Microrobotics

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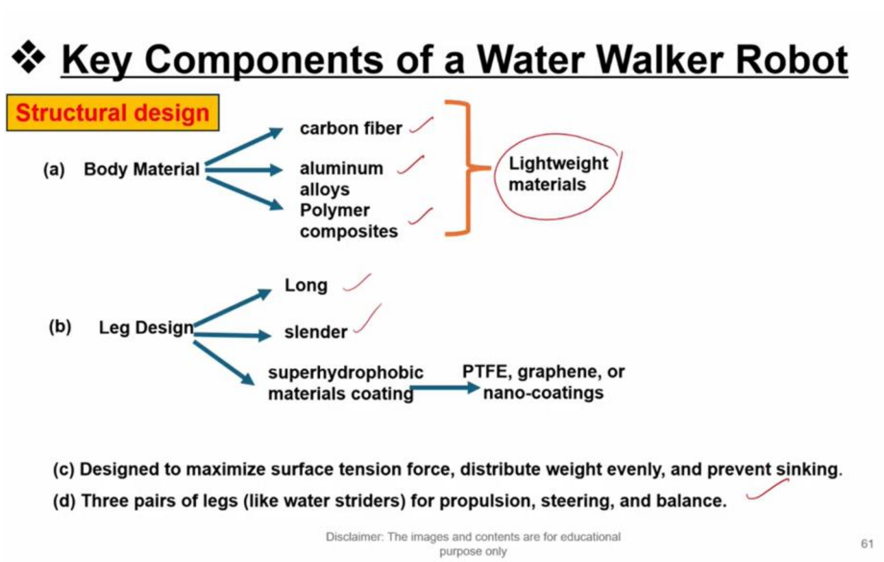
Week- 12

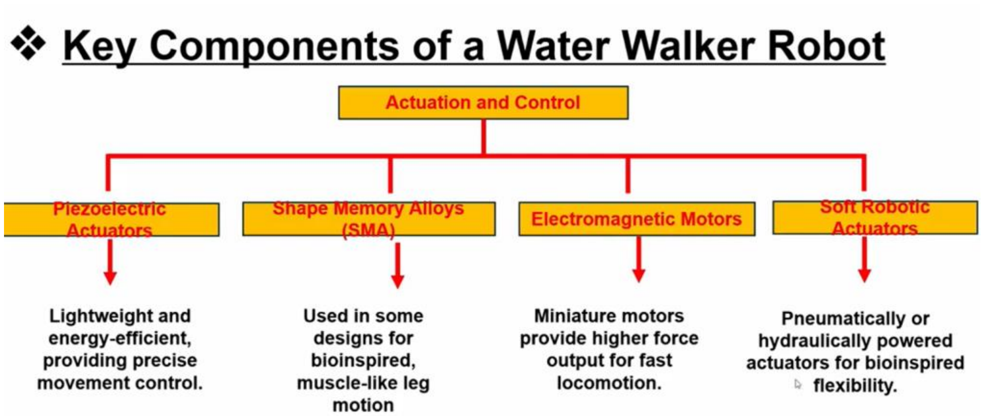
Lecture No- 60

Bio Inspired Micro Robots (Integrated Approach) - Module 05

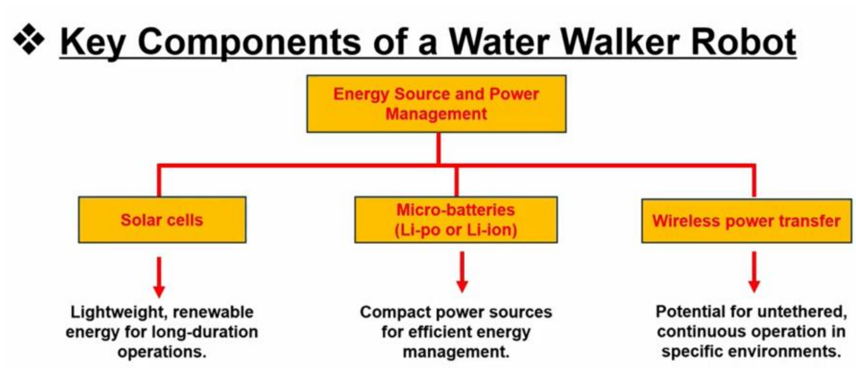
So, in the last class, we discussed in detail the water walker robot, some of the key mechanisms involved in these water walker robots, the locomotion involved in these water walker robots, and some of the subcomponents that cater to the robots. Now, in today's lecture, we will discuss some of the key components related to this water worker robot. With reference to the key components' perspective point of view, closely look into the structural design, body material, and leg design. With reference to body materials, some of the materials that contribute to the body materials are carbon fiber, aluminum alloys, and polymer composite. These kinds of body materials are lightweight materials that are being effectively used. Then, with reference to the leg design perspective, there is a long, slender, superhydrophobic material that is being coated, and there is a PTFE graphene or nano coating that is being applied here.



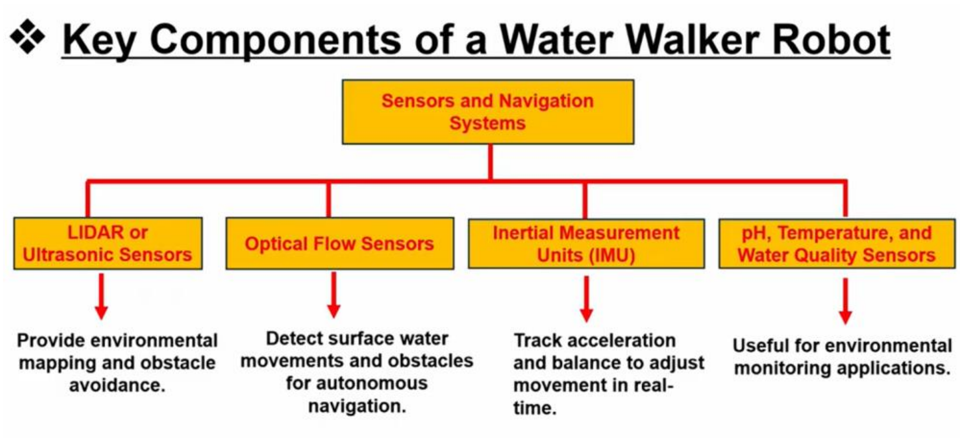
In order to design to maximize the surface tension force and to distribute a weight evenly, it is mainly meant for preventing sinking. There are three pairs of legs, like those of a water strider, for propulsion, steering, and balancing. These three pairs of legs are like water striders as they provide propulsion, steering, and balancing mechanisms. Now, when we look into the key components of these water walker robots from the perspective of actuation and control.



