BIOMIMETIC AUTONOMOUS ROBOTS: INNOVATION IN POLLUTION DETECTION

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Abstract**–***The Envirobot, designed by the Swiss Nano-Tero Program, is a robot built with the intention of detecting pollution in large bodies of water. This biomimetic robot is composed of a small string of chemical, physical, and biological sensors, built in the form of an eel.*

The Envirobot is an autonomous vehicle that can move on its own, guiding itself based on sensory input as well as the surveying-mode option, where a predefined path and coordinates are set for the bot to follow. Although this technology is still in its testing phase, the application of custom and commercial sensors into the Envirobot's modules allows the robot to test for multiple components at once and guide itself using sensory input.

This technology has proven to be a worthwhile investment as it revolutionizes the counter-pollution movement with its completely hands-off testing procedure. Instead of sending researchers to the field to hand-test water samples and take them back to a lab to be tested and analyzed, the Envirobot takes samples and analyses them on the spot, while simultaneously sending back the data to the base-station computer.

The purpose of this paper is to describe the multitude of technological advancements that hide within the Envirobot's biomimetic shell: the front compartment, head unit, modules, and tail. Ultimately, we conclude that this technology will make pollution detection more efficient, affordable and sustainable.

Key Words–Autonomous robot, biomimetics, water pollution, sensors, sustainability

ENVIROBOT: ENGINEERING A SOLUTION TO WATER POLLUTION

In recent years, the marine science world has been giving extra attention to the creation of machines, with capabilities including exploration and data collection in and above bodies of water. Research into autonomous robots has gained interest in nearly all areas of study in science, and marine science is no exception. Throughout the history of the marine robotic community, research has been focused on propeller-driven machines; however, the efficiency of this method has come under question recently because of the massive power output necessary to run properly. In their book, *Robot Fish*, authors Ruxu Du and Zheng Li explain that current rotary propeller-driven vehicles can only reach approximately half of the efficiency of fish in terms of power output. For fish, this number, on average, can reach about 90% efficiency [1].

With this in mind, the marine robotic industry has switched gears to refocus their research on biomimetic robots. A biomimetic robot is a machine that mimics the motion and physical make-up of an animal in order to maximize efficiency, just as evolution has done for these animals [2]. There have been a few different versions of marine biomimetic creatures, including the fish-like robot 'SoFi' created by researchers at MIT; however, some have found that the physical make-up of creatures like eels and lamprey have been easier to mimic and more effective to apply to robots [3] [4].

The Envirobot is exactly this. A group of researchers at the École Polytechnique Fédérale de Lausanne, in association with the Swiss Nano-Tera program, created an autonomous eel-like robot with the goal of having it be deployed in bodies of water in order to detect for water pollution. The main objective of this project is to create an amphibious robot that can sample and analyze water and communicate its data to an offsite location. The Envirobot can run in multiple modes, including remote, autonomous-navigation, and surveying mode. The technology behind the biomimetic robot is based on earlier projects by the team members, including three iterations of AmphiBot. During the work on AmphiBot, the team nearly perfected the science behind the movement of snake/eel-like creatures [5]. The Envirobot uses the same basic setup as the Amphibot, with multiple modules that perform different activities. The front compartment and head modules act as the brain of the Envirobot, controlling the smooth, eel-like movement and navigation, while the other compartments are built to house sensors. The Envirobot also has a tail which aids in forward propulsion.

On top of this technology, the Envirobot incorporates research into pollution-sensing devices, with the ultimate goal of detecting heavy metals in the water, such as mercury [6]. The Envirobot is built using customizable and interchangeable pollution-detecting units, which allow it to be adaptable and practical in many situations and bodies of water [5]. The application of future research into pollution-detecting sensors, such as Envirobot, creates a very optimistic future for the pollution-detecting industry as it shows the potential for an increase in effectiveness and efficiency.

The organization of this paper is as follows. The issue of water pollution and its effect on the environment is introduced in the section entitled, "Need for Envirobot: Water Pollution Detection." The technology within Envirobot is discussed next in the section titled, "Design: How Envirobot Came to Be." "Effect on Engineering and Sustainability" is devoted to the application of the Envirobot to engineering, an evaluation of the Envirobot as a viable pollution detecting tool, and to the issue of sustainability. The paper finishes with a conclusion and a look ahead at the future of the Envirobot.

