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A comprehensive review of driving mechanisms in amphibian spherical robots

M B Bahar*[,a,b], S S Abdullah[a], M S M Aras[b], M H Harun[a,b] & F N Zohedi[b]

[a]Department of Electronic System Engineering, Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia KL Campus, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

[b]Underwater Technology Research Group (UTeRG), Center for Robotics and Industrial Automation (CERIA), Fakulti Kejuruteraan Elektrik, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia

*[E-mail: mohdbazli@utem.edu.my]

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A spherical robot is based on the rolling concept inspired by the pangolins. This mode of locomotion is faster and safer as its spherical body becomes a protective shield. The mobility, adaptability, and concealment provided by a spherical robot can be used for terrestrial, aquatic, and amphibious applications such as harbour patrolling, defence tasks, rough terrains exploration, and agriculture. In designing the robot, priority on the centre of gravity position should be given as this will affect the robot's stability, either while static or in motion. A proper driving principle can overcome this issue while ensuring that the robot can perform a given task. Therefore, this paper intends to identify the driving principle proposed for spherical amphibian robots by systematically reviewing existing driving methods and the mechanisms used. From the search, 159 titles were published since 2015. The review has identified that the driving mechanism of a spherical amphibian robot depends on the actuation method, which is the legged actuation, combined actuation, and linear actuation. Each driving principle has its trade-off in performing the terrestrial and underwater motion. Furthermore, the driving principle also affects the advantages of a spherical robot system. Hence, studies on the driving principle that are more agile and do not ignore the spherical robot's main advantage need to be given emphasis.

[**Keywords**: Actuation, Amphibian, Driving principle, Spherical robot, Systematic review]

Introduction

A spherical robot is based on the rolling concept inspired by the pangolins[1]. This locomotive mode is faster and safer as its spherical body becomes a protective shield. The driving principle of a terrestrial spherical robot can be classified into three types: 1) Barycenter offset, 2) Conservations of angular momentum, and 3) Shell transformation[2,3]. A spherical robot has high mobility and is robust against its surrounding environments[4], which allows it to perform exploration and reconnaissance tasks in unfriendly or harsh environments[5]. Furthermore, spherical robots are naturally stable and can recover from collisions[1]. They also can conceal and protect all the essential parts inside the sphere against environmental states such as moisture, radiation, dust, hazardous material, or water pressure[6]. Therefore, three main advantages of a spherical robot are: 1. Mobility, *i.e.*, moving on all three axes when travelling terrestrially or underwater; 2. Concealment, *i.e.*, all the parts are located inside the spherical shell protected from water pressure and leakage; and 3. Adaptability, *i.e.*, capable of travelling on land, underwater, and seabed.

Since these robots can protect their essential parts inside the sphere, they are naturally suited for underwater applications. However, their driving mechanism might be different when travelling underwater as compared to travelling on land since, in water, water-jet propulsion or propeller are commonly used[7–9]. In addition, the steering hydrodynamic force can be reduced as the robot is spherical, which increases the moving flexibility[10]. Therefore, the robot may be made amphibious by integrating several driving components, which means it can move both on land and in water.

The mobility, adaptability, and concealment provided by a spherical robot can be used for various applications. For example, the terrestrial robot can be used for harbour patrolling, defence tasks, rough terrains exploration, and agriculture[11–14]. For marine applications, the robots can perform underwater observation or exploration, search and rescue[10], oil and gas pipeline inspection[15], and to aid in fishing[16]. Finally, for amphibious applications, spherical robots can perform tasks such as monitoring and exploration in both terrestrial and aquatic environments[17], detection of pollution and vision perception[18], reconnaissance and patrolling missions in the military field or even conduct search and rescue duties[19].

Several research groups have conducted a review of past spherical robots. In Chase & Pandya[20], explained the terrestrial driving principle of the spherical robot and discussed the essential utilisation, principles, and power limitation of each principle. The authors emphasise three principles: barycentre offset, the conversation of angular momentum, and shell transformation. Hebbar *et al.*[21] wrote another work that delves into the same driving idea. However, the report is more focussed on discussing the limitations of each method. Aside from that, Justus[22] examined several mobile robots for comprehending omnidirectional mobility[22]. According to the study, the spherical robot is one of a kind that has this potential. The author also concludes that the primary driving principle is the same as in Chase & Pandya[20] and Hebbar *et al.*[21]. To the best of the authors' knowledge, comprehensive literature regarding the recent driving principle (2015 to August 2021) of an amphibious spherical robot has never been done.

