Biohybrid Entities for Environmental Monitoring

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Abstract

In the wake of climate change and water quality crisis, it is crucial to find novel ways to extensively monitor the environment and to detect ecological changes early. Biomonitoring has been found to be an effective way of observing the aggregate effect of environmental fluctuations. In this paper, we outline the development of biohybrids which will autonomously observe simple organisms (microorganisms, algae, mussels etc.) and draw conclusions about the state of the water body. These biohybrids will be used for continuous environmental monitoring and to detect sudden (anthropologically or ecologically catastrophic) events at an early stage. Our biohybrids are being developed within the framework of project Robocoenosis, where the operational area planned are Austrian lakes. Additionally, we discuss the possible use of various species found in these waters and strategies for biomonitoring. We present early prototypes of devices that are being developed for monitoring of organisms.

Introduction

Our planet is faced with an unprecedented ecological crisis of colossal proportions owing to climate change (Poloczanska et al., 2013; Ripple et al., 2017). Environmentalists have increasingly raised concerns that in the upcoming decades, with no intervention, a large proportion of the world’s population will not have easy access to clean water (Damania et al., 2019). The worsening of water quality causes chain reactions leading to ecosystem collapse and directly and indirectly threatens the existence of various species of animals. In Damania et al. (2019), the authors propose the ladder of policy intervention in which they suggest passive, proactive and reactive strategies to respond to the water quality crisis. According to the authors, collection and sharing of water quality data are a clear part of the solution.

Environmental monitoring, especially of water bodies (Thenius et al., 2018) has become increasingly crucial for our society. Ecological systems are extremely complex, involving not only biological and abiotic factors, but also feedback to neighbouring ecological networks which might seem unrelated at first (Duffy et al., 2007; Pimm, 1984). Ecological systems are sensitive to human activities such as industry, farming, tourism, markets etc.. In order to gain deeper insights into the complex interactions of the changing ecosystems and to be able to have an early detection of disruptive processes, we propose a novel concept in robotics that allows low budget, long term, autonomous environmental monitoring to be executed by biohybrid robots. Apart from minimising human involvement and/or interaction with the ecosystem by using autonomous biohybrid robots, we will go a step further by making these robots biodegradable. Biodegradability of robots ensures that there is no long-term impact on the monitored system. Our approach to establishing such a concept is captured in the interdisciplinary project — “Robocoenosis”.

Through the use of biohybrids, we seek to introduce a novel paradigm of “life form in the loop”, which will allow the development of new types of complex biohybrid entities for environmental monitoring. We will put together living organisms and technological elements using a symbiotic/mutualistic method to form complex entities. The salient features of these biohybrid entities are energy harvesting, low-power electronics, sensing, and actuation. The lifeforms and their responses are intertwined creating a “virtual artificial organism”. The organisms are working together albeit being controlled by the electronic part of the bio-hybrid entity.

Additionally, these entities will be closely integrated and the parts remaining in the environment will be fully biodegradable (Figure 1). We intend the biohybrid entities to be autonomous, robust, and non-invasive owing to the use of adapted life forms and biodegradable materials. To explore and demonstrate the potential of such radically new biohybrid entities, we will perform a long-term autonomous field operation of underwater biomonitoring in the Austrian lakes. The general concept of Robocoenosis is shown in Figure 1.

In this paper, we will tackle the following research questions related to biohybrid entities:

• Can living organisms be used as surrogates for “classical sensors”?

• Can microbial fuel cells supply enough energy for the functioning of the robot under real-life conditions in the
Environmental monitoring in general is not a novel concept. Up until today, marine abiotic parameters are mostly monitored using technological measuring devices despite the rich variety of potential biology based bio-monitors. Some examples of bio-monitoring using life forms include the measurement of eutrophication of water by electrochemical quantification of the nitrous oxide released in denitrifying bacteria, detection of chlorophenols, pesticides and surfactants; heavy-metal pollution is monitored by observing the photosynthetic activity of photosynthetic bacteria and algae (Krøger and Law, 2005); natural and anthropogenic environmental stressors in the water-sediment interface are measured by the reburrowing behaviours of infaunal bivalves such as clams and cockles, as described by Pearson et al. (1981); Phelps (1990). Such biomonitoring is performed at population and at individual levels mainly by collecting organisms from the site and measuring their responses in the laboratory. The results refer to specific timeframes and require an analytical step for relating biological and environmental data. Bio-electronic methods recording physiological and behavioural changes according to environmental stimuli, such as mussel heart rate, have been developed, but are still at an early stage. Biomonitoring with the use of autonomous environmental set-ups has been attempted before with special focus on bivalves. MOSSEL-MONITOR® used a similar concept of detecting changes in the environment by close observation of freshwater or marine mussels and their movement patterns using electromagnetic sensors on each valve (AquaDect, 2021). This system gives accurate data on the valve openings, however it is limited to one species. Further, the Robocoenosis biohybrid entities will be able to react, e.g. by making an autonomous decision to relocate or react to the readings in a different way.