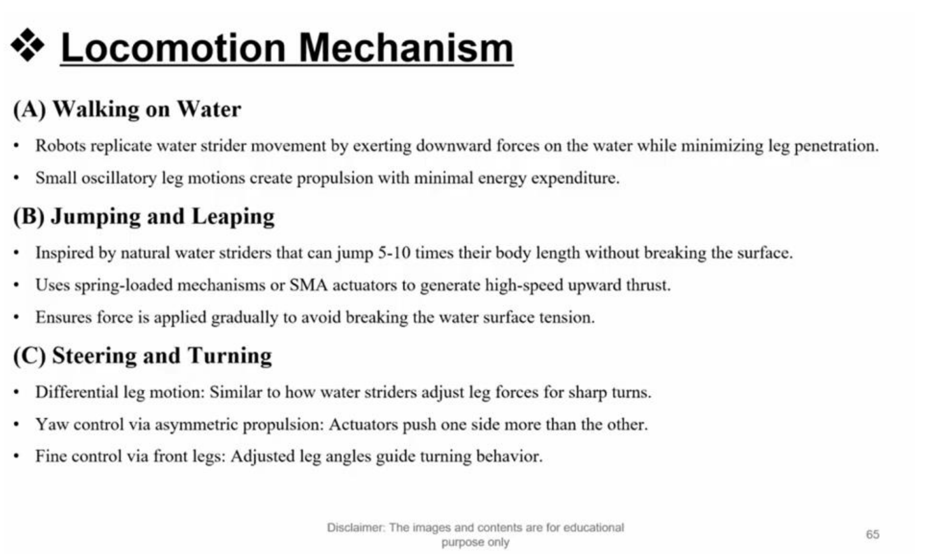
So, we can classify some of the components, which include the piezoelectric actuator, the shape memory alloys, the electromagnetic motors, and the soft robotic actuators. These piezoelectric actuators are of concern; we are well aware that they are lightweight and energy efficient, and they provide precise movement control. With reference to the perspective of shape memory alloys, it is used in some designs for bio-inspired muscle-like leg motions. With reference to the perspective of electromagnetic motors, these are some kind of miniaturized motors that provide a high force output for fast locomotion. From the perspective of soft robotic actuators, these are pneumatically or hydraulically powered actuators for bio-inspired flexible systems.



Some of the key components of these water walker robots include an energy source and power management, where we can closely observe the different energy sources involved. We have the solar cells in place, the microbatteries, and the wireless power transfer. So when we try to look into the solar cells, these are a kind of lightweight renewable energy source for long-duration operations, which can be embedded along with such biomimicking robots. And then, with reference to the battery perspective point of view, as and when we try to focus on the compact power source, it can be effectively used for different efficient energy management. And then we can also deploy a kind of wireless power transfer; it has the potential for untethered and continuous operation in specific environments.

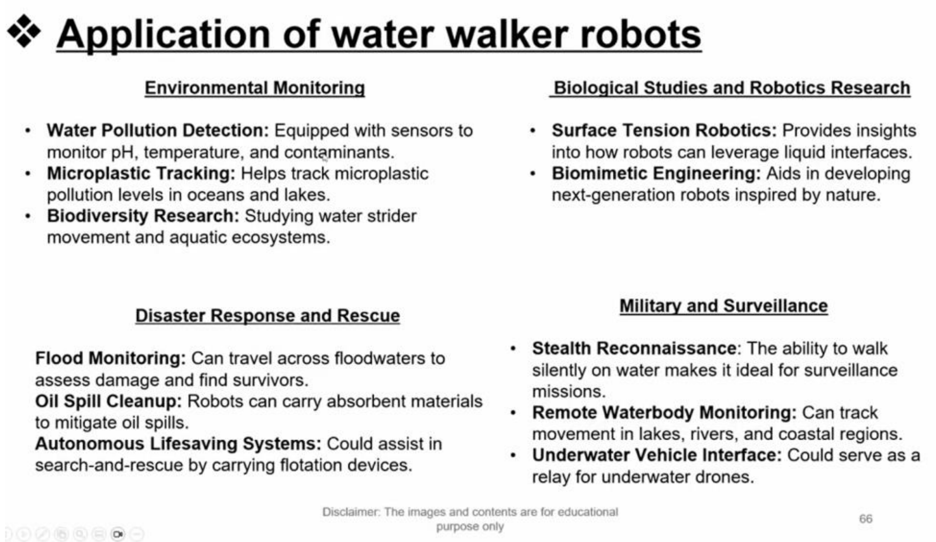


So, some of the key components of these water walker robots are the sensors and the navigation system. So, as far as the sensor and the navigation systems are concerned, we have a LIDAR or ultrasonic sensor, an optical flow sensor, an inertial measurement unit, and a pH temperature and water quality sensor in place. So, in the case of LIDAR or an ultrasonic sensor, it provides environmental mapping and obstacle avoidance. As far as the optical flow sensor is concerned, it is used to detect surface water movement and obstacles for autonomous navigation. Inertial measurement units (IMUs) are concerned; they are used for tracking acceleration and for balancing to adjust movement in a real-time environment.

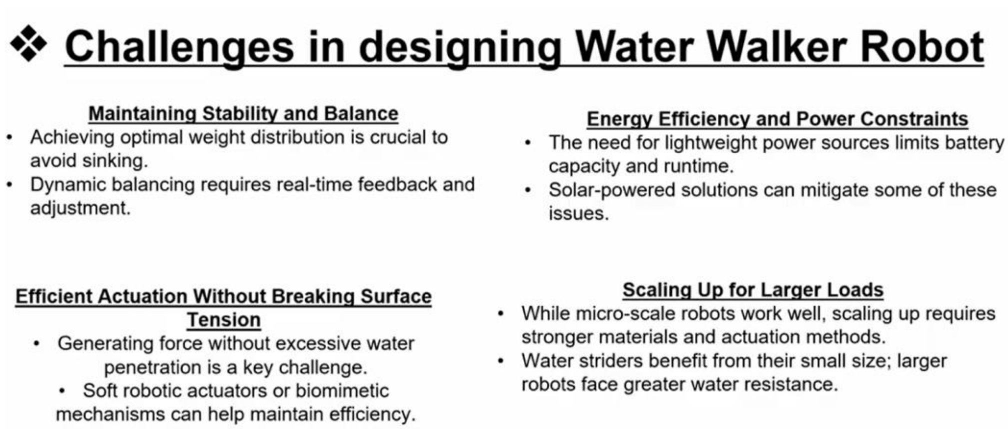


Now, if we try to map the reference to the application perspective point of view, these pH, temperature, and water quality sensors are highly useful for environmental monitoring applications. Now, when we try to look into the overall locomotion mechanism, there is one mechanism that is deployed that is kind of walking on water. These robots replicate a kind of water strider movement by exerting downward force on water while minimizing leg penetration. Second, it has a small oscillatory leg motion that creates propulsion with minimal energy expenditure. When we look into the jumping and leaping perspective, it is inspired by the natural water striders that can jump 5 to 10 times their body length without breaking the surface.

