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Designs in Bionic Robots: Compared with Conventional Robots

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Abstract. With the advancement in relative technology, robotics is gaining an increasing amount of attention among engineers and researchers as it is a current focus on enabling people's lives to become more convenient. However, there is another type of robot designed very differently from functional robots like delivery robots and quadrotors that most people are familiar with, bionic robots. This is a kind of robots that gets design inspiration from real animals in nature, from the design of structure to altitudes and mechanisms of motion. How bionic robots are designed, and how the conceptional difference of bionic robots with other robots is reflected on their physical designs are the focuses of this paper. In this paper, four basic types of bionic robots are introduced and 17 existing designs of bio-inspired vehicles are included. 10 bionic aerial vehicles in 3 smaller classifications are compared to 3 conventional aerial vehicles in order to figure out differences in 3 aspects (structure design, sensors, and control method). The results show that bionic robots usually have more degrees of freedom in order to mimic animals' attitudes, and are lighter in weight. Typically, bio-inspired aerial vehicles employ different wing systems compared with conventional ones. Additionally, while conventional vehicles favour PID more because of its ease of construction, bionic robots use machine learning techniques. Both types of robots use the same sensors, which is necessary for them to detect their environment. However, their control methods differ due to different purposes.

Keywords: Bionic robots, conventional robots, designs, control methods, aerial vehicles.

1. Introduction

In the modern era, robot technology has been increasingly integrated into various aspects of people's lives including agriculture, military, healthcare and manufacturing. However, apart from commercial robots people often see in daily life, there is another type of robot that is currently been developing and has yet used to serve similar demands to those commercial ones, the bionic robots. Fittingly, they get this name because their designs in structure and working principles are inspired by natural creatures. Although nowadays bionic robots may lack manifold applications, the field of bionic robots is still gaining an increasing amount of people's awareness as it not only helps researchers better understand principles behind different animals' behaviours and apply those in human work but also triggers researchers to make consistent attempts to mimic more creatures in nature out of human's curiosity and entertainment purposes.

This review summarises some existing designs of bionic robots as an introduction of a type of robot different from commercial robots to the general public. This collection of bionic robot designs may also

guide and act as a reference to future researchers who want to develop a robot taking inspiration from nature. After knowing what bionic robots are like, other questions may arise. For example, few scholars are exploring the functions of bionic robots other than exploring harsh environments that humans cannot get to, or the possibility for bionic robots to perform tasks that common robots do. Analysis of differences between bionic robots and traditional vehicles may provide insights into the answer of these questions as the characteristics of both bio-inspired and conventional robots can be better understood.
To serve the two aims of better understanding bionic robots and the differences between them and conventional ones, this paper will first move on to introduce different types of bionic robots with some specific examples in the next chapter, then provide the technology employed in bionic robots including their sensors and control method in chapter three and four respectively. After that, comparisons will be made between biomimetic and conventional robots in chapter five, taking aerial vehicles as an example, followed by a conclusion.

2. Existing bionic robots' classification and examples

There is no limit to the type of bionic robots people create. In other words, people design bionic robots in every classification in animals, from invertebrates to vertebrates, including types like insects, arachnids, myriapods, fish, birds, mammals and amphibians. To avoid this kind of complex classification, different working environments of robots (air, land, both) are used instead in this study.

2.1. Aerial robots

Aerial robots possess natural advantages in obtaining information and performing actions in special terrains and avoiding certain obstacles that robots worked on the ground found difficult to [1]. They also have a wide range of applications in both military and civilian fields [1]. The development of biomimetic air vehicles (BAVs) is highly predictable and indispensable in the current society, with sufficient knowledge and great progress in relative industries including the science of materials, electricity and manufacture, as their inspirations--natural creatures--surpass other classical air vehicles in terms of flight efficiency, noise produced, camouflage, mobility and stability [2]. Compared to classical aerial vehicles, bionic aerial robots often need to consider more kinematic properties, such as the frequency and amplitude of the swing of wings, span ratio and angles when they are flying. Popular types of existing BAVs are listed with examples below.

