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# Responsible innovation in molecular robotics in Japan

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## Abstract

**Over the last decade Japanese researchers have taken the lead in the emerging discipline of molecular robotics. This new technology aims to produce artificial molecular systems that can adapt to changes in the environment, self-organize and evolve. This paper explores the question of how to stimulate responsible research and innovation in the field of molecular robotics technologies. For this, we first draw lessons from earlier societal responses in Japan to emerging technologies, such as genetic engineering, nanotechnology, synthetic biology and genomic research. Next we describe various real-time technology assessment (TA) activities on molecular robotics in Japan to depict the state-of-the-art of the academic and public debate on the social aspects of molecular robotics. Lessons from earlier societal responses to emerging technologies demonstrated three potential challenges: finding and involving the 'right' experts and stakeholders, keeping regulations up to date, and getting scientists and citizens involved in science communication. A literature review, 'future workshop' and scenario workshop raised a number of ethical, social, political and cultural issues, and addressed desirable and undesirable scenarios for the next few decades. Twitter text mining analysis indicates that the level of attention, knowledge and awareness about molecular robots among a broader audience is still very limited. In conclusion, we identify four activities crucial to enable responsible innovation in molecular robotics—getting to grips with the speed of the development of molecular robotics, monitoring related technical trends, the establishment of a more stable TA knowledge base, and a sustained interaction between molecular roboticists and social scientists.**

**Key Words:** real-time technology assessment, responsible research and innovation, ELSI, research and innovation governance, molecular robotics

**Area of Interest:** Emerging new technology

 

# 1. Introduction

Molecular robotics is an emerging discipline that aims to produce artificial molecular systems that can adapt to changes in the environment, self-organize and evolve [1]. While 2016 Nobel Prize winners in chemistry synthesized molecular machines at a supramolecular level, molecular robotics enables more flexible design of self-assembled complex molecular systems by bringing nano-design technologies and programming technologies into the field of supramolecular machines. Unlike molecular machines, which are passive systems where molecules aggregate and function, molecular robotics is a dynamic, active and programmable supramolecular system consisting of an outer envelope and inner mechanism, such as 'amoeba robot' [2−4] and 'slime mold robot' [5]. In contrast to conventional top-down approaches in molecular bioengineering and synthetic biology, molecular robotics is a bottom-up fabrication technology. It is more directed to perform sensory-motor intelligence functions than neighboring disciplines, like nanomotors, nanobiotechnology, synthetic cell research, DNA computing and artificial life research. Such an interdisciplinary idea can be traced back to converging technologies as the synergistic combination of NBIC (Nano-Bio-Info-Cogno) domains of science and technology [6]. The concept of molecular robotics is rooted in DNA molecular computing first developed in the 1990s [7] and then facilitated by the development of DNA origami [8]. For this kind of systems engineering, chemical modification and molecular arrangement is key to developing dynamic, effective and various structures and functions in the system. Despite a large cultural difference between chemists and biologists [9, 10], Japan has succeeded in bringing these two disciplines together because some young chemists joined a research group on DNA computing in the late 1990s. This group developed into the Molecular Robotics Research Group in 2010, under the aegis of the Society of Instrument and Control Engineers (SICE) in Japan. Its researchers have developed molecular robot prototypes under the Japanese government-funded project since 2012 [11].

Such an emerging technology challenges society to analyze and anticipate its societal impacts and steer its development for desirable futures. As an analytic and democratic practice, technology assessment (TA) aims to contribute to the timely formation of public and political opinion on societal aspects of science and technology [12]. A more academic approach is research on the ethical, legal and social implications (ELSI) of emerging technologies, which was originally developed in the context of the Human Genome Project and then applied in other areas of research, such as nanotechnology research and development [13]. Currently, responsible research and innovation (RRI) is an umbrella term covering these approaches and has recently gained increasing attention in the EU policy context [14], where RRI is now a 'cross-cutting issue' in the latest European Framework Programme for Research and Innovation ('Horizon 2020') from 2014 to 2020. There are four key elements of RRI—(1) anticipatory: including new perspectives on wider societal effects of research and innovation (R&I), (2) inclusive: involving diverse stakeholders in R&I process, (3) reflexive: examining and reflecting on researchers and innovators' own ethical assumptions and their role and responsibilities in public dialogue, and (4) responsive: being flexible and capable to change R&I processes according to public values, concerns and expectations [15].