And it uses a kind of spring-loaded mechanism or a SMA actuator to generate a high-speed upward thrust motion, and it ensures a force that is applied gradually to avoid breaking the water surface tension. Now, when we try to look into the steering and the turning locomotion, it has a differential leg motion; it is similar to how a water strider adjusts a leg force for sharp turns. It has a kind of yaw control via asymmetric propulsion. The actuator pushes one side more than the other, and it has fine control via a front leg that adjusts the leg angles, which guide a guiding turning behavior. Now, when we closely look into the application perspective of these water strider robots. So when we try to look into environmental monitoring, it is meant for detecting water pollution and is equipped with sensors for monitoring pH, temperature, and contamination. With reference to microplastic tracking, it helps to track the microplastic pollution levels in the oceans and lakes. From a biodiversity and research perspective, it involves studying water strider movement and can create an aquatic ecosystem. With reference to biological studies and robotic research, these are kind of surface tension robots that provide insight into how robots can leverage the liquid interface, and they have biomimetic engineering that aids in developing the next generation of robots inspired by nature. Now, when we try to look at it, it also has potential applications in the case of disaster response and rescue, such as flood monitoring, so that it can travel across the floodwaters to assess the damage and find the surveyors.

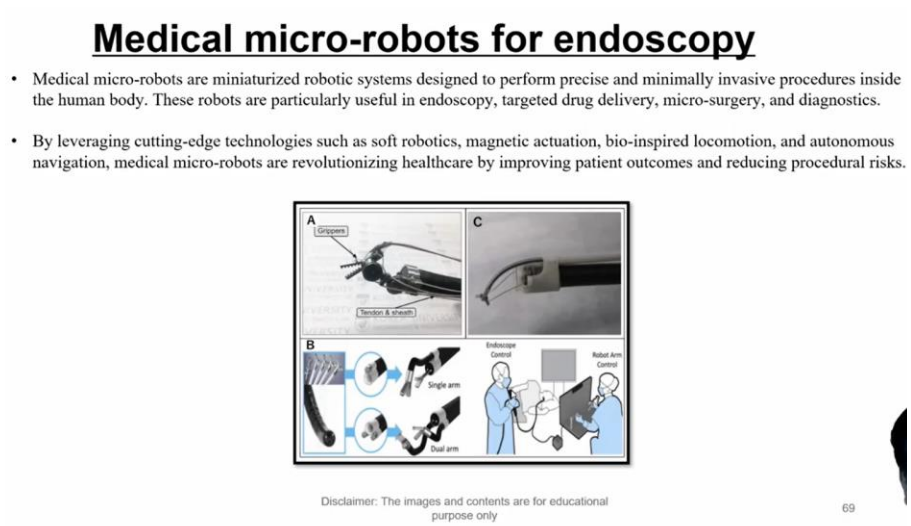


Oil spill cleanups allow these robots to carry absorbent material to mitigate the oil spills. Autonomous life-saving systems could assist in search and rescue by carrying floating devices. Military and surveillance involve a kind of stealth reconnaissance, with the ability to walk silently on water, which makes it ideal for surveillance missions and remote water body monitoring; it can track movements in lakes, rivers, and coastal regions. As far as an underwater interface is concerned, it could serve as a kind of relay for underwater drones. Now, with reference to some of the challenges involved in designing these water walker robots, one of the key challenges is maintaining stability and balance. Achieving an optimal weight distribution is crucial to avoid sinking. So, in order to maintain buoyancy, appropriate material selection needs to be made, and the design has to be optimized for efficient buoyancy. And then it also kind of involves a dynamic balancing, which requires real-time feedback and adjustment. From an energy-efficient and power-constrained perspective, there is a need for a lightweight power source that limits battery capacity and runtime, and it has a solar-powered solution that can mitigate some of these issues. From the perspective of efficient actuation without breaking surface tension, generating a force without excessive water penetration is a key challenge.

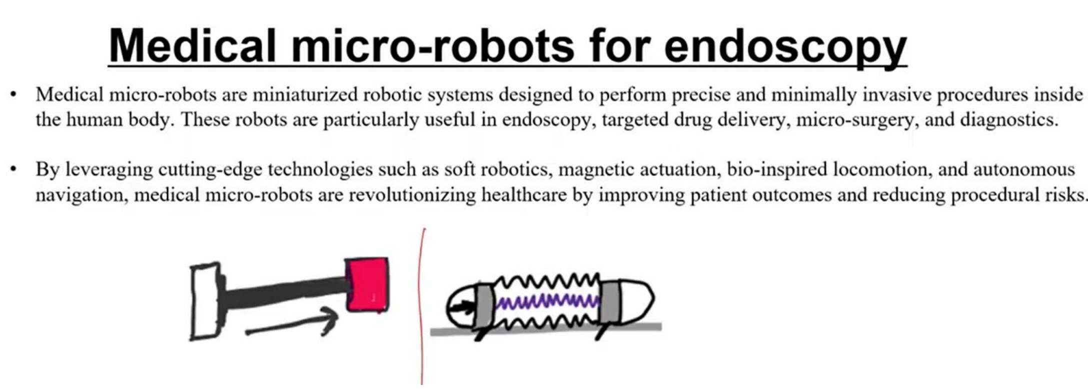


The soft robotic actuator or biomimetic mechanism can help maintain efficiency, and it can be used for scaling up to a larger load. While microscale robots work well, scaling up requires a stronger material and actuation method. These water striders benefit from their small size, while larger robots face greater water resistance. Now, to give you an overview, these are some of the mechanisms involved with respect to the water strider and some of the key parameter mechanisms that have been explained with reference to the slab phase and the stroke phase. Now let us discuss some medical micro robots that are used specifically for endoscopy-related applications.

