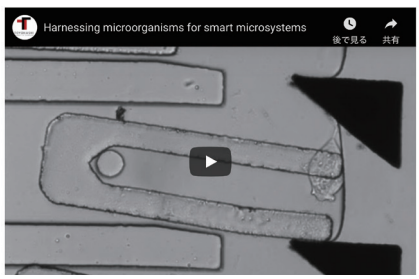
By Moeto Nagai

A research team led by Dr. Moeto Nagai of the Department of Mechanical Engineering at Toyohashi University of Technology has developed a method to construct a bio-hybrid system that incorporates *Vorticella* microorganisms. The method allows movable structures to be formed in a microchannel and harnessed to *Vorticella*. The bio-hybrid system demonstrates the conversion of motion from linear motion to rotation. These fundamental technologies help researchers to create wearable smart microsystems by using autonomous microorganisms. The results of their research were published in the IEEE/ASME Journal of Microelectromechanical Systems on April 11, 2019.



Complex control systems are required for the operation of smart microsystems, but yet they need to be as small as possible. It is thought that cells may be applicable as alternatives for these complex control systems. This is because a cell integrates many functions in its body and responds to its surrounding environment, they are intelligent and can be used in smart micromechanical systems.

In particular, *Vorticella* convallaria has a stalk (approximately 100 μm in length) that contracts and relaxes, and it works as an autonomous linear actuator. The combination of stalks and movable structures will form an autonomous microsystem. However, the construction of biohybrid systems in a microchannel is difficult, as it is necessary to establish a cell patterning method and a biocompatible assembly process for the structure and cell.



Structure Integration and Motion Conversion by *Vorticella*: A free-floating component is harnessed to *Vorticella* and the component is autonomously rotated and returned by means of a biohybrid approach.

The research team has developed a method to construct a biohybrid system that incorporates *Vorticella*.

"Harnessing microorganisms requires that a batch assembly method be applied to the movable components in a microchannel. It is necessary to pattern a water-soluble sacrificial layer and confine the movable components in a microchannel," says Moeto Nagai, a lecturer at Toyohashi University of Technology and the leader of the research team. *Vorticella* cells were placed around blocks in the channel by applying magnetic force. These processes were applied to demonstrate how *Vorticella* converts the motion of a movable component.

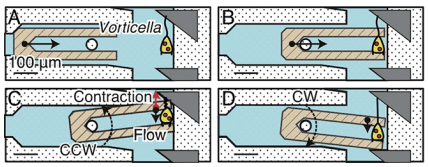


Fig.1. Harnessing a structure to *Vorticella*: Integration of a structure with *Vorticella* (Upper, A, B). Repetitive movement of a structure due to the force of *Vorticella* and flow (Lower, C, D).

"The concept of harnessing a component to a microorganism seems simple, but it is difficult for even a microfabrication expert to make harnesses that can follow the motions of microorganisms. Hazardous chemicals should be avoided, and a multidisciplinary approach should be taken," says Nagai. His group is familiar with microfabrication and has conducted considerable research in the field of microbiology. They found a biocompatible approach for making and releasing harnesses in a microchannel.

After permeabilized treatment, *Vorticella* stalks respond to changes in calcium ion concentration, and they can operate as calcium ion-responsive valves. The research team believes that calcium ion-sensitive motors of *Vorticella* will facilitate the realization of autonomous fluidic valves, regulators, and mixers, as well as wearable smart microsystems, such as an automated insulin infusion pump for diabetes.

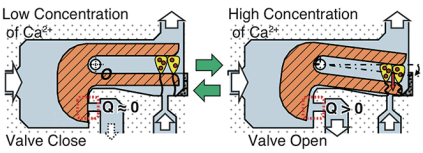


Fig.2. Calcium-responsive valve actuated by *Vorticella*: A channel is closed at low calcium-ion concentration (Left). *Vorticella* opens the channel at high calcium-ion concentration (Right).

This work was supported by JSPS KAKENHI (Grant Number 22810012, 25820087), the Ebara Hatakeyama Memorial Foundation, and The Foundation for the Promotion of Ion Engineering.