Based on these insights, in this paper, we introduce Robocoenosis biohybrid entities developed as tools for environmental monitoring and show preliminary results of experiments regarding this topic. In the following sections, we will introduce the core features of the Robocoenosis biohybrid entity, the methods that we employ and finally discuss the early results of the Robocoenosis project.

**Core features of Robocoenosis biohybrid entities**

A conceptual image of the biohybrid entity is shown in Figure 2. The main features of this entity as outlined below are that it uses life-forms (bio-monitoring or “life-form in the loop), biodegradability, and long-term autonomy through energy harvesting and energy efficiency.

**Bio-monitoring** The biohybrid entities to be developed will enable the scientific community to evaluate the ecological/environmental status of the respective lake by improving existing biomonitoring techniques. Such data related to the biological response of the organism and other related environmental conditions will allow thorough evaluation of the pressures and impacts on the marine environment.

**Biodegradability** As depicted in Figure 1, biohybrid entities to be developed will consist of two fundamentally different parts: (1) the “classical” electronic part, environment-resistant, and (2) all other parts (i.e. structures for holding and housing lifeforms, and the lifeforms themselves) which will be fully biodegradable. This will allow us to minimise usage of non-renewable materials during the robot production, minimise waste from the non-reusable parts, and allow the used organisms to remain in the their habitat.

**Long-term autonomy** We enable the Robocoenosis biohybrid entity to have long term autonomy using energy harvesting and by using low-power electronics. Microbial Fuel Cells have, so far, been tested mostly under laboratory conditions. Main challenges are the very low energy currents produced by single cells and other difficulties emerging when using their larger numbers (Oh and Logan, 2007). Here, we will improve and test their usability for the in-field use coupled with other standard energy harvesting techniques and low-power electronics to offer a wide range of operating conditions for the autonomous entities. This will advance the state of energy harvesting for autonomous underwater systems, demonstrating long-term operation in field conditions. Moreover, we will also use MFCs as biosensors. The currents produced by MFCs reflect the metabolic activity of bacteria and can be used to gain information about the environment, for example the presence or absence of oxygen or other electron acceptors.

**Methods and Goals**

Until recently, aquatic biomonitoring was performed mostly ex-situ with the use of various sampling methods and laboratory analysis. While this approach gives accurate, easily quantifiable data on the environment, such as the concentration of heavy metals, chlorophyll, presence of pesticides etc. it is not sustainable in long-term monitoring due to its high cost and time expenditure (Volkov and Ranatunga, 2006). Therefore, the use of lifeforms as natural sensors offers the opportunity for early detection of environmental changes and continuous real-time monitoring (Krøger et al., 2002). Moreover, unlike periodical chemical analysis, the use of living organisms provides a more rounded measure of water quality as they are affected by overall environmental factors, not just those that are the focus of any specific experiment (Michels et al., 1999). There are multiple ways in which animals can be used as bioindicators, for the most part, through observing behavioural, ecological or physiological changes (Manickavasagam et al., 2019). Changes in behaviour can present themselves through abnormal feeding patterns, swimming patterns, burrowing behaviours etc.
and are typically an early sign of stress (Manickavasagam et al., 2019). Ecological change is a fluctuation in population density, biodiversity, sudden disappearance or appearance of key species etc. Physiological changes could be CO\textsubscript{2} production, accumulation of heavy metals, different protein synthesis etc. and are usually traceable on an individual-level (Manickavasagam et al., 2019; Holt and Miller, 2011).

Below, we consider the constituent parts of our proposed biohybrid in detail.