Therefore, this paper will focus on an overview of driving principles for a spherical amphibian robot that can move on land (terrestrial) and underwater environment (amphibious). The objective is to understand the driving principles used by these robots, as reported in previous research done recently (from 2015 up to 2021). From these overviews, the limitation of each driving principle can be analysed, and a conclusion can be made.

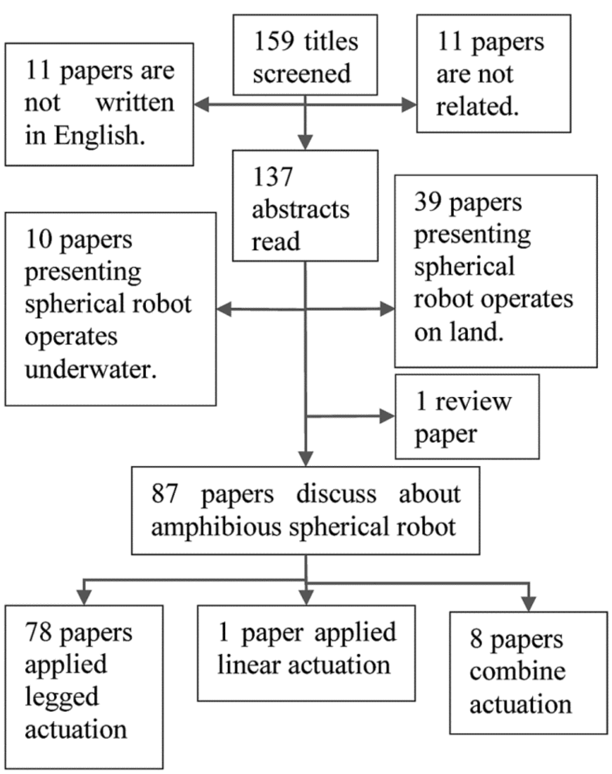

Fig. 1 — Systematic review flowchart

Methodology

This review is based on studies published from 2015 to August 2021 and includes published research and conference articles. One hundred fifty-nine papers were identified using the keyword "spherical robot" and within it "amphi*". The search is done to determine an overall research trend before focusing on the driving principle. The data was gathered from IEEE, Scopus, and Web of Science (WoS). The driving principle was first identified based on the robot actuators used, followed by the proposed driving principle implemented. Figure 1. shows the summary of the articles reviewed.

Among the papers reviewed, eleven of them were not written in English, while eleven articles were not related to the amphibious robots. The abstracts of remaining papers was appropriately reviewed where ten papers only discuss underwater spherical robots and 39 articles about spherical robots operated on land. One review paper discusses state of art and trends of triaxial symmetric robots[23]. The papers covered the driving principle of a spherical robot that operates on land. Altogether, eighty-seven papers were reviewed in detail.

Amphibian spherical robot actuation method

Eighty seven papers discussed an amphibious spherical robot that can be classified into three main actuation methods, which are the legged (78 articles), one paper on applied linear actuation, and eight papers documents using a variety of methods. From each design, the driving principle is discussed based on the flexibility of the technique to travel in both environments, the method's complexity to control and perform the motion, and concealment capabilities. These three requirements are essential in developing a novel design and driving concept for an amphibious spherical robot.