NEED FOR ENVIROBOT: WATER POLLUTION DETECTION

The growing threat of water pollution affects everyone, and it is becoming more and more important that the necessary actions are made, including taking frequent water samples to test for pollutants. The current water testing methods in use can be extremely time consuming and may require entire research teams to collect samples. Envirobot functions autonomously to collect these samples and sends corresponding data to researchers working off-site, where their time is better spent. With its ability to be modified to fit different environments and to be improved as newer technology is developed, the Envirobot is a sustainable solution to mapping and collecting data on water pollution.

Severity of the Problem

Water pollution is a serious problem with considerable consequences for people's health and the environment. With such a large threat, researchers are working to develop lasting solutions, like the Envirobot, to help combat it. Polluted water is something that negatively impacts everyone, as it affects a resource that each person needs and uses. Nearly 2 billion people worldwide endanger their health by drinking contaminated water [7]. This danger extends to consuming food prepared using this contaminated water or meat from animals that had been exposed to it. Simply inhaling vapors while near highly polluted water sources can be dangerous for human health. Areas of polluted water can additionally be harmful to plants and animals in the surrounding environment. Polluted bodies of water can contain any mixture of harmful chemical substances, numerous infectious agents, radioactive waste, and many more. Exposure to polluted water can lead to a range of health consequences for the individual including contracting and possibly spreading deadly diseases [8].

Water can become contaminated from a wide variety of pollutants. The pollutants range from chemical waste to sewage to food processing waste and even fertilizers and pesticides used for farming [7]. These pollutants can even be as common as sunscreen [9]. When an average of 22 million tons per year of chemicals and fertilizers are used, it's easy to understand why this is becoming such an environmental issue. While regulations have been put in place in many areas to restrict industry and agricultural operations from dumping pollutants into bodies of water, there are still many parts of the world where there are less environmental restrictions. "In developing countries, 70 percent of industrial wastes are dumped untreated into waters, polluting the usable water supply" [9]. In these regions, where restrictions on dumping contaminants are uncommon, water pollution becomes even more of an issue and a threat.

As more advanced pollution treatments are developed, it will become increasingly essential that researchers are able to determine exactly where these treatments are needed. The Envirobot is a sustainable solution for this because it can work autonomously, and it is also highly customizable. The Envirobot's mapping and data collecting technologies will allow for researchers to decide which bodies of water should become a higher priority for treatment. Its modifiable structure allows Envirobot to be revised for each specific area it is deployed in and for newer technologies to be added as they are developed. By allowing researchers to collect map data on areas where water pollution is present more straightforward, the development of Envirobot will be critical in confronting the issue of water pollution.

Inefficiency

There are a multitude of methods that are currently used to test water for pollutants, many of which can be extremely time consuming and take away from potential research that could be taking place. Many of these tests involve samples being taken and sometimes even being tested on site. There are a wide variety of different tests that need to be completed in order to test the water for different toxins. Additional tests must be taken if the water needs to be tested for basic stability. One particular test that finds the biochemical oxygen demand of the water, in order to determine the concentration of dissolved oxygen, takes five days to complete using a 5-day bioassay test. During a test of this length and longer, measures must be taken to prevent contaminating samples while transporting them. While these tests are integral to the water testing process, they are time consuming and inefficient compared to the ability of using autonomous robots to complete the task.

Envirobot can complete many of these tests on its own within its interchangeable modules. It is also able to complete these tests without the need for onsite researchers. The process of testing water for pollutants, a process that currently takes a trained team, can be collected and reported by the Envirobot without a team on site. Compared to the currently inefficient pollution detecting process, this innovation is invaluable not only to researchers but to everyone affected by water pollution.

Hope for Envirobot

The Envirobot is an autonomous robot, meaning that it can direct itself and run on its own, that is being developed to track and map areas of water pollution in bodies of water without the need to be controlled by a person. Using its mapping technology, Envirobot can be sent to a specific location to collect data or can even follow a pollutant that it detects and follows. Envirobot can be sent into highly polluted or dangerous areas that may not be safe for researchers to go themselves. Envirobot is also designed to move through water and test for pollutants without disturbing its environment. Utilizing its structure of different modules, Envirobot tests bodies of water for pollutants and collects a plethora of data. The robot is designed to function on its own and send data remotely back to researchers off site. This allows for efficient data collection without the need of researchers expending their time. Envirobot is also highly customizable, so the modules can be changed and altered based on the needs of the researchers or the body of water it is being used in. This also allows for different variations of Envirobot to be constructed depending on the needs of the researchers or the specific body of water.