**Zebra mussel (Dreissena polymorpha)**

Mussels (Bivalvia) are a good model species for bioindication thanks to their longevity, high density populations and because they use filtration as a feeding mechanism (Grabarkiewicz and Davis, 2008). Zebra mussel (D. polymorpha, Figure 3) is an invasive species, native to lakes of southern Russia and Ukraine and, thanks to its resilience, now occupies various freshwater habitats in several countries. It is one of the most widely used freshwater species of molluscs for environmental monitoring. Several studies have confirmed its high sensitivity to water pollution which often results in abnormal burrowing behaviour or erratic valve movements. *D. polymorpha* is considered a poor oxygen-regulator and its oxygen level and temperature tolerance is narrow (Alexander Jr and Mcmahon, 2004). Although it has been found rarely in hypoxic conditions, it can thrive only in well-oxygenated environments (Benson et al., 2021).

Observing the behaviour of this species, with particular interest in valve movements, can provide valuable data on the overall condition of the lake. Such monitoring could be achieved using wireless cameras to acquire real-time footage and to then use image analysis to extract the potential stressors from the images. In this case, *D. polymorpha* will be mounted on a platform in front of the camera setup which will monitor the valve moments using image analysis. The exact percentage of the opening/closing is measurable and is directly and indirectly affected by the stress levels in the environment.

**Swan mussel (Anodonta cygnea)**

Another species of interest is swan mussel (Anodonta cygnea), which is one of the largest freshwater mussels. In recent years its population has been declining due to a rising popularity of its use in artificial ponds and garden pools (Rosińska et al., 2008). The interest behind this species is its high sensitivity to oxygen levels. An abundance of *A. cygnea* is a good indicator of clean, well-oxygenated waters with nutrient-rich bottom sediments, and its valve movements are significantly affected by stress, particularly low oxygen levels (Chojnacki et al., 2007). This will be used in a Robocoenosis biohybrid entity by either actively using the swan mussel in a similar setup to the one described for *D. polymorpha* or by passively observing the surroundings and making deductions based on the relative presence or absence of this species.

**Daphnia**

The *Daphnia* genus belongs to a taxon Cladocera and is one of the most well-described planktonic crustaceans and has been used for toxicological studies for decades (mostly *D. magna* and *D. pulex*) (Hoof et al., 1994). It is considered a good bioindicator due to its sensitivity to water pollution, such as heavy metals, which often presents itself in changes of breeding patterns, mortalities or migration. It is also easy to breed under laboratory conditions, produces
Figure 2: Preliminary design concept of the Robocoenosis biohybrid entity. A number of different “organs”, each hosting a different life form, form a complete biohybrid entity. (A: Microbial fuel cells, B: Biodegradable frame, C: Technological elements and mission terminating module. D: Organs hosting different bioindicators).

large numbers of offspring and its responses are easily quantifiable. *Daphnia* uses both sexual and asexual reproduction depending on the environment, preferring asexual reproduction (parthenogenesis) under favourable conditions (Siciliano et al., 2015). It responds well to light cues (phototactic) and the degree of response varies depending on the pH, temperature and presence of pollutants (Michels et al., 2000). This property can be used to indicate potential stressors when the phototactic ability is severely affected. The degree of response to light cues is easily quantifiable with the use of a phototactic index defined as the ratio between the number of individuals responding positively to the light cue to the number of individuals presenting any other behaviour (no reaction, negative phototaxis or mortality). A light cue would be applied once within a specified timeframe and readings would be made using image analysis. Monitoring the pH and temperature of the surrounding waters will help to identify the potential stressors disrupting any phototactic behaviour.

**Chironomidae**

*Chironomidae* is a family of insects whose larval development occurs in the water (McLachlan, 1977). The eggs of *Chironomus plumosus* (Figure 4) are laid in the water and after hatching, the larvae accumulate in the sediment and produce silk, which forms a glue around themselves, resulting in the production of a tube-like structure. The shape and time needed to build such a tube is an indicator of the environmental conditions (McLachlan, 1977). Moreover, the behaviour of a late-stage larva inside the tube is affected by oxygen, which itself affects the filtration:feeding activity ratio.

*Chironomidae* are unique in the context of other insects as they use haemoglobin to collect oxygen from the surrounding water (Walshe, 1950). They also contribute to bioturbation and bioirrigation processes (Schaller, 2014). Bioturbation is defined as the reworking of soils and sediments by animals or plants, and bioirrigation refers to the process by which benthic organisms flush their burrows with overlying water. The effect of bioturbation is to increase redox processes within the sediments, creating strong electric gradients that may also have a crucial role for energy harvesting in the MFC. The tube produced by *Chironomus plumosus* has two holes at each end and the water is pumped by the larvae who feed by filtering out food particles from the produced stream.