We will also discuss the different mechanisms that are involved and how these mechanisms are deployed for different applications. Now, we will discuss these medical micro robots for endoscopy-related applications. What are the different mechanisms involved in the design and development of these medical micro robots, particularly for endoscopic applications? As far as a biomedical perspective is concerned. Even if you have gone through the entire modules, we are referring to the biomedical perspective; we are more focused on targeted drug delivery as well as on endoscopy. There is a need for micro robots to pitch in to the system.



In this regard, let us see some of the mechanisms that are being deployed for these endoscopy-related applications. When we consider that these medical micro robots are miniaturized robotic systems designed to perform precise and minimally invasive procedures inside the human body. These robots are particularly useful in endoscopy, targeted drug delivery, microsurgery, and diagnostics-related systems. By leveraging cutting-edge technologies such as soft robotics, magnetic actuation, bio-inspired locomotion, and autonomous navigation, medical micro robots are revolutionizing healthcare by improving patient outcomes and reducing procedural risks. Now, if you closely observe this particular mechanism of developing these micro robots from an endoscopic perspective, two mechanisms are well established for locomoting these micro robots in endoscopic-related systems.



One is with respect to a kind of peristaltic motion. In fact, we have discussed this peristaltic motion in some of the modules earlier, and this is a kind of open and close actuation that happens. Now let us discuss in detail the different types of actuation. This is a kind of shape memory alloy-based robot; basically, it tries to mimic an earthworm-related structure. When we closely observe these earthworms, they behave similarly to the gecko; it has a kind of setae, through which it will try to grip the structure, and then locomotion will be exhibited.

If you closely observe this particular movement of this earthworm, you will see that it is basically a kind of open and closed system. What happens is that there will be a kind of contraction and expansion. An alternative contraction and expansion will help a form of locomotion move in an appropriate direction. If we need to biomimic this earthworm-related structure, we may need to design it in such a way that it is a kind of hollow structure with two ends, and then we may need to mimic this contraction and expansion to achieve appropriate locomotion. Here we can discuss the different states of these locomotions and how these locomotions are deployed for movement of the system.

If you consider the overall construction of the system, this system comprises two regions and there is a kind of shape memory alloy that is integrated into it. In an initial state where the shape memory alloy is integrated, we have a kind of support, or I should say that in order to have an appropriate support, these setae will work on it so that these setae will be helpful in providing appropriate support to the structure, and then an appropriate moment can be depicted in this particular system. Now, in this particular case, initially, we have an initial state; then there is going to be a retraction state. The retraction state is going to be a kind of expansion; then we have a kind of elongation state. In this elongation state, you have an elongated structure, where these kinds of setae will be fixed into the structure, and then we have a retraction.

❖ Shape memory actuator based microrobot

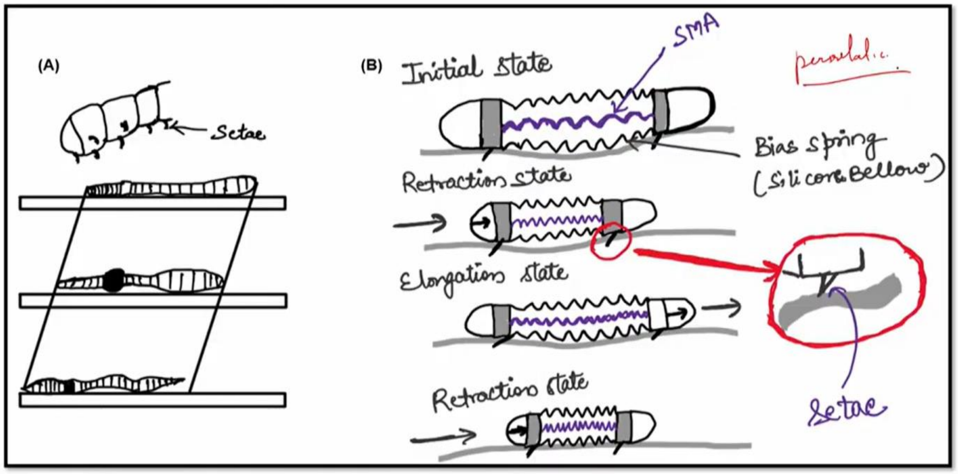


Figure: (A) Structure and locomotive mechanism of earthworm and fabricated microrobot and (B) Working principle of locomotive mechanism

This sequence will be followed throughout to generate such kind of locomotion. We will be having an initial state, a retraction state, an elongation state, and a retraction state. So this overall mechanism we call it as a kind of called as perislatic mechanism. This pericelatic mechanism is a kind of earthworm-based mechanism that is used for situations where we have a hollow or delicate structure. These systems can easily penetrate the structures, and appropriate alternative contraction and expansion occur, allowing it to slide through the system for proper locomotion.

Now we can see the next principle. As far as this principle is concerned, it is something like a kind of piezo; these kinds of systems are actuated using a piezoelectric-based actuator. As far as this piezoelectric-based actuator is concerned, we will have an elongation, and then there will be an alternating moment of elongation and retraction. If we try to look into the overall construction of the system, there will be a rigid structure and then there will be a flexible structure. From the rigid structure to the flexible structure, there is a kind of limb structure being attached to it.

Initially, this is in an initial phase when the limb structure tries to elongate; then, there is an expansion that happens, and when there is a contraction, there will be a retraction that occurs, followed by another retraction. There will be an alternative generation of an initial phase of elongation, then retraction, and then again the retraction. These kinds of alternative approaches occur, which will be helpful for the movement of the structure. In this particular mechanism, when we try to use this mechanism for endoscopy-related applications, there are two sets of moments experienced using these particular PZT-based actuators. One is a kind of forward movement; in this forward movement, we have a motion of the rigid structure, and in the reverse movement, we have a motion in the reverse stroke.