A. Legged actuation

The legged actuation was published the most where the robot implemented a legged-water jet actuator. Compared to other designs, the robot does not roll to generate motion on the ground. In general, the robot legs are perpendicular to each other. Each leg consists of two[24,25] or three[17,26] servo motors. All electronic components were placed on the top semi-sphere while another half is the leg location. As in Figure 2, the sphere at the bottom was used only if the robot travels

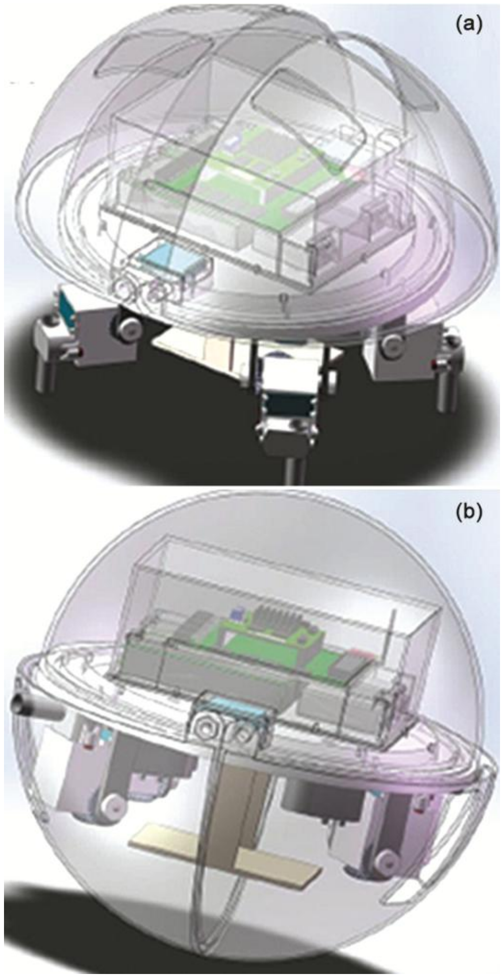

Fig. 2 — 4 legged water-jet amphibian robot[ref. 26]

underwater, but it is not compulsory. However, when travelling on the ground, the sphere was disassembled to allow the leg to move.

Crawling gait was implemented the most for the legged design to manoeuvre on the ground[24,27–31]. The gait was based on a four-beat gait which is more stable when compared with a two-beat gait[27]. As depicted in Figure 2, the sequence mimics a turtle motion where only one leg is on air at each phase. Based on the comparison done in He *et al.*[25,32], the crawling gait performs more stable than the trotting and pacing gait. However, both trotting and pacing gait perform a faster movement.

The trotting and pacing gait can move faster than a crawling motion due to the gait allows two legs to be simultaneously on-air while another two touches the ground. Unfortunately, this phenomenon is the same reason the movement becomes much more unstable when compared with a crawling gait. The gait plan is in Figure 3.

Modification on the same system was done in Li *et al.*[33]. The end effector was equipped with a motorised wheel. The system implemented wheel drive when travelling on an even surface while using the walking gait when travelling along an uneven surface. Using the same concept, a roller-skating gait was proposed in by applying a wheel at each leg[34]. The system does not require a DC motor because the robot moves by skating, as shown in Figure 3(c).

For underwater motion, the feet coordination is essential in generating sway, surge, and heave motion. For example, Xing *et al.*[35] planned each leg's locomotion while the bottom sphere is installed, as shown in Figure 4. Forward and reverse motion generated is shown in Figure 4 (a & d). Figure 4 (b & c) show how the robot performs floating and sinking motion, while Figure 4 (e & f) for turning motion.

The same strategies were also implemented by Zhong *et al.*[36], but without the bottom sphere cover. As the leg is free to rotate, the forward and reverse motion was made by placing the water jet parallel to each other. Thus, only two water jets need to provide thrust when moving forward and vice versa. Two units cross to each other were used for turning while all four water jets will provide trust parallel with the z-axis for floating and diving motion.

This design is also equipped with three servo motor units at each leg to increase the motion ability[17,26,28]. The water jet position for floating, diving, and turning motion is the same in each work. The strategy is depicted in Figure 5.

B. Combine actuation

Six designs were identified that combined terrestrial driving principles with underwater actuation to generate motion underwater. While for the terrestrial, researchers play around with the three driving methods.

Research done by Li *et al.*[10] proposed a spherical amphibian robot equipped with a flywheel, two units of a pendulum, and a propeller. The flywheel and pendulum were used as an actuator when it travels on the ground. The propeller is then used as the primary actuator to move underwater. However, the same actuator generated the turning motion on the x, y, and z-axis as terrestrial motion. The proposed design is shown in Figure 6(a). The heavy pendulum controlled the Pitch angle while the flywheel changed the rotational speed to get the motor's reaction torque to influence the course angle.