The conduct of this study and the involvement of the authors illustrates a new form of research governance and gives some hints on how to steer an emerging technology while giving due consideration to its social implications. The authors of this paper include members of two projects funded under the "Human-Information Technology Ecosystem" (HITE) program by Research Institute of Science and Technology for Society (RISTEX), Japan Science and Technology Agency (JST). One focuses on legal, ethical, economic and educational aspects of molecular robotics, and the other focuses on real-time technology assessment of information technology. Under the auspices of RISTEX, both projects collaborated and jointly organized workshops. Reflecting the interdisciplinary culture of the synthetic biology research community in Japan and motivated to increase public accountability, molecular roboticists in the former project have been open to social scientific input from the early stages of their research. Social scientists in the latter project are thereby able to behave not merely as ‘contributors’ who contribute to and facilitate the progress of this field, but rather as ‘collaborators’ who can potentially influence the scientific knowledge that is produced [16]. As some cases illustrate [17], it is possible for scientists and engineers to participate in the governance of technology development in a reflexive manner. It is symbolic that the above molecular robotics researchers have also organized the 1st International Conference on the Ethics of Molecular Robotics in Japan by inviting social scientists and technology assessment practitioners from across the globe.

This article presents our perspective on how to govern the potential social implications of molecular robotics technologies in the Japanese context. Our main approach is real-time TA, which aims to explore possible social impacts of an emerging technology and integrate social values into ongoing technological development and innovation [18, 19]. We first analyze some earlier Japanese experiences with societal responses to emerging technologies. We then describe the results of various anticipatory activities that were organized in Japan to assess scientific expectations about future applications of molecular robotics and potential public concerns about these developments. The final section discusses the role of relevant stakeholders in the governance of molecular robotics research and innovation.

## 2. Lessons from earlier societal responses to emerging technologies in Japan

In the mid-1990s, Japanese media coverage of genetically modified organisms (GMOs) was initially positive with high expectation of medical and industrial applications [20]. Science and policy experts did not see any need for public engagement and open scientific debates, but this changed with the consumer campaigns in 1999–2000 [21, 22]. After this experience, in 2008, the government adopted precautionary policies on nanomaterials triggered by the publication of studies on the hazards of multi-walled carbon nanotubes. However, the rationale for policymaking was not clear, and the consequences for the possible development of nanomaterials were not considered [23]. In the case of synthetic biology, the scientific community has discussed its social and cultural dimensions by involving social scientists and humanists since 2007 [24]. In the fields of stem cell research and regenerative medicine, the interests of scientists and citizens differ. Scientists put more weight on scientific validity and relevance of the research whereas citizens show pragmatic interests in risks and accidents as well as responsibility, credibility and predictability of the research [25]. Scientists do not feel stimulated to communicate their findings to a broader public because they are confronted with administrative overload and a lack of resources and time. Furthermore, they perceive that effort spent on science communication will decrease their time to secure funding, promotion or employment [26, 27].

To summarize, the awareness of the importance of studying and discussing potential social and ethical issues from the early development of emerging technologies has grown among experts and stakeholders. This has also raised various potential challenges of 1) finding and involving the ‘right’ experts and stakeholders (as lessons from the case of synthetic biology), 2) keeping regulations up to date (from the case of nanomaterials), and 3) getting scientists and citizens involved in science communication (from the cases of GMOs, stem cell research and regenerative medicine).

## 3. Early real-time TA activities on molecular robotics (2017-2018)

In 2017 and 2018 various real-time TA activities on molecular robotics in Japan were jointly organized by the above two HITE projects, including the international conference (March 2017), the 'future workshop' (January 2017), the scenario workshop (February 2018) and the Twitter text mining analysis (January-February 2017). This section shortly describes some results of these activities and what this implies for the state-of-the-art of the academic and public debate on the social aspects of molecular robotics.