Reference

Moeto Nagai, Kohei Tanizaki, Takayuki Shibata (2019). Batch Assembly of SU-8 Movable Components in Channel Under Mild Conditions for Dynamic Microsystems, Application to Biohybrid Systems, IEEE/ASME Journal of Microelectromechanical Systems,

https://doi.org/10.1109/JMEMS.2019.2907285

ヒルの柔らかい体に学ぶ ― 壁登りロボット

壁の手前側から反対側まで180度グルっと回転

真下　智昭

豊橋技術科学大学機械工学系 真下智昭准教授らとケンブリッジ大学工学部 飯田史也准教授らの研究チームは、垂直な壁を登るヒル型ロボット「LEeCH」を開発しました。LEeCH（Longitudinally Extensible Continuum-robot inspired by Hirudinea）は、シャワーのホースを素材とした柔軟な体と2つの吸盤を持っており、本物のヒルのように自在に伸びたり曲がったりすることが可能です。柔らかい構造と吸盤を活かすことで、垂直な壁を登りさらに壁の反対側まで移動することを可能としました。本研究の結果は、3月27日に米国の科学雑誌Soft Roboticsに掲載されました。

壁登りロボットはビルの点検・検査や災害現場での捜索・救助などでの活躍が期待されています。垂直な壁を真っすぐに登るだけならばそれほど難しくはありません。しかし実際には、壁の途中にある段差や障害物を越える、または、方向の異なる壁へ移動しなければならない場合もあります。特に難しい課題は、壁の反対側に移動することです。ロボットが、壁を垂直に登って頂上に辿り着いたのちその壁を乗り越えるのは、ロボットにとっては至難の業でした。

そこで、研究チームは自然界の優れた登山家である山ヒルを模倣したロボットを開発しました。山に生息する山ヒルは、その両端にある2つの吸盤と伸縮自在な体を用いて、複雑な地形や壁面を自在に移動することが出来ます。また、その柔らく軽い体は、万が一高所から落下しても大きなダメージを負いません。

この軽量・柔軟・伸縮自在といったヒルの特長を模倣するために、シャワーのホースの構造を用いた新しい動作機構を考案しました。このホースはS字形状の金属板が螺旋状に巻かれたもので、一般の家庭でも使用されているものです。ホースの螺旋状の溝に歯車の歯をかみ合わせると、歯車の回転に応じてホースは前後に動きます。開発したロボットは3本のホースを束ねた体を持ち、歯車で送り出したそれぞれのホースの長さに応じて、伸縮または曲げ運動を行うことが出来ます。

開発したロボットは垂直な壁において、昇降方向や水平方向の移動に成功しました。この2つの移動方法を組み合わせることで、ロボットは2次元の壁面上であれば自由な位置に移動することが可能です。さらに柔軟かつ大きく変形する体を活かして、垂直な壁から反対側の壁への移動を達成しました。このように自由な壁面移動ができる柔らかいロボットの開発は、世界初の研究成果です。

開発者であり論文の筆頭著者である博士後期課程の金田礼人は「このアイデアは実は、自宅のお風呂場でひらめきました。シャワーの水を間違えて勢いよく出してしまったところ、ホースが生物のように勢いよく暴れだしました。それを見て私は、ホースを自由に動かすことができたら生物のようにダイナミックな動きを行うロボットが実現できるのではないかと考えました。」

研究チームは、シャワーのホースの中空構造を活かし、内部に液体を流してロボットの硬さを変化させるアイデアも検討しています。柔軟な構造をもつロボットは、環境への適応性が高いだけでなく、衝突に対する安全性も高いことから、将来的には人の近くで働くロボットとしても活躍できる可能性もあります。

光合成に黄緑色光を使うための光スイッチを発見

広瀬　侑

光合成を行う細菌の一種であるシアノバクテリアは、緑色もしくは赤色の光を効率よく光合成に利用するための光スイッチを持っています。豊橋技術科学大学、東京大学、生理学研究所らの研究チームは、光合成に黄緑色光を利用するための新たな光スイッチを発見しました。さらに、ゲノム情報の解析により、この光スイッチが約21億年以前に誕生し、シアノバクテリア同士の遺伝子の交換によって進化してきたことを明らかにしました。

光合成とは、光エネルギーを化学エネルギーへと変換する反応であり、地球上の全ての生命の生存を支える重要な反応です。シアノバクテリアは酸素発生型の光合成を行う原核生物であり、世界中のあらゆる環境に生息しています。シアノバクテリアは光を集めるためのアンテナタンパク質として、赤色光を吸収するフィコシアニン、緑色光を吸収するフィコエリスリン、黄緑色光を吸収するフィコエリスロシアニン、の3種類を持つことが知られています。これまで、フィコシアニンとフィコエリスリンの量が光スイッチによって調節されることは知られていましたが、フィコエリスロシアニンの調節は報告例がありませんでした。