The design proposed by Zheng *et al.*[37] has two omniwheel as a drive unit for rolling motion when travelling on terrestrially. Therefore, the driving mechanism is likely as cart motion. The robot moves in the heave direction in the water by using a ballast system. The semi-sphere of the shell was a ballast that controls by two air pumps. The air pump will inflate a gasbag inside the ballast to drain the water inside it. The draining of water from inside the robot will decrease the robot's weight causing it to float. To dive underwater, the gasbag will be deflected so that more water can enter the ballast. As for manoeuvre on a

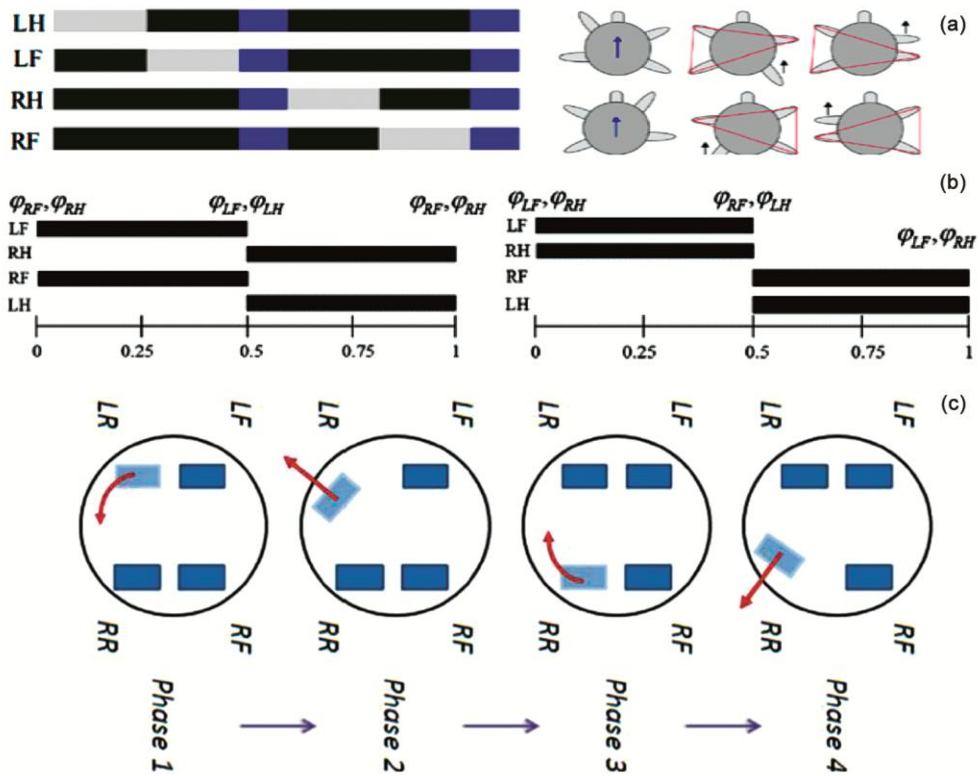

Fig. 3 — a) Crawling gait(ref. 27), b) Trotting gait (left) and pacing gait (right)(ref. 25), and c) Roller skating gait(ref. 34)