❖ PZT Actuator based Microrobot

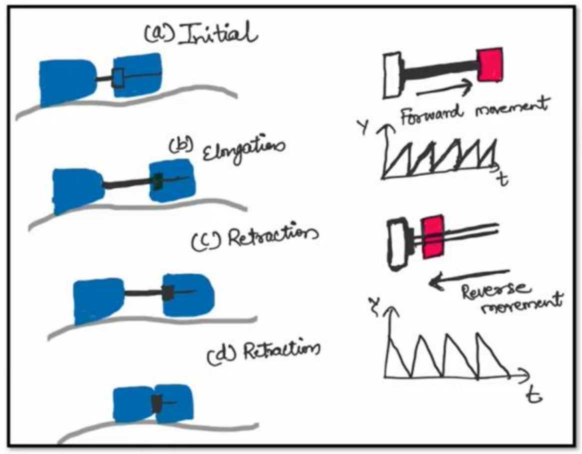
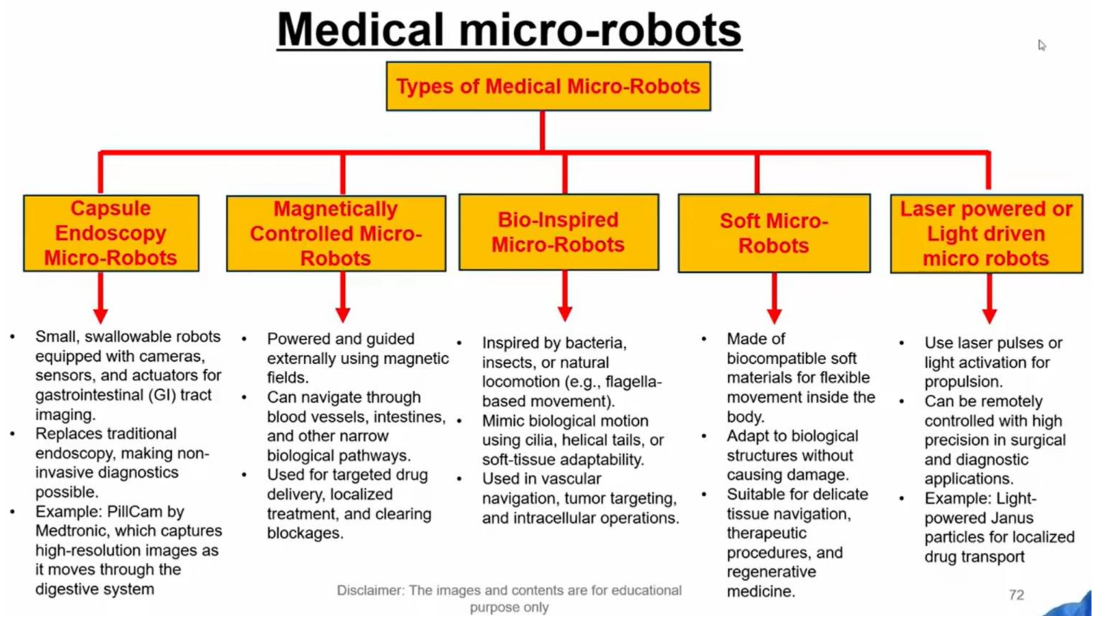


Figure: Working principle of inchworm-like robot and the developed Piezo actuator

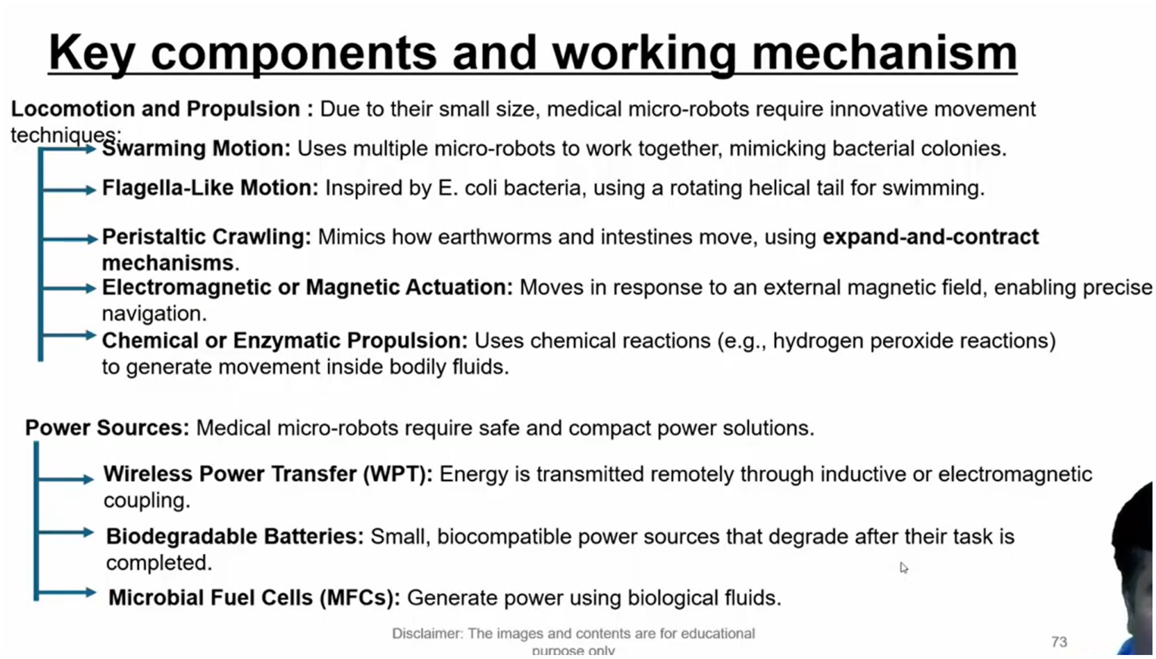
By giving at a high frequency appropriately, you can have control over the displacement, and this displacement can be efficiently used for endoscopic and related applications. Now, to summarize, as far as these medical robots are concerned, these are some of the classifications with reference to these medical robots. As far as these types of medical micro robots are concerned, they are used for different applications. One is a kind of capsule endoscopy-based micro robot. These kinds of micro robots are small, swallowable robots equipped with cameras, sensors, and actuators for gastrointestinal (GI) tract imaging.

It replaces traditional endoscopy, making non-invasive diagnostics possible, with different examples such as PillCam by Medtronic, which captures high-resolution images as it moves through the digestive system. So when we try to consider the magnetically controlled micro robots, they are powered and guided externally using a magnetic field. It can navigate through blood vessels, intestines, and other narrow biological pathways. It is used for targeted drug delivery, localized treatment, and cleaning the blockage. Next, when we try to talk about the bio-inspired micro robots, they are inspired by bacteria, insects, or natural locomotion examples, such as flagella-based movement.