豊橋技術科学大学応用化学・生命工学系の広瀬侑助教らは、東京大学、生理学研究所との共同研究で、フィコエリスロシアニンを調節するタイプの光スイッチを発見しました。研究チームは、データベースに登録されたシアノバクテリアのゲノム情報を探索し、フィコエリスロシアニンと光スイッチを併せ持つシアノバクテリアの一群を特定しました。さらに、そのうちの1株を培養し、フィコエリスロシアニンの量が光の色によって大きく調節されることを実験的に証明しました（Fig.1）。さらに、約450株のシアノバクテリアのゲノム情報を詳細に解析したところ、このフィコエリスロシアニン調節型の光スイッチが約21億年以前にたった1度だけ誕生し（Fig.2）、その後、シアノバクテリア同士の遺伝子の交換（水平伝播）によって進化してきたことを明らかにしました（Fig.3）。また、光スイッチは、細胞同士が数珠のようにつながったシアノバクテリアに多く分布していました（Fig.3）。この理由としては、黄緑色光を吸収する量を調節することで、光合成に用いる光の色を細胞間で変え、光の奪い合いの競争を避けている可能性が考えられました。光スイッチは、限りある光エネルギーをシアノバクテリアが分かち合うために進化してきたのかもしれません。

フィコシアニンやフィコエリスリンは天然由来の色素としてアイスクリーム等の食品着色料として使用されています。本研究の成果は、フィコエリスロシアニンの大量生産やそれを用いた新たな食品開発への応用が期待できます。また、光合成の改変による光エネルギー変化効率の向上や、光照射によって生物の遺伝子の働きを制御する研究への応用が期待できます。

真空消火法（VEM） ― 宇宙環境での使用を目指した消火器の新しいコンセプト

中村　祐二

豊橋技術科学大学の中村祐二教授らの研究チームは、真空消火法という消火の新しい手法を提唱しました。真空消火法は、従来の消火法の「逆」の手順に基づいて行われるもので、炎や燃焼生成物、燃焼源そのものを真空室に吸い込み、火災空間をきれいにできます。この方法では、火災に伴い発生する有害な物質が広がるのを防ぐことができるため、閉鎖度の高い宇宙空間等での使用に適しています。

現在、国際宇宙ステーションで使用されている消火器は、主に二酸化炭素を噴射して消火させる仕組みを採用しています。しかしながら、対象室内は閉鎖度の高い狭い空間であり、消火により二酸化炭素濃度も上昇するため、消火活動を始める前に酸素マスクを着用する必要があります。この手順では消火活動開始に遅れが生じ、その間に火災が延焼して手遅れになる可能性があります。さらに、噴射式の消火方法では、炎が消せたとしても燃焼で生成した有害ガス成分等が室内に広がり、消火室内の現状復帰が遅れてしまいます。

このような問題を解決するため、中村教授らの研究チームはこれまでにない消火戦略を提案しました。それが、VEM（Vacuumed Extinguish Method）と呼ばれる真空消火法です。VEMは消火の操作がこれまでと全く逆で、（高圧を利用した噴射ではなく）真空にした箱への吸引を活用しています。具体的には、炎や燃焼生成物、燃焼源そのものを「まるごと」真空にされた箱内に吸引し、必要であればその中で消火します。この方法であれば、火災場で二酸化炭素ガス濃度が増えることがないため、消火活動前に酸素マスクを装着する時間は不要となり、火災による有毒ガスは直ちに火災発生空間から除去され、消火後の現状復帰が早まります。

研究チームはVEMが今後の宇宙ミッションにおいて次世代技術となることを期待していますが、適用先は宇宙に限りません。例えば、家庭や工場などで多用される粉末消火器は、精密機械があるクリーンルームや手術室等で用いると消火後に機械が使用できなくなる可能性があります。このような空間の消火活動にもVEMが役立つと期待できます。自宅の中でも消火薬剤を撒くのをためらわれることもあるでしょう。もしかすると、近い将来、消火機能のついた「次世代掃除機」が家の中で使われる日がくるかもしれません。

微小ハーネスをツリガネムシに取り付ける

自律的に環境に応答するウェアラブルマイクロシステムの実現へ

永井　萌土

豊橋技術科学大学機械工学系の永井萌土講師らは、微生物であるツリガネムシに微小ハーネスを取り付けて、微生物融合マイクロシステムを構築する方法を開発しました。ハーネスとなる可動構造をマイクロ流路内に形成し、生きているツリガネムシと組み合わせ、ツリガネムシの直線運動を回転運動に変換しました。これらの基礎技術は、自律動作する微生物を使用してウェアラブルなスマートマイクロシステムを作製するのに役立ちます。

マイクロシステムを周囲環境に適応しながら動作させるには、複雑な制御システムが必要で、さらにそのサイズの縮小が望まれます。これらの複雑な制御システムの代替として、細胞を適用することが期待されています。細胞は小型な体内に多くの機能を統合し、周囲の環境に反応できることから、環境適応型のマイクロシステムの部品に使用できます。