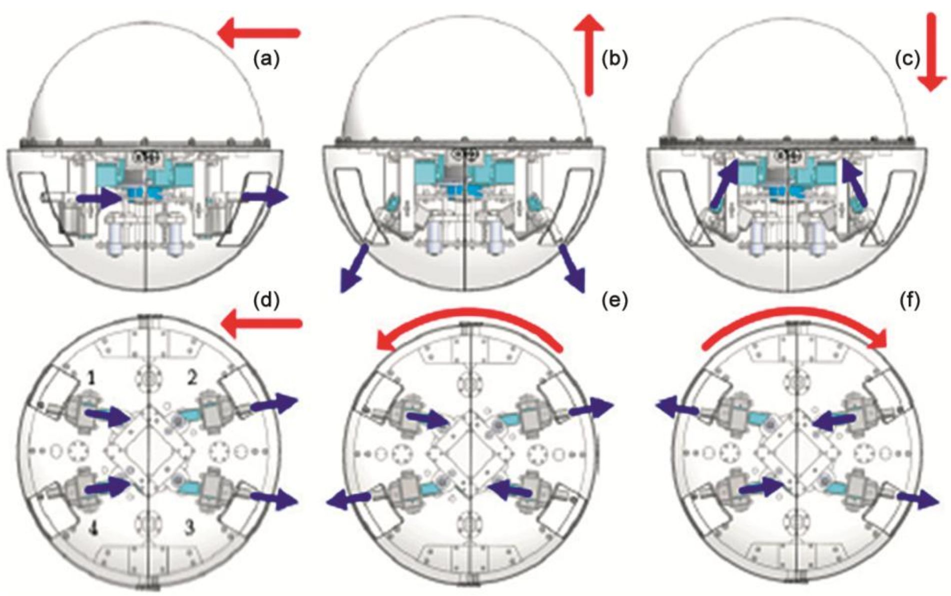

Fig. 4 — Underwater locomotion proposed by Xing *et al.*(ref. 35). The red arrow represents the motion direction while blue shows the water jet direction. The figure on top is the robot side view, and the bottom is the robot top view

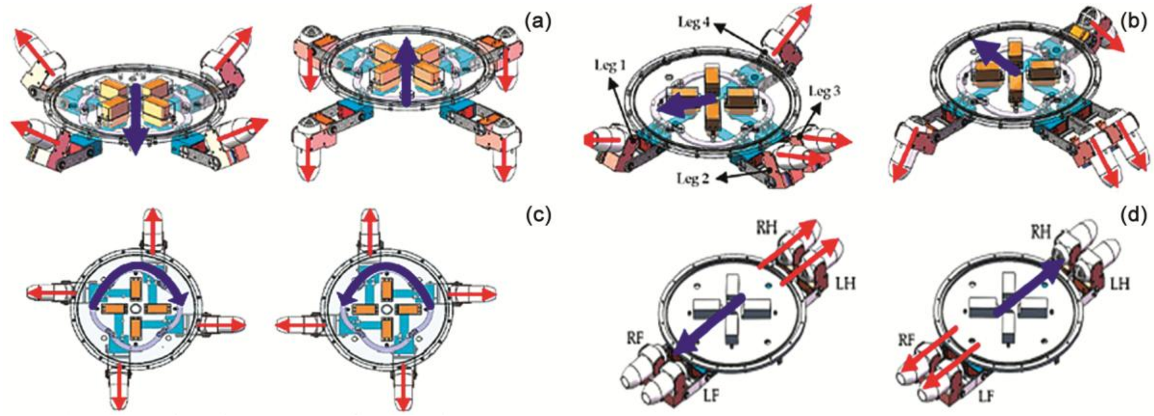

Fig. 5 — a) Floating and diving motion; b) Turning motion; and c) Top figure is forward and reverse motion with direction control trust, and the bottom is without directional control. The Blue arrow represents the robot's motion, and red is the trust direction(refs. 17,28)