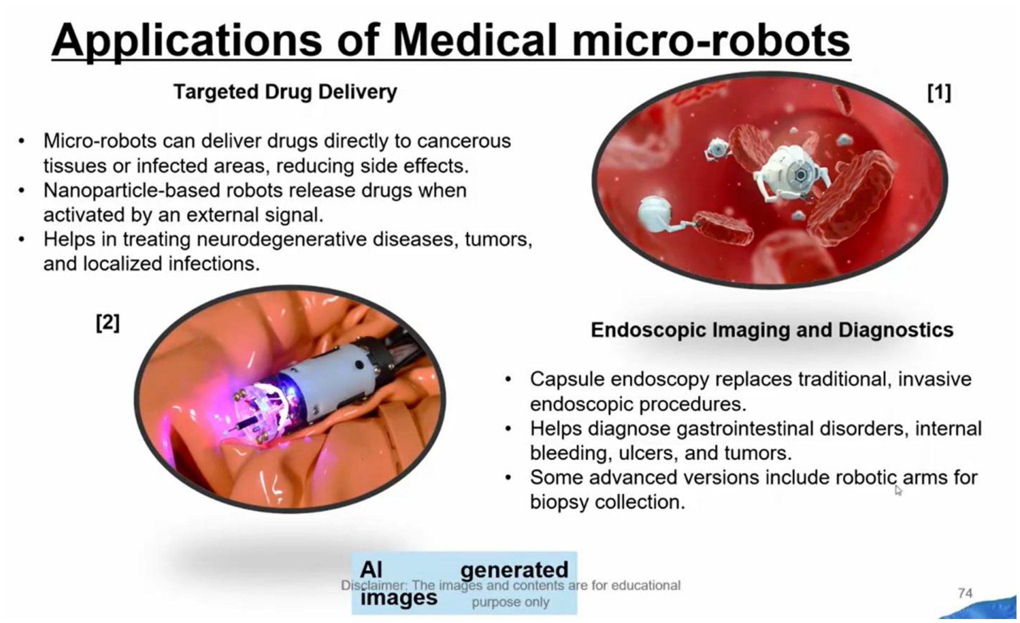
So, these mimicking biological motion use cilia, helical tails, or soft tissue adaptability. It is ideally used in vascular navigation, tumor targeting, and intracellular operations. These are some of the applications of this bio-inspired micro robot. Now when we try to talk, consider the soft micro robot; it is made of biocompatible soft materials for flexible movement inside the body. It adapts to a biological structure without causing any damage. It is suitable for delicate tissue navigation, and it is also used for some therapeutic procedures; it is also widely used for some regenerative medicine-related applications. The other classification works on the principle of laser-powered or light-driven micro robots. These are effectively used, and these are kind of non-contact-based systems that are being effectively deployed for different applications. Here, in order to activate these micro-robots, it uses a laser pulse or light activation for propulsion. It can be remotely controlled with high precision in surgical and diagnostic applications. Some of the examples, including a light-powered Janus particle for localized drug transport, are related to this laser-powered light robot. This slide will summarize the overall types of medical robots, how they are classified, and the different modes of actuation that are being employed in the system.

Now let us discuss some of the key components and working mechanisms. So, as far as this particular case study is concerned, we are focusing more on the lasers and more on the micro robotic system for endoscopic-related applications. So in this regard, we will be discussing locomotion and propulsion. So due to their small size, medical micro robots require innovative movement techniques. So one has a kind of swarming motion. So as far as this particular swarming motion is concerned, it uses multiple micro robots to work together and mimic bacterial colonies. So it moves like a swan and tries to attack the specific target for a different functionality. Next, we have the flagella-like motion. So this flagella-like motion is inspired by the E. coli bacteria, which use a kind of rotating helical tail for swimming. Then we have a kind of peristaltic crawling that basically mimics how earthworms and intestines move using expansion and contraction mechanisms. So, where we have a kind of peristaltic crawling that we exhibit, we have electromagnetic or magnetic actuation. This moves in response to an external magnetic field, which enables a kind of precise navigation.

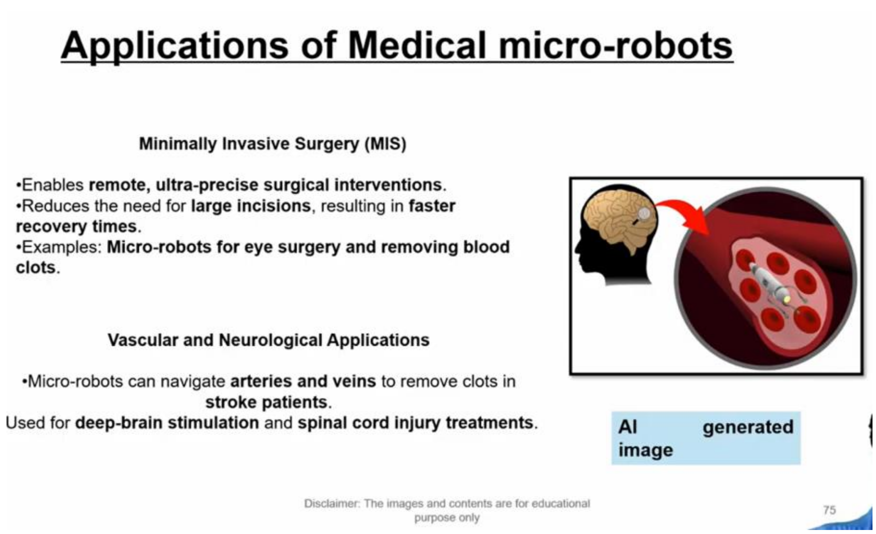


Next, when we try to talk about chemical or enzymatic propulsion, these kinds of chemical or enzymatic propulsion use chemical reactions, such as hydrogen peroxide reactions, to generate movement inside the body fluid. So, now when we try to look into the power source perspective, these kinds of medical micro robots require safe and compact power solutions. So, one of the aspects is with reference to this wireless power transfer. So, the energy is transmitted remotely through inductive or electromagnetic coupling. Then, as far as biodegradable batteries are concerned, it is a small biocompatible power source that degrades after its task is completed. As far as these fuel cells are concerned, it is a kind of microbial fuel cell that generates power using a biological fluid. Now these are some of the images which basically talks about the targeted drug delivery. So in this particular case, the micro robots can deliver drugs directly to the cancerous tissues that are in the infected areas, reducing the side effects. And then there are a certain number of nanoparticle-based robots that can be developed which release a drug when activated by an external signal. It helps in treating neurodegenerative diseases and tumors for a kind of localized inspection.

