学 位 論 文 内 容 の 要 約

博士の専攻分野の名称　博士（理学）　氏名　ジャキア　ジャンナット　ケア

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Study on Biomolecular Motor based Micro-Robot Programmed by DNA Processor
（DNA プロセッサーによりプログラムされる生体分子モーターを基盤としたマイクロロボットの研究）

Swarming or collective behavior is a fascinating phenomenon exhibited by living organisms in nature. Through this collective behavior they obtain some unpredictable functions like parallelism, flexibility, robustness and scalability that are not achieved in single state. Being inspired by the attractive features of natural swarming, alongside the theoretical and simulation based studies, considerable amount of experimental works, using various kinds of self-propelled mechanical robots have been undertaken to mimic the swarming of living organisms which emerged a new field named ‘swarm robotics’. The limitation of mechanical robots, however, lies on their large size and low efficiency that restricted their application for demonstration of swarming. On the other hand, chemists and biologists have independently employed self-propelled biomolecular motor system, the smallest natural machine that has been promising for demonstrating swarming. Their small size and high efficiency of energy conversion offers controllability over a large number of swarm units. In recent years, demonstrating swarming based on biomolecular motor system such as microtubule (MT)-kinesin system has been promising which has been studied by controlling the interaction among them. However, still the key challenge has been modulation of the interactions among the neighbor units which can control the swarms in a programmable way. In this way, DNA, the most attractive molecular computer remarkable so far could be employed to design and control biomolecular swarming by selective and specific interaction in a highly programmable fashion. Therefore in this dissertation, I have studied control of swarming using self-propelled MTs driven by molecular motor kinesin in vitro through DNA programming. Swarming of MTs was controlled by DNA interaction and further programmed by employing unique features of DNA such as logic gate operation and DNA induced photoirradiation introducing sensitivity and responsiveness in the system. I have also studied different features of gliding MTs and protofilaments (PFs) using high resolution images by high speed AFM (HS-AFM) method that provides information about mechanical change of this self-propelled system at the molecular level.

In chapter 1, the purpose of this dissertation and background of this study have been described.

In Chapter 2, swarming was demonstrated by self-propelled MTs through DNA interaction. DNA conjugated MTs or swarm units were prepared using click reaction. Swarming takes place with input DNA signals complementary to DNAs modified to MTs by active self-assembly through formation of linear bundle shaped structures with translational motion. Different shape of pattern and mode of motion of swarming was also controlled by changing the physical property of MTs where the flexible one exhibits circular mode of motion unlike the rigid one which shows translational motion. For both type of swarm units, the swarming depends on a number of relevant parameters which were varied to optimize the conditions which not only affects the initiation of swarming but also their morphology. The shapes and size of swarm groups were controlled by tuning the length and rigidity of MTs. Dissociation of swarming to their initial single state and change of their mode of motion was also successfully demonstrated by introducing DNA strand displacement reaction which was reported for the first time for controlling swarm based on biomolecular motor system. These functions of biomolecular motor based swarming would help to develop and understand swarm behavior observed in nature.

In chapter 3, swarming was further controlled by unique features of DNA programming such as DNA logic gate operations. Logic gate programming has been first introduced in biomolecular motor system which helps to modulate the swarming in presence of designed sequence of input DNA signals. Different types of logic gates such as YES, AND and OR gates were demonstrated that can program the swarming following the true mathematical computation. Moreover, through logic gate operation different patterns such as linear and circular pattern with their corresponding mode of motion was able to control simultaneously through DNA molecular recognition process. Two different swarming modes with distinct physical properties of swarm units were responsive to the corresponding input DNA signals which help to sort out the patterns without any crosstalk. Finally, inserting photoresponsive DNA using azobenzene molecules in the swarm units, repeated control over reversible swarming was successfully demonstrated by input physical signals through cis-trans isomerization of azobenzene. This work provides us the way to control of biomolecular swarming by responding to external stimuli through sensing capability that would provide the knowledge to design swarm robots with programmable functionalities.

In chapter 4, gliding of MTs and single PFs was investigated using the advantage of high resolution imaging by HS-AFM at molecular scale. The straight motion of PFs and its corresponding features was first observed by HS-AFM that was not reported by conventional technique. The PFs were found to move with lower velocity than the velocity of MTs with shorter path length and pausing events. Furthermore, splitting of the gliding MTs into single PFs has also been observed directly for the first time from the tapered leading end of the MT, which may give the answer of the cause of sudden directional change of the gliding MTs in gliding assay. From the detail investigation of motile MTs at the molecular level using HS-AFM, relationship between structure of MTs and their motility behavior would be understandable in detail.

In chapter 5, all the important results have been summarized and future perspectives have been discussed. This dissertation describes about how to control the swarming using self-propelled biomolecular motor system by programming features of DNA. In nature, swarming is of great importance where through self-assembly process living beings obtain great advantages. The results obtained in this study will deliver deeper understanding about swarming and regulating their behavior by sensitivity and responsiveness which would help to develop functionalities like natural swarm. Therefore the study will provide the knowledge to design micro robots controlling the swarm of self-propelled biomolecular motor system using supramolecular DNA interactions in a non-equilibrium process. I expect the work would offer a wide range of perspectives to explore it in the view point from the field of biology, chemistry and engineering system. In addition to this, the reported results on gliding MTs from higher resolution images using high speed AFM would help to acquire profound insight about the phenomena that occur at the molecular level in the gliding assay of MTs that will be also helpful for designing micro-robots.