特に、ツリガネムシは収縮伸張する柄（長さ約100μm）を持ち、自律型のリニアアクチュエータとして機能します。この柄と可動マイクロ構造（ハーネス）の組み合わせにより、自律型のマイクロシステムを形成できます。しかしながら、マイクロ流路内でのシステム構築には、細胞配置技術とハーネスの組立方法を確立し、なおかつ細胞を生きたままにする必要がありました。

そこで研究グループは、ツリガネムシを生きたまま組み込み、微生物融合システムを構築する手法を開発しました。複数の微生物を利用するには、マイクロ流路内の可動部品を並列的に構築することが求められます。まず微細加工技術を応用して、微小なハーネスをマイクロ流路中に並列的に配置しました。続けてツリガネムシの細胞を磁力により、選択的に配置しました。最終的にハーネスをツリガネムシに組み付けて、ツリガネムシの運動を用いてハーネスの動きを回転運動に変換することに成功しました。

微小ハーネスを微生物に利用するという概念は、マクロな発想からは単純に思えます。しかし、微細加工の専門家にとっても、微生物の動きに追従するハーネスを作ることは困難でした。ハーネスを生きた微生物に組み付けるには、有害な化学物質の使用を避ける必要があり、解決には学際的なアプローチが求められます。研究グループは微細加工に精通しており、なおかつ微生物学の分野でも研究を進めてきました。これらの蓄積があり、生体適合性を持たせたまま「マイクロ流路内でハーネスを作製し、なおかつ可動化する手法」を見つけました。

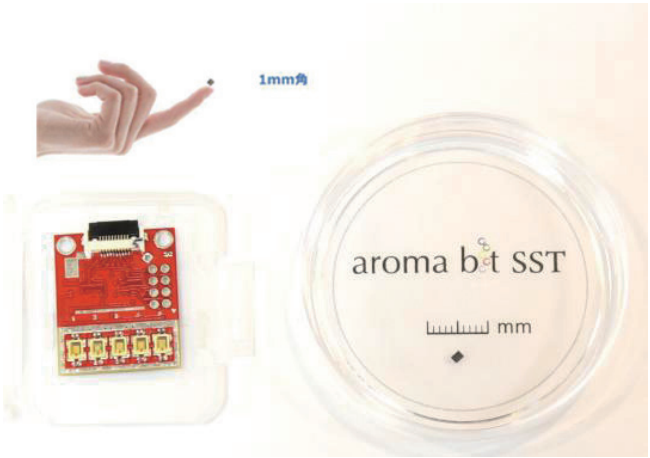
細胞膜の透過処理を行った後、ツリガネムシの柄は周囲のカルシウムイオン濃度の変化に反応するようになります。これにより周囲のカルシウムイオンに反応するバルブとして機能するようになります。また、ツリガネムシのカルシウムイオン応答アクチュエータは、自律型の流体バルブ、流量調整器やミキサーの構築につながり、さらに糖尿病用の自動インスリン注入ポンプのようなウェアラブルな環境応答型マイクロシステムの実現に貢献すると研究チームは考えています。

Pick Up

TUT and Kobelco advances “KOBELCO CONSTRUCTION MACHINERY ADVANCED CRANE LABORATORY”

In April 2019, TUT launched the “KOBELCO CONSTRUCTION MACHINERY ADVANCED CRANE LABORATORY,” strengthening the existing collaboration between TUT and Kobelco Construction Machinery Co.,Ltd, a leading manufacturer of construction machinery in Japan. The aim of the collaboration is to create more innovation through both our current research in automation, AI, and the utilization of big data and research into the ideal form for the next generation of cranes. This collaborative research system will advance how a university and a company can work together to offer great benefits to society and foster highly skilled engineers through practical education.

TUT establish a venture company to market a super small odor sensor



TUT established a new venture company, Aroma bit Silicon Sensor Technology Co, LTD, to market the super small and high resolution CMOS type odor sensor which they developed. The venture company plans to combine the the ion image sensor, which was developed by TUT Professor Kazuaki Sawada’s research group, with the odor receptor membrane developed by Aromabit. It is the first university-launched venture company certified by the Toyohashi University of Technology.

The impressive potential of the sensor is evidenced by the fact that its 1,200 kinds of odor receptors, with the equivalent power of a “dog’s nose”, will be packed onto an element of only 1 mm square.

The aroma bit silicon sensor technology Co, LTD aims to market their product as a super small and low-cost sensor that can be installed in smartphones and IoT devices. Its potential applications could range from detecting deterioration in the quality of wine after it has been opened to determining possible illnesses from a breath test.

TUT Research
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