As technology is continuously developed to aid in treating and combating water pollution, having the ability to track areas with high amounts of water pollutants will be just as valuable. Having technology that can fully function on its own without the need for researchers on site is invaluable and allows for time to be devoted to other aspects of their research in treating water pollution. Researchers are given more time to analyze this data and decide what the next course of action should be instead of spending a large chunk of their time on collecting data. This efficient balance of robotic monitoring and human research and evaluation will allow for tasks to be assigned and completed as needed without expending valuable time.

Development of autonomous robots, like Envirobot, is important for the future as it allows tasks to be delegated to machines. Tasks that are time consuming or dangerous for human researchers to complete, such as collecting and testing water pollution, can be left to machines to perform. In turn, more complicated tasks, such as evaluating the collected data, can be left to human resources. It also allows for data collecting processes to transpire without taking any of the researchers' time other than taking Envirobot to the body of water and allows for them to focus on other tasks. When everyday products can be deadly pollutants if they make their way into our water supply, the threat of water pollution is becoming increasingly real. The amount of people using these dangerous products only continues to rise, bringing a heightened rate of water contamination along with it. This threat calls for technology that will last and sustain itself now and in the future. The Envirobot is already proving to be a lasting technology with its high customizability and uses in many situations. The structure of Envirobot allows for it to be upgraded as technology improves. As the threat of water pollution continues to grow, it will be the technology of Envirobot that will lead us into the future.

DESIGN: HOW ENVIROBOT CAME TO BE

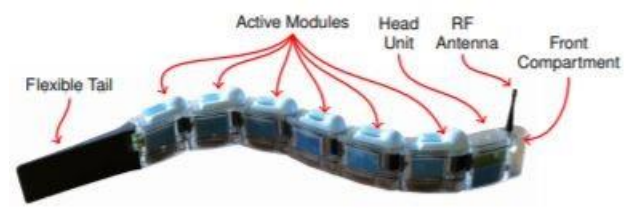

FIGURE 1 [5]
Envirobot with a front compartment, RF antenna, head unit, six modules, and a flexible tail.

According to École Polytechnique Fédérale de Lausanne, one of Europe's most famous science and technology institutions, Envirobot is made up of a few key parts: a front compartment, radio frequency (RF) antenna, head unit, modules, and the flexible tail. Starting from the front of the robot, there's the front compartment which adds navigation and computational abilities. In the future, the front compartment will have an antenna for long range communication. The RF antenna is for remote command and control. The main low-level controller is held in the head unit of Envirobot. Next are the modules, which contain a variety of sensors including "chemical, physical, and biological sensors" [6]. The head unit and modules require a lot more explaining and will be described further below. The final piece of Envirobot is the 240mm flexible tail that provides thrust during swimming. Envirobot is both a biomimetic and autonomous robot.

Technology Within the Modules

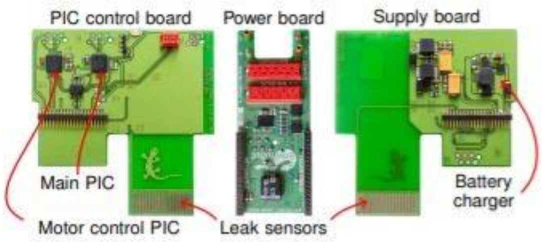

FIGURE 2 [5]
Electronic board within Envirobot's active modules.

One of the reasons that Envirobot is so unique is its customizability. The number of active modules can be increased or decreased depending on the application and availability of the modules. Each module is 125mm x 50mm x 90mm in length, width, and height respectfully [5]. To allow Envirobot to stay afloat, each module is designed to be slightly buoyant [5]. Each sensor within the modules can be personalized to measure for different pollutants, temperature, pH, etc.