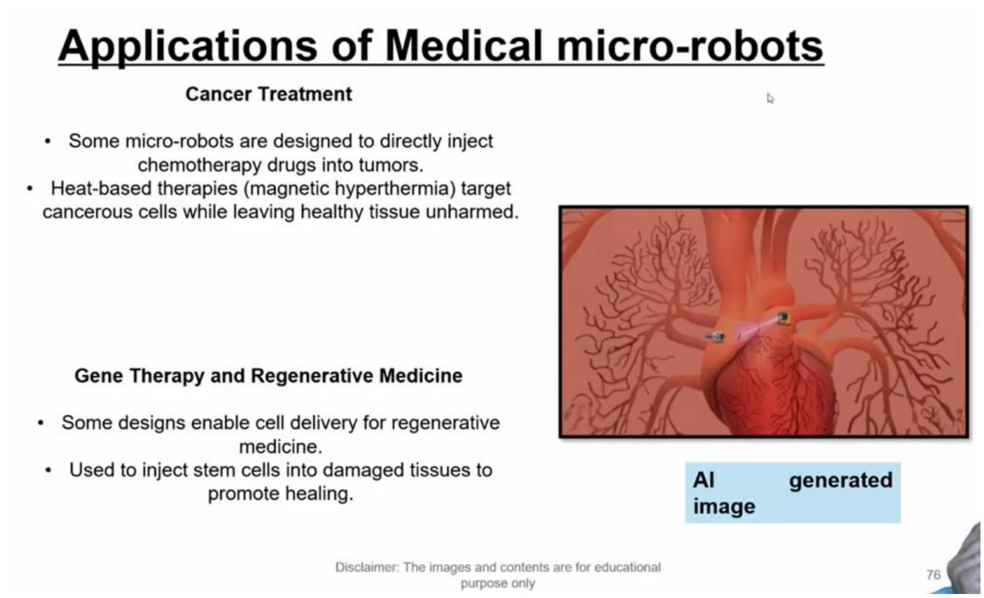
Now, with reference to the endoscopic and imaging diagnostic perspective, capsule endoscopy replaces traditional and invasive endoscopic procedures. It helps to diagnose gastrointestinal disorders, internal bleeding, ulcers, and tumors. Some of the advanced versions include this robotic arm for biopsy collection as some of the examples that can be generated using these medical micro robots. Now let us discuss other sets of applications of these medical micro robots. One of the key applications of these medical micro robots is minimal invasive surgery.



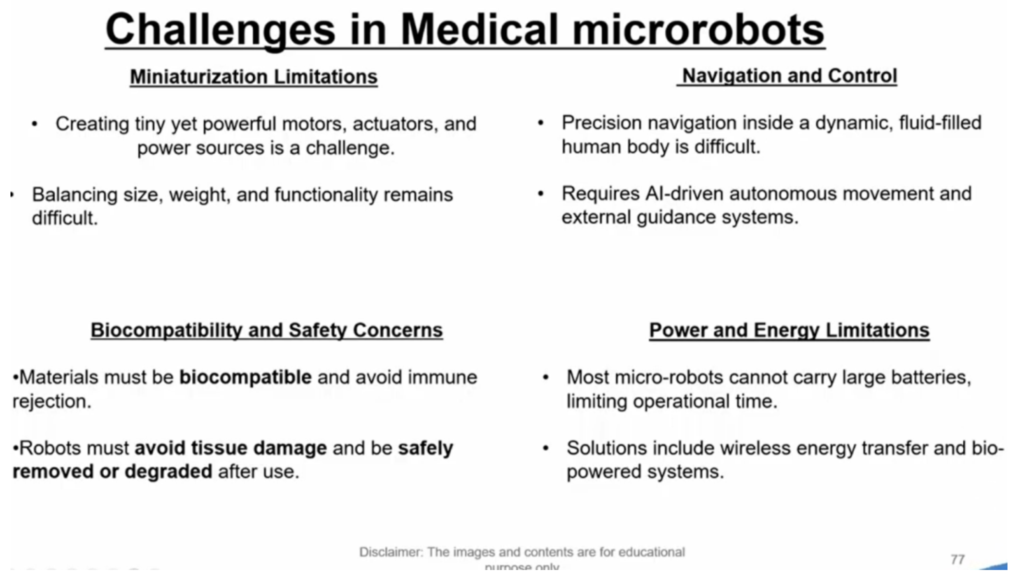
So as far as this minimally invasive surgery is concerned, we might have heard about keyhole-based operations, etc., where there is a minimal amount of interaction with the human body so that it can recover appropriately. So this kind of minimally invasive surgery enables remote and ultra-precise surgical interventions. It reduces the large number of inclusions, resulting in faster recovery times. Some examples, such as micro robots for eye surgery and removing blood clots, are key instances where a well-renowned technology has been established in reference to minimally invasive surgery.



The next application is with reference to the vascular and neurological applications where a micro robot can navigate into the arteries and veins to remove the clot in stroke patients. Like we have seen, when we try to use a kind of ferrofluid structure. So these ferrofluid kinds of structures are getting magnetically actuated, and they become a kind of grinding wheel, which can then be navigated through the arteries and used for grinding the fat content. So these are some examples of where such kinds of selective micro robots can be used. Selective localized attacking micro-robots can be used to address some of the key challenges.



The use of deep brain stimulation and spinal cord injury treatment is one of the applications that is being focused on with reference to these minimally invasive surgeries. Now when we discuss cancer treatment, some micro robots are designed to directly inject chemotherapy drugs into tumors. So, as we have seen, there is a kind of algae-based micro robot that we discussed in the earlier module. So we had a kind of algae that is surrounded by the targeted drug so that it can reach a particular portion and then be used for dispersing the chemotherapy drug into the tumor. So there are different models and different technologies that have been established with these micro robotic structures so that they can reach and cater to the targeted drug delivery-based systems. Then there are some heat-based therapies, basically a kind of magnetic hyperthermia, which are mainly focused on targeted cancerous cells while leaving healthy tissues unharmed. So these are some examples of where it can be deployed for cancer treatment. Then we have gene therapy and regenerative medicine. So some designs enable cell delivery for regenerative medicine. So it is used to inject stem cells into the damaged tissue to promote a kind of healing.