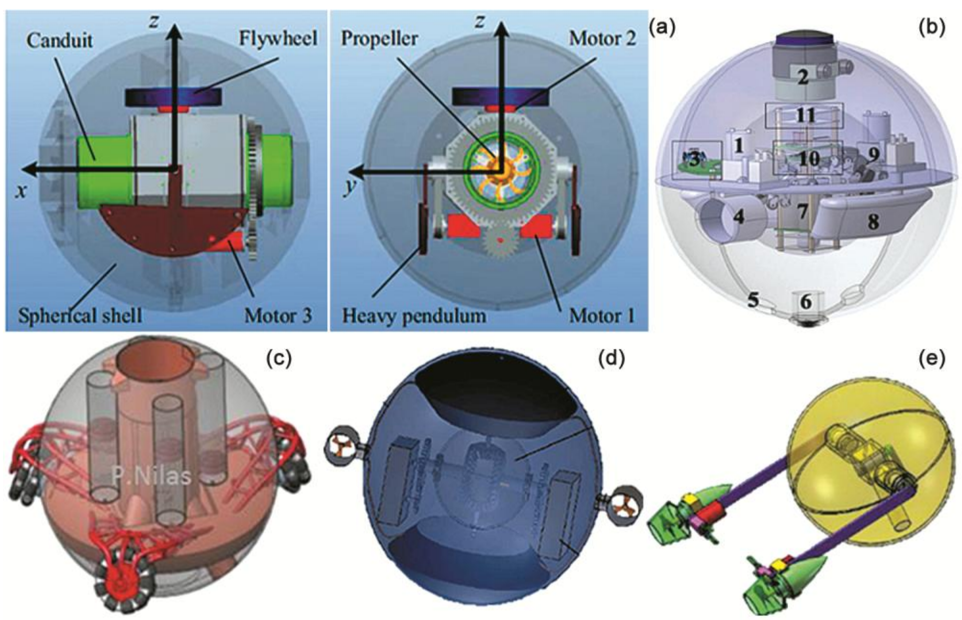

Fig. 6 — a) Design proposed by Li(ref. 10), b) Design proposed by Zheng *et al.*(ref. 37), c) Design proposed by Nilas & Ngo(ref. 38), d) Geng robot design(ref. 39), and e) Design proposed by Jia(ref. 40)

surge, a propeller located at its centre is used. Changing the propeller thrust is made by turning the propeller using the omniwheel inside the sphere. Figure 6(b) depicted the proposed design.

Nilas & Ngo[38] also applied the onmiwheel for terrestrial actuation, as depicted in Figure 6(c). The robot has two spherical bodies. The inner sphere is the waterproof compartment with three omniwheels, water hulls, a submersible mechanism, and a propeller. The outer sphere is designed with threads and tiny channels to aid terrestrial and underwater motion. A horizontal movement was driven by rotating the outer sphere similar to the boat paddle when moving underwater. Floating and submerging implemented the propeller located at the centre of the inner sphere to provide thrust. Additionally, the submersible mechanism helps to stabilise the sphere orientation while increasing the system weight to submerge.

These three designs place their equipment within the sphere, which improves concealment over legged actuation. Furthermore, the device is capable of travelling from land to water without requiring any user interaction. However, applying a single propeller decreased the system's capability to generate multiple motions when operating underwater.

A design with some similarities to Li *et al.*[10] is the design proposed by Geng *et al.*[39]. The design similarities are in generating motion on terrestrial where two pendulums were used but no actuator for yawing movement. Besides, the system also uses a propeller to move in the water. However, the propeller is placed on the robot's side with one unit on each side. The pendulum system is driven by a differential driving mechanism located at the sphere's centre, as shown in Figure 6 (d). Electronic devices for the propeller are stored in the cabin on top of the driving mechanism. On the ground, surge motion is generated by rotating both pendulums in the same direction and magnitude. The yawing motion was generated using the same magnitude but in the opposite direction. For underwater movement, surge motion is achieved when both propellers provide the same trust. If there is a difference, the robot will change the yaw angle. The proposed design can adapt but with less mobility and concealment ability than the previous design proposed by Li *et al.*[10] due to the propeller being located outside the sphere, limiting the robot to rotate freely. The propeller is also prone to collide or get stuck with any element in the environment.

Jia *et al.*[40] also uses the same concept, but instead of using the pendulum placed in the sphere, the pendulum designed is a set of arms. At the end of it is a propeller that will be used when moving in the water. Forward motion is generated by placing both arms in the same direction. For this robot to rotate on the z-axis (yaw), a pendulum inside the sphere rotating in the x-axis (roll) is used. This design definitely cannot fully move on the x-axis because of its arm, the same as the design made by Geng *et al.*[39]. The proposed design is shown in Figure 6(e). When moving in the water, the arm holding the propeller and the pendulum inside the sphere will be used. For heave direction movement, both arms will be aligned in the z-axis, and trust will push the robot into the water. Yaw motion is achieved by differential speed of the two propellers, while roll motion used the inside pendulum parallel to the thrust direction. As a previous design proposed in Geng *et al.*[39], the robot's concealment is not satisfied because the arm is located outside the sphere body.