Within each module there are three electronic boards, including the control board, power board, and supply board. The control board is composed of two Programmable Intelligent Computer (PIC) Microcontrollers (MCU), which each serve a different purpose. A PIC MCU is essentially a small computer on a single integrated circuit. The motor control PIC MCU is devoted to the low-level motor control, while the main PIC MCU is to "collect information from local sensors, accept commands from the head module, and even if needed, perform a local sensory feedback control" [5]. The supply board holds the battery charger, which will charge the two 6.66 Wh LiPo batteries when an external power source is collected. The supply board also provides the different electronic components of the module, including different sensors, with varying voltage levels, depending on need [5]. Both the supply board and control board have leak sensors to ensure that Envirobot is not, as the name implies, leaking.

Technology Within the Head Unit

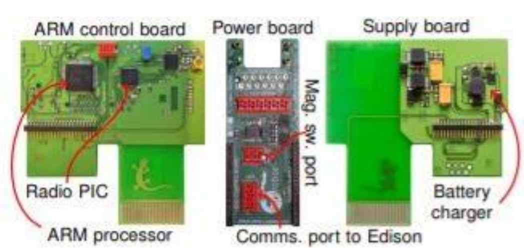

FIGURE 3 [5]
Electronic board within Envirobot's head unit.

The head unit has a similar makeup as the active modules. However, it does not contain a motor. The head unit "synchronizes the movements of each joint" to ensure smooth swimming. The head unit communicates to the other modules through the Controller Area Network (CAN) bus which runs from tip to tail. The CAN bus can be compared to the central nervous system of the human body, facilitating communication between all parts of the body. The primary purpose of the CAN bus is to allow any MCU to communicate with the entire system without causing an overload to the controller computer [10]. Additionally, the CAN messages are "prioritized based on IDs so that the so that the highest priority IDs are non-interrupted" [11]. There are eight key parts to a CAN message and the CAN-ID is the component that contains the message priority. This means that the more important messages are sent to and read by the head unit first.

The power board of the head unit is very similar to the power board in the modules, except for a few adjustments. The power board "hosts a connector for a magnetic switch" which is used to turn the robot on and off [5]. Also, it has a connector which provides power and a UART port, a physical circuit in an MCU with a primary purpose of transmitting and receiving serial data, for connecting the ARM processor to the Linux computer-on-module (COM). The supply board in the head unit is identical to the supply board in the modules.

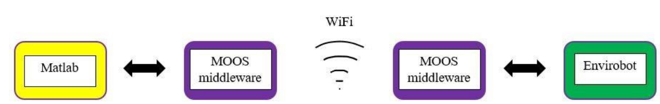

FIGURE 4 [12]
Visual for MOOS

Another very important piece in Envirobot is MOOS. MOOS is a "cross platform middleware for robotics research" [5]. The Envirobot team uses two MOOS middlewares, one on the base-station computer and one on Envirobot. The software modules are developed in Matlab and integrated with MOOS middleware. Matlab is used because of its' fast prototyping. The MOOS middleware on the base-station computer communicates with the MOOS middleware on Envirobot via WiFi. Before the new software modules are implemented into Envirobot, they must go through a series of extensive tests to test module stability among other things.

Sensors: Different Types for Different Tests

The last and most important piece of Envirobot is the sensors. The modules come 'empty' without sensors; this is purposeful so that researchers and scientists can design and develop their own sensors [13]. The Envirobot team has already successfully designed and tested two sensors, including temperature and electrical conductivity. There are many scientists designing assorted kinds of sensors right now, including a pH sensor and biosensors.

The pH sensor employed in Envirobot is not a standard pH sensor. This sensor is small, flexible and based on iridium oxide nanoparticles. The pH sensor was fabricated using the layer-by-layer technique. The layer-by-layer technique layers "alternating oppositely charger materials" to produce a film [14]. There are a couple different ways to do this process, but this particular project used ink-jet printing. The pH sensor will be alternating iridium oxide nanoparticles and the poly(diallyldimethylammonium chloride) polymer on an indium tin oxide foil. The pH sensor was tested on the surface water of Des Ils Lake (Sion, Switzerland) and tap water taken from the municipal water supply of Sion. Both samples of water were tested by the iridium oxide-based pH sensors designed for Envirobot and compared with the readings of a glass electrode. The new sensors displayed excellent reproducibility and stability [14].