It is possible to introduce a substratum for this species that will increase the likelihood of *C. plumosus* settlement, by exploiting their natural tigmotacticism. This substratum would ideally be quite porous, with artificial tubes/wires (made of biodegradable materials such as cotton or wood) that would be introduced beforehand to encourage their natural building processes.

**Microbial Fuel Cells (MFCs)**

One key element of any technical system is its energy source, including power management, power saving and energy harvesting. In the case of the Robocoenosis biohybrid system the production of electric power is managed by a MFC, that is colonised by local microbial life forms and uses locally available organic matter as an energy source. Energy
Figure 4: Buzzer midge larvae *Chironomus plumosus*. Photo by Donato Romano.

harvesting based on bacterial activity has been actively investigated in specific and optimized lab conditions, as well as in non-aquatic robotics and field applications (Walter et al., 2020; Ieropoulos et al., 2012; Tsompanas et al., 2021). In previous studies, it has been shown that single MFCs do not scale well (Dewan et al., 2008) and when these cells are connected together, the phenomenon of voltage reversal disables the entire system (Oh and Logan, 2007). Due to these limitations and the low currents produced, applications of MFCs have been limited (Santoro et al., 2017). Recently, energy harvesting using multiple stacked cells and natural sediments was successfully demonstrated to be capable of powering a microcontroller, environmental sensors and communication devices. We designed a bio-hybrid prototype (see Figure 5) that can embark multiple MFCs and operates underwater for long periods of time. We report first results obtained from real-world experiments in the Venice lagoon using six stacked MFCs in Figure 6. Figure 6(a) shows the voltage plotted across time for each of the stacked cells. Figure 6(b) shows the voltage built up across the super capacitor that the cells charge. This hybrid technology will be enhanced to support field experiments, coupled with other standard energy harvesting techniques and low-power electronics to offer a wide range of operating conditions for the Robocoenosis entities. Moreover, since the currents produced by MFCs reflect the metabolic activity of bacteria, it can also be used to gain information about the environment. For example, the energy harvested using MFCs can provide an indication of the presence or absence of oxygen or other electron acceptors. Therefore, the MFCs will provide insights into the microbial status of the respective lakes, and detect changes in the condition of the body of water.

Figure 5: Prototype of the MFC-Bot, capable of embarking several MFCs. Here configured with three different cells.

Low-power electronics

The challenge when building electronics for the biohybrid entity is in maximising functionality, while minimising the power consumption and physical size of the biohybrid. We anticipate that our final platforms will be manufactured on kapton (polyimide) or printed electronics paper, allowing the electronics to be flexible. To balance functionality and flexibility for researchers and users, with minimising power consumption we plan to adopt a dual processor approach. An ultra low-power STM32 (an Arm M4 based platform) will be used as the heart of the biohybrid, which will be operational permanently (potentially in sleep mode). Connected to this will be a computational module equipped to perform complex computations in a power efficient manner. Several boards from Sipeed, equipped with RISC-V processors, are suitable to be used as a computational module in the biohybrid entity. These boards with relatively higher energy consumption will be switched off by default, but will be woken by the STM32 when required. Amongst many other benefits, this architecture allows us to have a basic set of cameras connected to the STM32, and much higher resolution cameras connected to the computational module.
Low-power software, sensors and actuation

Modern microelectronic sensors have extremely low leakage currents, that is, if they can be powered off for most of the time then the average power drawn is in the range of micro-Watts. Achieving low-power operation not only requires low-power sensors but also careful software design for maximization of computational efficiency. We will employ cutting-edge engineering approaches for reducing the energy consumed by running the software on the STM32. In terms of our dual STM32 and computational module architecture, one of the key challenges is to minimize the start up time of the computational module. Energy storage and re-conversion always incurs losses, and so we will seek to minimise this step by using the energy as and when it is harvested and scheduling operations to align with peaks in the collected power. It may be that emerging ultra low-power deep learning accelerators (such as the Ambiq Apollo) can be used to help predict these times, and moreover to reduce the processing requirements on the computational module. Figure 7 shows our early prototype, which utilised a Raspberry Pi to observe a swan mussel. In this system we used a standard underwater enclosure to ensure water-tightness.