The 'future workshop' on molecular robotics (Tokyo, January 2017) aimed to develop new ideas or solutions to social problems based on the development of molecular robotics. In this workshop, a dozen participant experts, including molecular robotics researchers, social scientists and journalists, were free to join in one of three groups, which either focused on past analogical cases, potential innovations, or 'wild cards'—events with a surprising character, a low probability and a high impact [28]. The in-group discussions were then shared between the groups. Findings from the future workshop and the associated literature review reveal a number of possible applications of molecular robotics. These include scaling up the size of robots [29, 30], with the combination of existing molecules and non-DNA artificial molecules. Some participants suggested that multi-cellular robots could take a more hybrid form in which biomolecules and electronic devices coexist, cooperate and collaborate [1]. Another idea is a so-called 'thinking gel', a gel consisting of DNA with computing functions [31]. This could serve as small-scale and energy-saving brain and neural computing system. Another potential application is an artificial muscle, which is being developed with the support of the New Energy and Industrial Technology and Development Organization (NEDO) in Japan [32]. One of the most promising potential applications of molecular robots is drug delivery [33], for which signal processing and diagnosis will be more effective, efficient and elastic.

The risk debate on artificial intelligence (AI) and robotics inspires the debate on molecular robots. As in the context of AI and robotics, autonomy and self-replication raise many worries regarding the development of molecular robots and issues around responsibility and liability in case of accidents. In addition, some medical applications raise bioethical and social issues – e.g. eugenics in the development of artificial sperm or selection and fertilization technology of a genetically-rich sperm; infection of infrared photoresponsive molecular robots, and pseudoscientific popularization of molecular robots by extensive application in cosmetics, dietary foods and cancer treatment. In particular, molecular robot technologies converging with gene drives could potentially open the door for eugenics or ethnic cleansing through an engineering system to decrease the birth rate of a specific racial group. This technology may also be applicable to design mutants more efficiently and to enhance living systems in engineering, biological, chemical and military terms. It is worth recording that some of participant molecular robotics researchers observed that such speculations are unrealistic whereas social scientific experts tend to regard them as plausible.

At a scenario workshop on molecular robots (Tokyo, February 2018) a wide range of Japanese experts saw interdisciplinary research, open innovation and medical applications as promising and desirable scenarios. In contrast, they regarded a research moratorium, uncontrollable development, military use and widening gap between ethics guidelines and social practices as undesirable future scenarios. The experts believe that lobbying may yield champion politicians and public funding to encourage further interdisciplinary research in the field of molecular robotics for the next decade. At the same time, experts fear that current regulatory regimes are not prepared for the activities of new emerging actors like biohackers. Biohackers might stimulate innovation in radical new ways, like for example designer humans. Such a scenario bears the risk of discrimination between 'designed' or genetically enhanced humans and 'natural' humans and raises ethical issues in human enhancement. The technological development may provide unintentional military applications and a back door for the misuse of chemical and biological weapons. Some of the participants anticipate that the development of open source and innovation on molecular robots would provide an alternative treatment option for drug addicts, but the free market can allow costly or poor medical treatment.

Twitter can be used as a social web tool for retrieving future-oriented information from the public [34]. The Twitter text mining analysis applied a modified automatic term recognition method which counts the number of distinct single-nouns that come to the left or right of a single-noun term when used in compound noun terms. This method concerns the number of nouns that adjoin the noun in question to form compound nouns [35], whereby terms related to molecular robotics were extracted from press releases and other popular publications. The selected 8 words ('molecular robot', 'nanorobot', 'molecular motor', 'molecular device', 'molecular system', 'amoeba-like', 'structure prediction', and 'synthesis service') were then retrieved via Japanese tweets for one month (January 15-Feburary 14, 2017) on Twitter (N=171). As a result, 'nanorobot' is the most frequent word (appeared in 66 tweets) out of the selected words, followed by 'synthetic service' (64 tweets), 'structure prediction' (19 tweets), and others (<10 tweets). Whereas the phrase 'synthetic service' fluctuates in reference, the word 'nanorobot' has been disseminated conceptually as a technical gadget in pop culture, for instance, in order for heroes or villains to exercise extraordinary power in science fiction. Accordingly, the notion of molecular robotics is likely to be represented as a nanorobot in the mass media. This twitter analysis indicates that the level of attention, knowledge and awareness among a broader audience is still very limited. The fact that the public debate on molecular robotics is currently non-existent may promise open and effective communication on molecular robotics between experts and public audiences in future, but anxieties expressed in the group discussions and potential discursive linkage to the imaginaries of nanotechnology imply that even emerging discussions on molecular robotics in the society are likely to follow the course of previous technologies.