One biosensor that is currently being developed is filled with tiny crustaceans called Daphnia, also known as water fleas. These tiny creatures are currently very popular in chemical and environmental research because they are incredibly sensitive to contaminants. Daphnia can measure pollutants without actually knowing what they are looking for; this is a remarkable feat because Daphnia can tell if there's a problem, even if there doesn't appear to be [13]. The water flea's movements are affected by the toxicity of the water. In this module, there are two vessels containing Daphnia and the difference between these two vessels is the water. One of the containers is filled with clean water, while the other container is filled with the water Envirobot is swimming in. The container of clean water acts as a control group for the movement of the Daphnia, so researchers can compare the movements from the clean water to the movements from the other water.

Another cell-based biosensor in the works is based on a Xenopus Laevis oocyte. A Xenopus Laevis is a genus of African frogs, which are fully aquatic and easy to maintain, and an oocyte is a cell in an ovary. The eggs that these frogs lay are large in diameter and are delivered in large quantities year-round. The Xenopus oocytes can tolerate extensive manipulation and are easy to inject with an array of materials. In this sensor, the Xenopus Laevis Oocyte are microinjected with cRNA coding ligand-gated ion channels. This means that the cells are injected with cRNA, a human engineered strand of synthetic DNA, telling the cell when to open in response to a ligand binding. A ligand can be a small ion, molecule, or protein and in this case, it's the pollutant. When the ligand binds to a specific site on the cell membrane, the transmembrane proteins opens allowing specific ions such as Na^+, K^+, Ca^{2+}, or Cl^- to cross the membrane of the oocyte cell. The charged ions entering the oocyte change the voltage of the oocyte [15]. Therefore, a change in voltage is correlated with a pollutant being present.

Biomimetics: Taking Inspiration from the Evolution of Sea Creatures

Envirobot is an example of biomimetics, taking inspiration from snakes and elongated fishes, such as an eel. When these creatures swim, their entire body moves like a wave starting from the head and ending at the tail. This type of movement is called anguilliform locomotion, where the waves cause each portion of the body to "oscillate laterally across the axis of movement" [16]. This type of movement is very effective in eels, who can cover long distance in short periods of time. During migration, eels can cover distances of approximately 5000 km in about 180 days [5].

In the joint connecting two modules, there is "one degree of freedom that controls the angle (on the horizontal plane)" [5]. Degrees of freedom refers to the freedom of a solid body in three-dimensional space, specifically how it moves. By adjusting the relative angle at each joint, it's possible to generate a traveling wave down the body of Envirobot. The amplitude (A) and frequency (f) of oscillation have a direct impact on the propelling force. Additionally, both the amplitude and frequency are used in the forward speed control. To bend the traveling wave and change the direction of Envirobot, the turning offset (Θ_{offset}) can be altered or changed [5].

Envirobot is in a biomimetic form is because of the issues that have come from the previous underwater vehicle propulsion systems. While the rotary propeller has been used for almost 200 years, researchers who have taken a closer look at the propeller suggest that it is wildly inefficient [1]. When taking energy output and battery life into consideration, a propeller system was clearly not the right decision for the Envirobot. The researchers who designed and built the Envirobot and its predecessor, the Amphibot, decided that in order to create a robot that is not only useful now, but also for the future of this technology, they needed to find a more efficient propulsion system. They looked to nature, and the thousands of years of evolution that went into modern sea creatures. An eel is particularly efficient when it comes to forward propulsion, and it has been shown that they are able to reach nearly two times the efficiency of human-made vehicles [1]. For this reason, the Envirobot is shaped like an eel [5].

When looking at comparable machines like remote controlled boats, we see that the Envirobot almost doubles the battery life, going from 8 to 16 minutes [1] [5]. While 16 minutes may not seem like a lot, a doubled battery life on a similar power output is quite impressive for the biomimetic robot. Biomimetics is a relatively recent field of study, but the Envirobot proves that the application of biological mechanisms from animals can improve a variety of other research fields, including autonomous vehicles.