Another challenge is to allow the bio-hybrid entity to move with the given power regime. We plan to enable the biohybrid entity to emerge and submerge for a limited number of times, using mechanical or electrical energy storage devices. This way, the actuation does not over-consume the energy produced by the entity and only uses it to trigger the movement. The feasibility of using the drift to generate a directed movement will be investigated in Robocoenosis.

Fields of operation

To test the proposed method of analysing biohybrid entities for bio-monitoring, two types of lakes with distinctly different features were chosen as test-sites for the experiments and development of the biohybrid entities: glacial lakes and shallow endorheic lakes. Lakes Millstätter See (46°45’N 13°37’E) and Hallstätter See (47°33’N 13°39’E) were chosen as examples of glacial and oligotrophic lakes and lake Neusiedler See (47°56’N 16°50’E) was used as a classic example of an endorheic body of water.

Glacial lakes are bodies of water created by glacier activity, such as a glacier carving the lake basin or providing the lake with melt-water (Buckel et al., 2018). These types of lakes are mostly oligotrophic or ultraoligotrophic, which are characterized by clear water and low nutrient content (Netto et al., 2012). These waters are usually strongly stratified with a large hypolimnic volume (water layers below the thermocline), which remains cold all year-round resulting in a well-oxygenated bottom. Low algal content extends the euphotic zone (layers penetrated by light) and causes less decomposition on the bottom.

On the opposite side of the spectrum, there are eutrophic lakes which are characterised by nutrient-rich waters, high algal content and anoxic conditions in the bottom sediments. Both Hallstätter See and Millstätter See are classified as oligo-mesotrophic, which means their parameters fall in between oligo- and eutrophic conditions, but leaning towards the former (Dokulil, 1991; Ernst et al., 2009).

Millstätter See is a meromictic lake meaning that there are layers of water which rarely or never undergo mixing and are strongly stratified for an unknown period of time (Stewart et al., 2009). This state is enforced by both temperature...
and salinity differences with the lower layers being much colder, richer in salts and usually anoxic (oxygen-depleted). The anoxic layers are rarely inhabited, other than by bacteria, protozoans and some species of larvae that can survive without oxygen for certain periods of time, such as the Chironomidae (Stewart et al., 2009).

Endorheic lakes are water basins that have no external outlet, which typically connects all water on Earth to the ocean. The only water exchange occurs via evaporation and precipitation, which often results in high salt content as there are no means for the salts to be continuously removed (Soja et al., 2013). An example of that state is Neusiedl See, the largest lake in Austria, which is unique because of its extreme shallowness that never exceeds 1.8 m in the deepest point. Due to the low water volume, this reservoir is vulnerable to even minor changes in temperature or increases in nutrients and thus, is more susceptible to eutrophication (Soja et al., 2013).

Using such a variety of habitats will allow us to perform a broad range of tests for the autonomous experimental setup. The wide range of experiences that we gain from these experiments will reveal challenges and enable us to find ways to overcome them. This will enable faster development and easier utilization of the biohybrid design in other parts of the world where conditions are different.

**Discussion**

In this paper, we show that the research questions raised in the introduction can be answered as follows:

- Promising results were obtained for future use of living organisms as surrogates for “classical sensors”.

- Microbial Fuel Cells are a sufficient energy source to power a biohybrid entity, which offers the potential for environmentally friendly batteries.

We have briefly looked into the importance of aquatic monitoring and how we can achieve this with the use of lifeforms and organic energy sources. We have introduced an ambitious project and presented our early work in constructing an autonomous system for environmental monitoring. The paradigm of using life forms for biomonitoring, “life-form in the loop”, has been shown to be promising in other areas (Schmickl et al., 2013; Wahby et al., 2018; Komasilova et al., 2020). This paradigm opens doors to concepts such as ecosystem hacking where existing symbioses between organisms and their habitats can be found and manipulated to avoid collapse of ecosystems. Additionally, other salient features of Robocoenosis, namely “long term autonomy” and “bio-degradability”, are topics that will pave the way for sustainable long term autonomous monitoring in the future. These salient features of Robocoenosis could be transferred to other fields related to monitoring such as passive environmental monitoring (Albaladejo et al., 2010), classical robotics (Thenius et al., 2018) etc. The concept of using biohybrids for observing and early reporting is one step towards novel technologies to better protect, sustain and monitor the environment. An overview of this vision is shown in Figure 8.

