【Grant-in-Aid for Transformative Research Areas（A）】

Molecular Explorers: Adaptive Robots for Real-World Molecular Systems

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Project Information	Project Number : 26A402　　Project Period (FY) : 2026-2030 Keywords : Self-X Functions; Real-World Operation; DBTL Cycle; Intelligent Matter Engineering

Purpose and Background of the Research

●Outline of the Research

A molecular robot is an extremely small artificial machine—about 1/100 the thickness of a human hair—built from molecular components. Sensors, processors, and actuators implemented at the molecular scale execute tasks autonomously in their environment (Fig. 1). Proposed by Japanese researchers in 2009, the field has grown through "Molecular Robotics" (2012–2017) and "Molecular Cybernetics" (2020–2025), with Japan leading the world (Fig. 2). However, demonstrations have been confined to idealized lab conditions; molecular robots have been unable to function in "real-world environments" where temperature, pH, and salt concentration fluctuate continuously. This is transdisciplinary basic research that takes molecular robotics beyond proof of concept toward next-generation robots that thrive in real-world settings.

What is Molecular Robot?

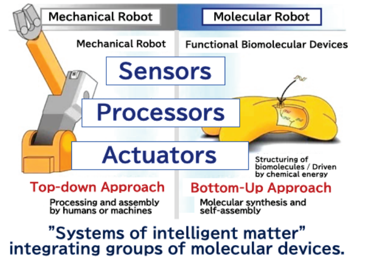

Figure 1. Molecular robot concept

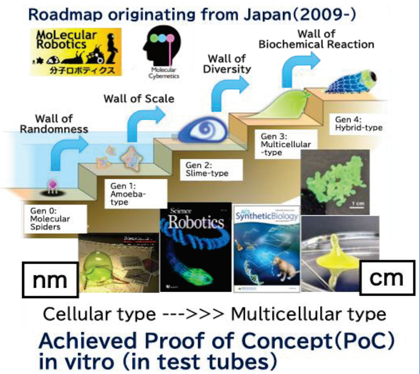

Figure 2. Molbot research field progression

●Creating "Molecular Robot Explorers (MolBot EX)" with Self-X functions

The key to autonomous, continuous operation in real-world environments is the **Self-X functions: self-repair, self-adaptation, and self-stop** (Fig. 3)—drawing on living systems.

Self-repair regenerates damaged components at the molecular level; self-adaptation senses environmental change and modifies behavior; self-stop safely decomposes the robot when its mission ends.

Together these functions let molecular robots keep working in fluctuating environments only as long as needed. Uniting researchers across chemistry, physics, biology, engineering, and information science via a "refine-while-running" process, we will create the "**Molecular Robot Explorers**".

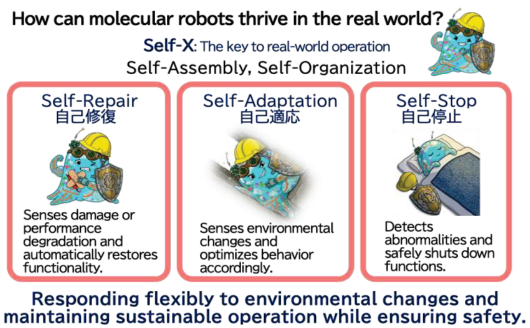

Figure 3. "Self-X" capabilities of molecular robots required for real-world exploration

Expected Research Achievements

●Quantitative target: "one-week operation" in real-world environments

By FY2030, operate molecular robots **continuously for one week** in both **biological environments** (inside mammals) and **extreme environments** (100°C/100 atm, akin to deep-sea hydrothermal vents)—thousands of times beyond current proofs of concept. This enables in vivo diagnostics, therapy/drug delivery, and exploration of harsh settings (space, deep sea, soil).

●Transforming the research process: 10x acceleration of the DBTL cycle

We accelerate the Design-Build-Test-Learn (DBTL) cycle more than tenfold by integrating five planned groups, three support hubs, and AI-driven analysis—turning fragmented lab-by-lab work into systematic interdisciplinary research.

●Five planned research groups (Fig. 4)

A01 "Verification in biological environments": develops molecular robots with nucleic acids, proteins and lipids for use inside organisms.

B01 "Verification in extreme environments": builds robots for 100°C/100 atm, dryness, and seawater from modified molecules and artificial nucleic acids.

C01 "Materials & verification-device development": develops XNA/DNA nanostructures, artificial metabolism, and a "Molecular Robot Test Field" for automation.

D01 "Foundational models & design theory": derives design principles via cross-scale models—coarse-grained MD to distributed-system theory.

E01 "Experimental automation, data integration, AI analysis": accelerates DBTL with de novo protein design, lab automation, and explainable/generative AI.

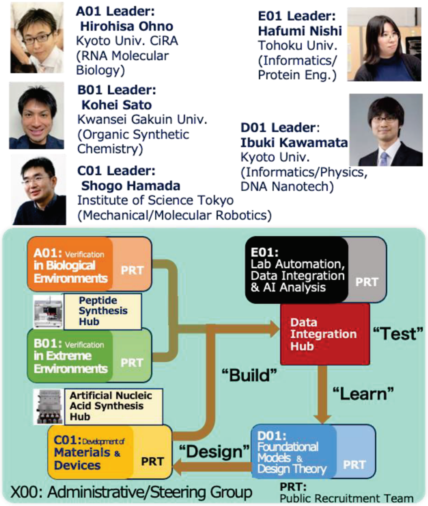

Figure 4. Five groups + three hubs running the DBTL cycle

●Three research support hubs

Data Integration Hub: all data—successes & failures—as an AI-ready database.
Peptide Synthesis Hub: designs & supplies functional peptides.
Artificial Nucleic Acid Hub: supplies highly robust XNA/ functional artificial DNAs.
The hubs let teams focus on their own Technologies and their integration, accelerating area-wide development.

●Academic transformation & societal impact

A new discipline—**"Intelligent Matter Engineering"**—integrates chemistry, physics, biology, engineering, and computer science to engineer molecular information processing, decision-making, and adaptive behavior. **Applications:** intracellular medicine, environmental remediation, and extreme-environment exploration.

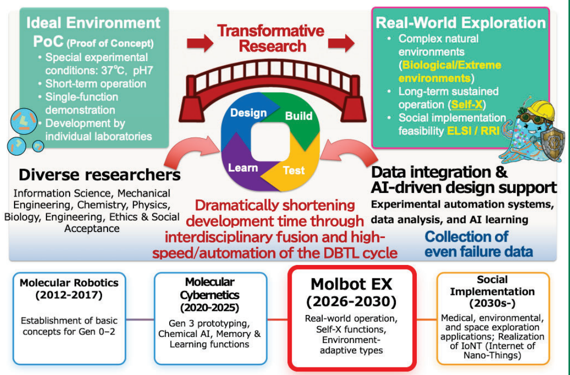

Figure 5. Overview of the Research Area

Website(s)	molbot-ex.org X(ex-Twitter): @MREX_PR_beta　/　Bluesky: @molbotex-pr