Autonomous Navigation: Using Sensor Data to Follow Pollution Trails

While most of the autonomous robotic research has been focused on land-based vehicles, a large amount of this research is applicable to marine-based vehicles as well. Autonomous underwater vehicles, also known as AUVs, have been in development for a very long time, and while not as main stream as something like a self-driving car, they are used just as much, if not more than land-based autonomous vehicles. While many may assume that an AUV would be easier to make and control because of the wide-open spaces the oceans provide, having an underwater vehicle causes its own problems. Other than the obvious issue of forcing robots to be fully water-proof, the immense pressure that water puts on submerged objects adds a complexity to the development of AUVs. Despite the design complications of AUVs, they have proven to be especially helpful for marine science. In his essay regarding the future of autonomous underwater vehicles, Russel B. Wynn spoke about how these vehicles can be cost effective and safer alternatives, especially when dealing with places humans cannot reach [17].

Envirobot has been granted the ability to move in three types of ways, including surveying mode, autonomous-navigation mode and remote. In surveying mode, the robot follows a predefined path and several waypoints it must pass through. In autonomous navigation mode, the robot can swim in autonomous-navigation mode where it "must guide its movements and sampling based on the sensory input [5]. This data can be stored or communicated to an external observer. Lastly, the robot can be driven remotely using RF. This is only used in case of an emergency to "manually override commands to drive the robot to a safe zone or out of danger" [5].

While the autonomous technology of the AUV is still being improved, the research has hit a relative stalling point because of propulsion issues. In their book, *Advances in Unmanned Marine Vehicles*, Geoff Roberts and Robert Sutton discuss the history of underwater vehicles, and where the autonomous underwater vehicles technology is heading. They detail the issues with the current AUV model by claiming, "AUVs with rigid hulls and powered by rotary propellers suffer from problems such as inefficient propulsion, positioning difficulties, limited turning agility and imprecise hovering" [18]. Here they explain that the current technology associated with underwater vehicles in general, is flawed, suggesting that there are more efficient ways of moving underwater. They later go on to discuss a biomimetic AUV very similar to the Envirobot. They bring up the Biomimetic AUV model, which has a slender body and is made up of three segments, with waves passing from nose to tail, similar to the eel-like motion of the Envirobot. They go on to explain how an AUV is the perfect system to run biomimetic mechanisms on as it would be very difficult for a human to remotely control something with such complex motion. The future of autonomous underwater vehicles is clearly going in the direction of biomimetic machines, and the Envirobot is a huge first step for this technology.

FIGURE 4 [6]
Envirobot in Lake Geneva.

EFFECT ON ENGINEERING AND SUSTAINABILITY

The development of Envirobot is bringing together many fields of engineering to make an autonomous innovation. The project shows how when engineers can combine skills, they can create something that will help solve a problem that threatens everyone. Autonomous robots as a whole are already proving to be valuable in a wide range of fields and applications, and as more advanced technology is developed their usefulness will only continue to grow. The Envirobot and its significance to the water pollution detection process will begin to grow until it is too massive to ignore, and its customizability allows it to be adapted as needed. As new pollution detection technology is developed, Envirobot will be able to adapt with ease. Envirobot is one of many autonomous robots in development that will continue to be the future of engineering as they continue to find new applications for these innovations.

Evaluation of Envirobot

While the Envirobot is still in its testing and research phase, there have been important strides towards its completion. The Envirobot has been tested many times in controlled bodies of water, i.e. pools, where it has successfully navigated on its own and using programmed parameters. The indoor tests are not nearly as impressive as its incredible feat of navigating and mapping Lake Geneva using its autonomous technology. The Envirobot was released into the lake in 2017, and over time it was able to maneuver itself around the natural features of the lake without interfering with the biological happenings of the lake [5]. The mapping of Lake Geneva was a huge step for the Envirobot because it showed the ability to make its way through the largest lake in western Europe without any malfunctions. Because the robot was able to drive through such a large distance by itself shows a very optimistic future.

In addition to mapping Lake Geneva, the researchers Behzad Bayat and Jan Roelof van der Meer deployed the Envirobot into the lake with another goal. Previously, the Envirobot had only been tested in controlled bodies of water such as pools, where it was able to test for different substances and follow the trail. Doing this in a large, natural body of water, however, is no easy task. The fact that Lake Geneva is a natural body of water means that there is an abundance of different substances in the water other than what the sensors in Envirobot are testing for. These different substances could interfere with the Envirobot's testing procedure. Despite these concerns, the Envirobot proved that it was up to the challenge. Envirobot's team intentionally contaminated a small portion of the lake with salt. The Envirobot was equipped with salt sensors and given the task of testing the water for salt and making navigation decisions based on this test. The Envirobot was able to maneuver itself to the highest levels of salt, which proves it has the capabilities of testing and following different chemicals or particles. The ability that Envirobot can successfully test for these pollutants shows the possibilities for the future of the Envirobot in a pollution-detecting environment.