As shown previously, the concept of using lifeforms to monitor the environment is powerful. However, it is of merit to also look at the challenges associated with this paradigm. Analysing behaviour provides a low-precision indicator of a stressor, which can introduce difficulties when using animals for environmental monitoring, particularly in situations where behaviour is affected by a variety of environmental factors and might not give exactly quantifiable data in response to a particular pollutant of interest. For example, a zebra mussel’s valve movement has been observed to be affected by many agents such as the presence of a predator (i.e. fish kairomones), mechanical irritation or chemical queues sent from an injured conspecific (Dzierżyńska-Białolączyk et al., 2019). This can be resolved by performing a thorough data analysis and identifying whether the behaviour is a sign of acute or chronic stress. Behaviour-based results are only as good as the degree of understanding of the species’ biology. For that reason, in this project, it is advisable to utilize well-researched lifeforms and compare the obtained results to lab-based or sensor-based experiments.
Similar concepts of real-time monitoring have been implemented in recent years, however rarely to the extent attempted in Robocoenosis. MOSSELMONITOR® (AquaDect, 2021) measures the shell position of each mussel within a set period of time and triggers an alarm if certain thresholds are crossed. The degree of valve opening is extracted by measuring the strength of the signal passed between sensors placed on each of the valves. While this system has tested well, it is limited in terms of species used, as it requires the use of bivalves. It is also powered by batteries, which is a feature this project aims to substitute with an autonomous power-source. Another aspect that will be improved by Robocoenosis is biodegradability. Our aim is to develop an entity as close to completely non-invasive as possible. Every non-biodegradable part will be retrieved and used in future experiments, while everything left behind will disintegrate and remain safe in the environment.

Another example of using a living organism to obtain real-time data for early warning is the Daphnia Toximeter II (Green et al., 2003). This piece of equipment is designed to detect changes in swimming pattern, distribution, distance, grouping and many other behaviours of this planktonic crustacean. If two or more of these patterns are disrupted, an early-warning system is implemented and an alarm is triggered (Enviro-Analytical, 2021). This system offers precise and fast detection of various pollutants, such as pesticides, neurotoxins and warfare agents by using image analysis on a continuous stream of river water flowing through the machine. It is a very promising application of the Daphnia genus, however it is heavily laboratory based and resource-intensive. Our system will take advantage of a similar approach while integrating the recent advances in computer vision and miniaturization of computational devices. This will enable us to enhance this basic methodology using embedded electronics and autonomous warning systems. The resulting biohybrid entity will enable real-time monitoring of bodies of water while being energy-efficient, autonomous and completely field-based.

There are certain challenges that come with the use of planktonic (swimming) species, such as Daphnia. For such species, the system must include a semi-enclosed vial that contains the animals and also allows a water flow to provide food particles, as well as exposure to potential pollutants. Daphnia is a well described species having been used as a bioindicator for decades. Their survival and reproductive efficiency varies depending on the temperature and food concentration. Observing this taxa will provide valuable information on the state of the environment, thus maintaining a holistic approach during the experiments, necessary for accurate environmental monitoring.

In addition to the difficulties associated with using the specific lifeforms mentioned above, there are other challenges when developing and using biohybrid entities. While projects such as Robocoenosis can kick off the process and establish a general methodology, the improvement of these ideas has to be done by long-term widespread use and further development and application of these tools. The solutions developed in Robocoenosis are transferable to other environments only with adaptations. Species-specific knowledge of relevant bioindicators and stressors is required to transfer our tools to a different habitats. In order to overcome this challenge, we will engage with the community through our open data plan and influence on neighbouring disciplines (Figure 8) to enable the use of our tools.

With regard to ethics, as elaborated in the “Methods” section, Robocoenosis will use invertebrates, that do not fall into the scope of animal rights laws. Although no formal ethical issues will arise, we take great care to investigate non-invasive methods for bio-monitoring.

In this paper, we have outlined our early progress in developing a biohybrid entity. The early results that we have obtained point to the immense possibilities that the given approach offers. We demonstrate early results that showcase the novel possibilities that our approach offers to the monitoring of environments using autonomous underwater robots working together with biological sensory systems.

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References


