Swarming is a collective behavior of living organisms observed in nature\(^1\). School of fishes, flock of birds and colony of ants are some typical examples. Thousands of individual units create fascinating swarm patterns through local interaction between themselves in a decentralized way. Through swarming, they achieve advantages like parallelism, flexibility, and robustness. Parallelism allows sharing of tasks, flexibility permits responding to their environments, and robustness helps ensuring tasks to execute properly.

Inspired by such unique swarming system, a new concept “swarm robotics” has been emerged in the field of robotics. Although using different kind of mechanical robots, swarming has been performed until now\(^2\), construction of large numbers of individual robots capable of programmable self-assembly is yet to be achieved. The creation of molecular robots composed of molecular actuators, processors, and sensors could be a means to address the challenge. Chemists and biologists have employed various self-propelled molecular actuators to demonstrate swarming\(^3\). Among them, biomolecular motor systems have been a promising one due to their small size\(^4,5\). For example, microtubule (MT)/kinesin system has been used to demonstrate swarming in the \textit{in vitro} gliding assay. In this system, MT filaments are driven on kinesin coated surface in the presence of adenosine triphosphate (ATP)\(^4,5\). By manipulating the interaction among MT filaments, different patterns with directional motion have been demonstrated by introducing crowding agents\(^6,8\). However, the systems still lack in a programmable control of the collective behavior. With these backgrounds, we aimed to demonstrate programmable swarming by constructing molecular robots equipped with a processor and sensor through a bottom-up approach. MT/kinesin system was employed as molecular actuators. DNA was used as a processor\(^6\). In addition, a photochromic molecule, azobenzene was incorporated in the DNA as a photosensor to regulate the swarming of robots\(^7\). In this review, we will briefly present the successful demonstration of programmable swarming of molecular robots and prospects of the system as an autonomous molecular swarm robot.

\textbf{Figure 1a} shows the schematic illustration of our molecular robot system. The basic unit of the robot was prepared by conjugating MT filament with single-strand DNA through copper-free click reaction\(^7,8\). DNA tethered MTs were then placed on kinesin coated surface and driven in the presence of ATP (Fig. 1a). The DNA conjugated MTs exhibited gliding motion with an average velocity of ~600 nm/s. Input DNA strands were designed to inter-crosslink the DNA conjugated MTs. Through the interaction between the input DNA strands and single-strand DNAs conjugated to MTs initiates swarming. Swarm behavior was controlled by tuning the physical properties of MTs. Short and rigid MTs polymerized in the presence of guanosine triphosphate (GTP) analog, guanylyl-(α, β)-methylene-diphosphonate (GMPCPP) result-
ed in the formation of the swarm with translational motion. On the other hand, long and flexible MTs polymerized using GTP formed the swarm with rotational motion (Fig. 1b). Dissociation of the swarm was also confirmed in response to a DNA strand with a sequence to withdraw the input DNA.

Considering the formation of swarm as output, logical operations, such as YES, AND, and OR gates, can be implemented by the molecular system. The precise molecular recognition ability of DNA also allows to control the formation of swarm with both of rotational and translational motion orthogonally.

Inserting azobenzene into DNA allows control on the formation of swarm by light. Visible light irradiation (\(\lambda = 480\) nm) triggers the isomerization of azobenzene from cis to trans state which permits the interaction of complimentary DNAs, thereby causing the swarming.

Conformational change in azobenzene from trans to cis state upon UV light irradiation (\(\lambda = 365\) nm) initiates the dissociation of the swarm (Fig. 1c, d). Repetitive switching of the swarming of MTs with light was thus successfully achieved by inserting a photoresponsive component into the system.

In conclusion, by integrating DNA and molecular motors through a bottom-up approach, we constructed molecular-sized robots. We have demonstrated MT swarming controlled by chemical and physical input signals. Our work will pave a new way to establish molecular swarm robotics. However, in order to make the system fully autonomous, the swarm robot system must be able to operate on its own without external control, which could be implemented by further DNA computation of the system. In the near future, molecular swarm robots are expected to make significant contributions to a variety of fields, including human health issues, molecular manufacturing, and sustainable energy sources etc.

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