This section ends with short reflection on the outcomes of the various real-time TA activities and implications about the state of the art of the academic and public debate on molecular robotics in Japan. This upstream technology has not yet prompted public debate. However, various upstream TA activities have been organized in Japan where molecular roboticists and social scientists explored potential applications and application domains of molecular robotics and related social and ethical issues. This has led to a burgeoning debate among technical and social scientists over to what extent possible future applications of molecular robotics in various domains are realistic or speculative. Next to technological promising and societally desirable lines of development, undesirable scenarios were uncovered. With respect to the latter fears were raised for military misuse (related to debate on biochemical weapons), uncontrolled development (related to AI and robot debate and debate on GM organisms) and future divide between enhanced and non-enhanced human beings (related to human enhancement debate) and bio-hackers (related to the limits of current regulation). Finally, experts thought it was likely that molecular robotics researchers will be able to find political support to publicly fund further research on molecular robotics.

## 4. Towards responsible innovation in molecular robotics

Our reflections on how Japan dealt with former emerging technologies showed three potential challenges as summarized in Chapter 2: 1) finding and involving the 'right' experts and stakeholders, 2) keeping regulations up to date, and 3) getting scientists and citizens involved in science communication. The various real-time TA activities that have been organized in the field of molecular robotics over the last two years have addressed the first challenge. In contrast, the latter two challenges have not yet been addressed. This is attributed to the fact that in the current situation it has turned out quite hard to get to grips with the potential future applications of molecular robotics and the speed of its development. A proper insight into the social practices that will be impacted by molecular robotics, however, presents a necessary starting point for a good (academic and public) conversation about the potential social and ethical aspects of molecular robotics, let alone its regulatory aspects.

Given this state of affairs the following four activities are crucial for the years to come to address the above identified three challenges related to the societal embedding of emerging technologies, and thus to enable RRI in the field of molecular robotics. Because a proper insight into the social practices that might be impacted by molecular robotics is a requisite for proper dialogue on the societal meaning of this innovation, we first should get to grips with the speed of the development of molecular robotics and clarify various social practices or domains in which it will play a role. The identification of socially desirable and undesirable scenarios may also guide the setting of the research agenda for molecular robotics, opting for stimulating certain technological trajectories and deliberately not supporting other trajectories.

Second, monitoring the development of molecular robotics and related technical trends is also important. Special attention should be payed to identifying at an early stage potential new regulatory challenges (See challenge 2: keeping regulations up to date). Since the biohacking community was identified as a potential disruptive social practice, new social research activities could also invest time to assess current developments in the social practice. These first two actions should be supported as part of TA research on a long-term and interdisciplinary basis, and ongoing public investment in molecular robotics research should go hand in hand with the support.

Third, the establishment of a more stable TA knowledge base could stimulate both molecular roboticists and social scientists to communicate with the media and stimulate public debate about molecular robotics (See challenge 3: getting scientists and citizens involved in science communication). As discussed above, the term ‘molecular robot’ is likely to be constructed and framed by the media. Formulating ethical guidelines by stakeholder engagement before technologies appear on the market seems too unspectacular to broadcast. In order to attract media attention, researchers need to build a good relationship with journalists by consistently disseminating scientific and societal issues on molecular robotics. An intermediary organization connecting scientists and journalists may be able to play a significant role in this [36]. Former emerging technology cases in Japan show that journalists and media workers must pay due attention to the gap and differences in risk perception of emerging technologies between scientists and citizens.

Finally, a sustained interaction between molecular roboticists and social scientists could strengthen the awareness and understanding of both groups on how science can work with and for society (See challenge 1: finding and involving the ‘right’ experts and stakeholders). In this respect it is important to get young molecular roboticists acquainted with technology assessment methods and ethical reasoning. BIOMOD could provide a platform for that. BIOMOD (biomod.net) is an annual biomolecular design competition open to undergraduate students, founded and sponsored by Wyss Institute at Harvard University. Compared to the International Genetically Engineered Machine (iGEM) competition for synthetic biology [37, 38], BIOMOD currently focuses less on ethics, sustainability, safety and security aspects of targeted technologies. Such a competition seems to have long-term educative effects in the field in the sense that participant students can experience team science through the competition. BIOMOD Japan is a preliminary one-day meeting for the official BIOMOD Jamboree and the 2017 organizers invited for the first time one of the authors (GY) for a lecture on ELSI of molecular robotics (Osaka, August 2017). This is expected to nudge the BIOMOD Foundation to integrate ethical and social considerations into the judging process and organization of the competition.

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