The pollution-detection industry has been plagued by issues with cost and time effectiveness. As stated earlier, the current pollution-detection methods are inefficient in that they require many personnel involved and time commitment [10]. The type of sensors, the way in which these sensors are deployed, and the retrieval of the data are all very time consuming and require an unnecessary number of steps. The Envirobot will be the solution to this problematic system. Instead of collecting samples, transporting them to testing facilities, and then delivering the data to a site for analysis, the Envirobot can do all these things instantly, and send the data back to its base-station computer. This efficient method of testing water samples is added to by the autonomous nature of the Envirobot. The Envirobot's ability to make navigation decisions based on the data it analyses means it is able trace the pollution to its source, allowing for authorities to deal with or dispose of the issue. This can be exceptionally helpful in a situation in which the cause of the polluted area is unknown.

If Envirobot were able to be mass produced, the bots could be placed in bodies of water all over the world and find a pollution issue before any major sort of environmental or health risks are caused. The application of future sensing or even filtering technologies to the effective biomimetic Envirobot structure will allow for a much easier way to detect and deal with pollution. The efficiency of the biomimetic motion on top of the impressive sensors could help prevent catastrophic pollution events like the Deepwater Horizon oil spill, which caused marine life to die at record rates [19].

While the Envirobot can become a useful tool for pollution-detection, it does have a few flaws that can be touched upon in future versions. The relatively short battery life of the Envirobot has proved to be an issue for the realistic wide-spread application of the robot. The application of solar-fueling technology to the Envirobot can help this; however, the Envirobot's battery life is held back by the current available technology. Researchers are looking to improve their size to power output of the next versions of the Envirobot. For this first iteration; however, it was the best decision for the creators to use the batteries used because they were the most efficient for the preliminary tests.

THE FIRST STEP TOWARDS ELIMINATING WATER POLLUTION

The path to creating the Envirobot has gone through many different iterations, and it has taken innovations in a variety of engineering fields. The autonomous navigation stored in the head, the chemical, physical and biological sensors as well as the biomimetic structure of the Envirobot come together to create a very impressive tool for dealing with issues of water pollution.

The issue of water contamination can be seen throughout human history, and while discoveries over the past few decades have helped the current status slightly, the anti-pollution research, detection and action is entirely inefficient. Increasing amounts of time and money are being wasted in outdated sampling and testing features, and if nothing is done about this, the pollution-detection and anti-pollution industries could possibly run themselves into the ground.

As discussed previously, the Envirobot is an enormous step in the right direction, away from inefficient techniques of the past. The Envirobot's ability to collect and analyze water samples as it is swimming is a massive improvement from the current techniques. The Envirobot's successful mapping and tracking tests in Lake Geneva prove that the application of biomimetic techniques to autonomous robots working with personalized sensors is a much more cost-effective way to use research resources.

The future of the Envirobot and products like it is very bright. The biomimicry technology is very important for the optimization of robots and autonomous nature of the robot allows for it to be used without extensive human interference. The application of biological, chemical and physical sensors will allow the Envirobot to test for a large variety of polluters, meaning it can be useful almost anywhere. If the Envirobot is able to improve on its flaws and add new features and adaptability, it will become an impressive tool for pollution detection and even elimination.