In other research, the researcher proposed a sparse fin structure that can be implemented to any spherical robot that rotates when travelling on land[11]. The fins will act as tiny paddles to the system to manoeuvre underwater or on the water surface. Attachable fins were also proposed, used when operating in water and detached when operating on land, as shown in Figure 7 (ref. 41). When operating on land, this design is comparable to the design in this section. However, it can only paddle when operating underwater. Therefore, there are limitations in speed, degree of freedom, and performing the diving motion.

C. Linear actuation

The design proposed by Mateos[42] is the only design that implements a linear actuation to travel on land and underwater. The design has fourteen foldable telescopic actuators equally distributed over the sphere. The driving motion was generated by extending two neighbour spines of the initially extended spine. At the same time, the initial spine is compressed. For terrestrial motion, the researchers outline two locomotives which are, on rough surface and flat surface. The difference is initial spine which is extended on an uneven surface while all other spines are compressed when travelling on a flat surface. The third locomotive is for seabed motion which implements the same driving principle with additional jumping motion. The design is depicted in Figure 8.

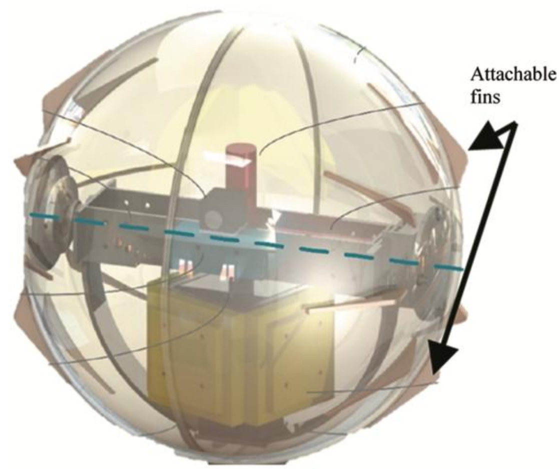

Fig. 7 — Design proposed by Chi & Zhan(ref. 41)

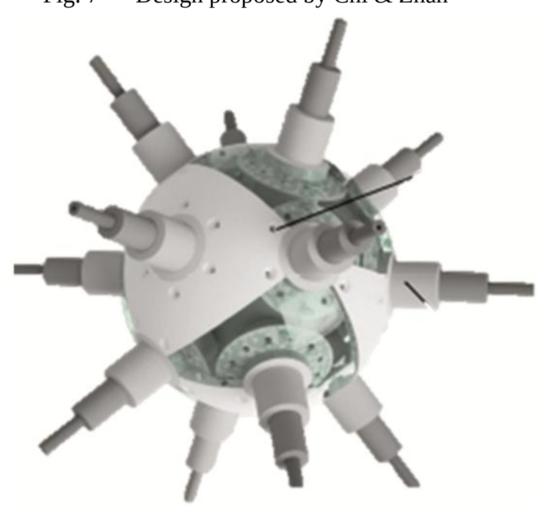

Fig. 8 — Design proposed by Mateos(ref. 42)

Table 1 — Amphibian spherical robot with combine actuation

Author(s)	Actuators		Driving principle	
	Terrestrial	Underwater	Terrestrial	Underwater
Zheng *et al.*[37]	4 Omniwheels	Propeller Ballast	Barycenter offset	Surge – propeller. Turning – omniwheel. Heave – ballast.
Nilas & Ngo[38]	3 omniwheels	Propeller Ballast	Barycenter offset	Surge – propeller. Turning – omniwheel. Heave – ballast.
Li *et al.*[10]	2 Pendulums flywheel	Propeller	Barycenter offset CoAM	Surge – propeller. Turning – pendulum and flywheel. Heave – turning the system facing down using the pendulum.
Jia *et al.*[40]	2 pendulum rotating on the y-axis. 1 pendulum rotating on the x-axis.	2 propellers	Barycenter offset	Surge and heave applied the changing of 2 pendulums (y-axis) position. Turning – differentiating the thrust of the propellers.
Geng *et al.*[39]	2 pendulums rotating on the y-axis. Differential driving mechanism	2 propellers	Barycenter offset	Surge – propellers. Turning – differentiating the thrust of the propellers. Heave – turning the system facing down using the pendulum.
Sun *et al.*[11]	Any terrestrial actuators	sparse fin structure	Barycenter offset or CoAM or both.	Heave – Paddles by rolling underwater.