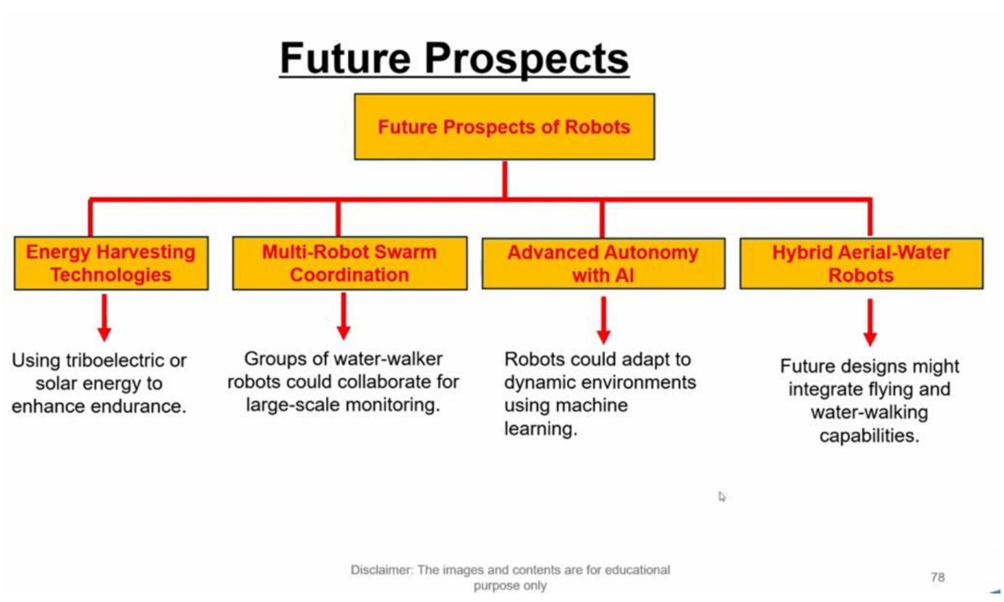
So these are some of the designs that are being established. Now, when we discuss the challenges of these medical micro-robots. One of the key challenges involved is the miniaturization and the limitation. Creating a tiny yet powerful motor, actuator, and power source is a challenging task; in most cases, it is well established through some micro fabrication and micro and nano fabrication techniques, but still, when we try to probe into its complexity, it has its own limitations. Next, with reference to balancing size, weight, and functionality, or characteristics, it remains difficult. Next, with reference to navigation and control precision inside a dynamic and fluid-filled human body, it is highly difficult.

The most important point regarding this recent development in the AI-related domain is that it requires AI-driven autonomous movement, and the external guidance system will be capable enough for appropriate navigation and control. Now, when we try to talk about biocompatibility and safety concerns, materials must be biocompatible and avoid immune rejection, and most importantly, the robot must avoid tissue damage and be safely removed or degraded after use. So these are some of the concerns that we may need to take into consideration with reference to biocapability and safety concerns. With reference to the perspective of power and energy limitation. So, in most micro robots, power management plays a vital role from the micro robotic perspective, especially in medical applications.

So most of the micro robots cannot carry large batteries; it limits the operational time, and solutions that include a kind of wireless energy transfer and a bio-powered system are considered to be some of the key limitations. Now to give you a kind of summary, as we have been discussing, about the biomimicking-based structures. Basically, in the last module, we discussed some of the key mechanisms that are involved in biomimicking. Here we have taken those biologically inspired locomotion mechanisms and deployed them for different applications. So, one of the applications which we have discussed is this gecko-inspired climbing robot.

We have discussed in detail the different types of mechanisms involved and the different models that are used for designing a gecko as a climbing robot. So, we have also discussed the different types of addition that have been established in this gecko-type robot in detail, and then we have also discussed the applications and the challenges involved. Then one of the most practically used micro robots is the magnetic swimming micro robot. So we have discussed the parameters involved in the different propulsion mechanisms that are exhibited with reference to this microorganism, especially for magnetic micro devices. So we have discussed the overall working principle, the applications, and the challenges involved in it.

So, we also had a detailed discussion about the acoustic-actuated micro robots, the types of acoustic-actuated micro robots, the different challenges involved, and how they have been used for microfluidic and microsurgery-related applications. So, one of the specialized adhesive techniques is this bio-inspired fibular-based adhesive. So, we have discussed the overall configuration of this bio-inspired fibular-based adhesive, how it looks, how it can be implemented, and what the different functions are with reference to these bio-inspired structures. And then we had a detailed discussion about this lizard-inspired water runner robot. In fact, our earlier background helped us understand the mechanism of this lizard-inspired water runner robot.



So we took the basilisk lizard as our case study. So we discussed in detail the different locomotions that are deployed, the key components that are catering to these lizard-inspired water runners, the different actuation and locomotion mechanisms that are being deployed, and the key components and locomotion mechanisms that are exhibited here. So we also had a discussion about the different challenges that are exhibited with these water runners. We had a discussion about water striders, the different configurations of water striders, the principles involved in the water strider mechanism, what the key components of this water walker robot are, some of the locomotion mechanisms that have been deployed, the applications of this water walker, and the challenges involved. Then one of the specific case studies we have discussed is a medical micro robot for endoscopy applications. So we have taken two different mechanisms: one is a pericelatic-based mechanism and the other is a PZD actuator-based mechanism.

Then, we discuss the types of medical micro robots that have been effectively used for different applications, the key components and working mechanisms that are employed, and the applications of these medical micro robots. We also have some discussions about this, such as different applications and the various micro robots that are being deployed. Now, to give you a summary, we also have a discussion about the challenges in medical micro robots. So, we are at the end of this micro-robotics course. So I want to summarize some of the key aspects so that people can take this up as their research career. So some of the key challenges involved with reference to these micro robots are concerning. One is energy harvesting. Energy management of these micro robots is highly challenging and needs to be addressed and looked into. Second is the kind of multi-robot swan coordination where a group of water walkers and robots can collaborate for large-scale monitoring. Third is with reference to advanced autonomy with AI so the robots could adapt to the dynamic environment using machine learning. So it requires quite a good amount of study and quite a good amount of data to generate such a kind of AI-based model so that it can be effectively implemented. Next is a discussion about the hybrid aerial water robot. Even though several hybrid aerial water robots are demonstrated, there are more requirements with reference to strategic areas from a perspective point of view. So, which can be explored in detail. These are some of the references. Thank you very much.