SOURCES

[1] R. Du, Z. Li, K. Youcef-Toumi, and P. V. y Alvarado. "Robot Fish". Springer Berlin Heidelberg. 2015. Accessed 02.27.2019.
[2] "Biomimetics." Merriam-Webster. Accessed 01.17.2019. https://www.merriam-webster.com/dictionary/biomimetics
[3] J. DelPreto and D. Rus. "SoFi – The Soft Robotic Fish." Distributed Robotics Laboratory. Massachusetts Institute of Technology. 12.07.18. Accessed 03.03.19. https://www.csail.mit.edu/research/sofi-soft-robotic-fish
[4] B. Bayat, N. Crasta, A. Crespi, A. Pascoal, A. Ijspeety. "Environmental Monitoring using Autonomous Vehicles: A Survey of Recent Searching Techniques." Polytechnique Federale de Lausanne. 01.25.2017. Accessed 01.17.2019. https://infoscience.epfl.ch/record/225318/files/environmental-monitoring-autonomous.pdf
[5] B. Bayat, A. Crespi, A. Ijspeert. "Envirobot: A Bio-Inspired Environmental Monitoring Platform." BioRob at Ecole Polytechnique Federale de Lausanne. 2017. Accessed 01.17.2019 https://infoscience.epfl.ch/record/223066/files/bayat-2016b.pdf
[6] Ecole Polytechnique Federale de Lausanne. "Pinpointing sources of water pollution with a robotic eel." PHYS.org. 07.25.17. Accesses 01.17.19. https://phys.org/news/2017-07-sources-pollution-robotic-eel.html
[7] "Water Pollution." The National Institute of Environmental Health Sciences. 09.1.2018 Accessed 03.02.2019 https://www.niehs.nih.gov/health/topics/agents/water-poll/index.cfm
[8] "What Is Water Pollution?" Environmental Pollution Centers. 2017. Accessed 03.02.2019 https://www.environmentalpollutioncenters.org/water/
[9] "Water Pollution" National Geographic. Accessed 03.02.2019 https://www.nationalgeographic.com/environment/freshwater/pollution/
[10] X. Luo and J. Yang. "A Survey on Pollution Monitoring Using Sensor Networks in Environment Protection." Department of Information Engineering at Zunyi Medical University. 01.14.2019. Accessed 03.05.2019 https://www.hindawi.com/journals/js/2019/6271206/
[11] "CAN Bus Explained – A Simple Intro (2018)" CSS Electronics. 07.21.2017 Accessed 03.02.2019 https://www.youtube.com/watch?v=FqLDpHsxvf8
[12] M. Brennan. "Visual for MOOS." 2019.
[13] Kennedy, Kelsey. "An Eel-Inspired Robot is Scientists' Newest Pollution Sniffer" Atlas Obscura. 09.27.2017 Accessed 03.04.2019 https://www.atlasobscura.com/articles/envirobot-water-quality-robot-switzerland-eel-pollution
[14] J. Acosta, H. Girault, M. Jovic. "Flexible pH Sensor Based on Layer-by-Layer Assembled Iridium Oxide Nanoparticles." Nano-Tera. 2016. Accessed 03.02.2019 http://www.nano-tera.ch/pdf/posters2016/Envirobot254.pdf
[15] B. Barfeton, R. Benton, D. Bonzon, P. Renaud, G. Zappia. "Xenopus Laevis Oocyte Based Biosensors." Nano-Tera. 2014. Accessed 03.02.2019 http://www.nano-tera.ch/pdf/posters2014/Envirobot244.pdf
[16] "Anguilliform Locomotion" Encyclopaedia Britannica. Accessed 03.01.2019 https://www.britannica.com/topic/locomotion/Anguilliform-locomotion
[17] R. Wynn. "Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience." Marine Geology. 06.01.2104. Accessed 03.04.2019. https://www.sciencedirect.com/science/article/pii/S0025322714000747#
[18] G. Roberts and R. Sutton. "Advances in Unmanned Marine Vehicles." The Institution of Engineering and Technology, London, United Kingdom. 2006. Accessed 03.04.2019
[19] "Deepwater Horizon Oil Spill: Longterm Effects on Marine Mammals." National Ocean Service. National Oceanic and Atmospheric Administration of the U.S. Department of Commerce. 04.20.2017. Accessed 03.05.2019 https://oceanservice.noaa.gov/news/apr17/dwh-protected-species.html

ADDITIONAL SOURCES

"What is a Ligand?" Chemicool Dictionary. Accessed 03.25.2019 https://www.chemicool.com/definition/ligand.html
"Introduction to Xenopus, the frog model." Xenbase. Accessed 03.25.2019 http://www.xenbase.org/anatomy/intro.do
Oxford Mobile Robotics Group. "What is MOOS?" MOOS. Accessed 03.26.2019 http://www.robots.ox.ac.uk/~mobile/MOOS/wiki/pmwiki.php/Main/Introduction

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