Table 2 — level of mobility, adaptability, and concealment

Actuation	Mobility	Adaptability	Concealment
Legged	High	Medium	Low
Combine	Medium	High	Depend on design
Linear	Medium	High	High

Conclusion

To conclude, several driving principles of spherical amphibian robots have been reviewed and generally were found to belong to one of three categories: the legged actuation, combine actuation, and linear actuation.

The legged actuation has received much attention in recent years, with crawling, trotting, and pacing being the driving principles for terrestrial motion. While the system is updated with a roller, the motorised roller implements cart motion when travelling on a flat surface and crawls when travelling on a rough surface. The roller-skating gait, on the other hand, is designed for a non-motorised roller. All of the articles that deal with underwater motion use the same driving approach, which involves using a water jet thruster as a thrust source and changing leg position to create different movements.

The legged design offers more opportunities to explore. Several choices exist in motion generation, the number of joints or legs and the actuator type. The design has a high ability to travel on uneven surfaces due to the leg mechanism. For the same reason, a variety of motions can be made when compared with other spherical robots. On the other hand, this design adds complexity to the system's design, development, and modelling. Besides, the additional actuator will increase the costs, controller complexity, and energy consumption. Furthermore, if one of the joints fails to function correctly or the gait is not adequately planned, the robot will soon lose its stability. The design is mobile and adaptable, but it has less concealment because most actuators are not sufficiently shielded.

In contrast, only one paper discusses the design and the driving principle of systems based on linear actuation. Rather than moving underwater, the design is focused on rolling on the seabed when operating underwater. As a result, the main downside of the design is that it can only roll on the bottom, whereas others can float at a specific depth.

Combined actuation has multiple driving methods based on the design proposed. In general, the driving principle for terrestrial motion is based on barycenter offset and Conventional Angular Momentum (CoAM). Propeller and ballast are then used for underwater motion. Table 1 shows the driving principle for each design discussed. The system's mobility is classed as medium since certain designs have restrictions due to the number of actuators; for example, a single propeller limits the system's underwater motion, while other designs include actuators outside the sphere that prohibit it from moving freely. The system's concealment is also dependent on the placement of the actuators, with some being high and others being partially covered. The main advantage of this kind of system is operating in both environments without any setups. Furthermore, the driving principle is less complicated to planned and control when compared with the legged system. Finally, the system's stability is higher due to its nonholonomic behaviour. However, it can be developed as an underactuated system.

Table 2 presents the designed actuation with the advantages of the spherical robot based on mobility, adaptability, and concealment. High mobility is given when the system can travel at rough land and perform heave and surge motion underwater. Adaptability is high when converting from terrestrial to underwater does not need any interface from the user. Finally, high concealment is given when all the equipment is protected from the environment.

The recent method proposed has affected the spherical system values with a certain degree of trade-off. It is acceptable as the researcher has their interest and target application. Legged actuation is a promising driving method for terrestrial and underwater motion, but all the actuators are prone to collide with the environment. This is not an issue for the combined actuation design, where all actuators can be placed inside the sphere. The weakness of this system is when travelling on a rough surface or ramp. The main driving principle of a terrestrial spherical robot has lower torque as it must consider the size limitation. Therefore, investigations on improving the system's mobility should be conducted to fulfil the benefits of a spherical robot. Additionally, research on optimising an underactuated system is also essential to minimise power consumption and expand its applications.

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Conflict of Interest

The authors confirm that they are not affiliated with or involved in any organisation or institution that has a financial or non-financial interest in the subject matter or materials addressed in this work.

Author Contributions

MHH & FNZ gathered, analyzed, and evaluated all the relevant articles. MBB conceived the report, and SSA & MSMA oversaw the overall direction and planning of the research.

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