2.1.1. Bird-like robots. An example of bio-inspired robots mimicking birds is "Phoenix". "Phoenix" is a large bionic flapping wing robot mentioned in Guangze Liu, Song Wang and Wenfu Xu's research in 2022. It uses a pendulum to control the movement of wings while using a roll and pitch rudder to mimic the flying attitude of the tail. Compared to classical robots, it does not apply prismatic or spherical joints. It uses an improved version of Kalman Filter algorithm to adjust the robot's attitude and make the robot more robust. Guangze Liu, Song Wang and Wenfu Xu suggested that algorithms used in "Phoenix" achieves a high accuracy of position and attitude calculation and control while using sensors that are not very expensive. However, as the wings of "Phoenix" are constructed by rigid bodies, it fails to mimic the real birds' actions with high precision. As a result, they also asserted that a method is still needed to improve the state analysis in real-time performance [3]. Other prior BAV examples include "Black Hornet", iBird-bot, Smartbird, Dove, Humming bird [4].

2.1.2. Bat-like robots. Researchers draw attentions to the development of bat-like robots because bats are agile among flying animals, and they are special in terms of their sophisticated structure of wings and flight mechanism which is believed to have more than forty degrees of freedom [4, 5]. Most of the bat-like robots belong to flapping-wing system.

For instance, Bat Bot, a relatively large flapping-wing micro aerial vehicle, is designed to have an actuation degree of five and involve functional group joints (wrists, ball-and-socket joints; elbows, revolute joints for example) to better imitate the flying attitude of real bats. It uses Proportional-

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Derivative (PD) control to ensure its flight performance and a simplified Lagrange method to obtain dynamic equations. Despite Bat Bot, microbat is another invention in this field [4].

2.1.3. Insect-like robots. Under this type of bio-inspired aerial robot, there are still a number of various designs due to that many creatures with almost totally different outlooks and flying mechanisms are all classified as the same biological term----insects.

Existing works include Bionic Opter, a micro aerial vehicle with 13 degrees of freedom that gets inspiration from a kind of dragonfly called Infraorder Anisoptera. It sacrifices the lengths of wings in order to manage to flap the wings faster [6]. EMotionButterflies, different from Bionic Opter, use a design of wings resembling butterflies and are characterised by their large wings but slim bodies [7]. For both vehicles, servo motors are utilised to actuate the movement of wings. While BionicOpter uses 9 of them, e-Motion Butterflies are only equipped with 2.

2.2. Terrestrial robots

As the major workplace for human as well as many other natural creatures is on the land, terrestrial robots are widely used and acknowledged by the general public. They usually use legs, wheels or tracks to support their movement. It is impossible for natural creatures to have tracks or wheels, which are exactly inventions of humans, makes bio-inspired robots working on ground draw experiences from legged robots.

Taking quadruped robots as an example, they were born from combining features of mammals like cheetahs and dogs with robotics, provide opportunities to the achievement of high-speed movement regardless of the complexity of terrains. To be specific, Pegasus (mimicking dogs and being able to carry loads) and robots studied in (using traits of a goat and having good ability of obstacle jumping as well as stability on slopes) are such kinds of robots [8,9]. Despite that, prior researchers also create robots imitating spiders and other land dwellers animals [10].

2.3. Aquatic robots

The importance of robots working underwater is self-evident. Due to the physical limitations of the human body and the harsh environment in oceans, people fail to explore deep regions of ocean on their own, which creates a good chance for the use of robots. A ray-inspired bionic fish robot acts as a specific example of an underwater bionic vehicle [11].

Designs of underwater bionic vehicles greatly differ from conventional ones in terms that the latter's actuators are usually blade propellers, while bio-inspired ones draw experiences from bionic propulsion rules. In this way, the drawbacks of using blade propellers can be avoided. In other words, bionic underwater robots have a greater possibility to achieve higher efficiency, lower energy consumed, less noise, etc. However, this may also reflect some shortcomings of bio-inspired ones as using blade propellers as actuators brings advantages in thrust and speed [11].

2.4. Amphibian robots

Combining the tasks of functional aquatic robots and terrestrial robots on one subject, robots working in both underwater and land environments are designed. There are countless different designs of bionic amphibian vehicles, including the frog-like robot and the snake-inspired robot [12, 13]. It is addressed that those bionic amphibian vehicles also possess similar application prospects as traditional ones, including exploring harsh environments like deep oceans, doing search and rescue tasks, as well as military reconnaissance [13].

3. Sensors utilised

3.1. Camera

Camera plays an important role in allowing robots to have a vision, like human's eyes. There are various types of cameras that specialises in different objectives and environments. In eMotionButterflies, infra-

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red camera is used whereas a 180 degrees fisheye-lens bottom-looking camera is favoured in the traditional aerial robot [7, 14].

3.2. Inertial measurement unit

Inertial measurement unit (IMU) involves accelerometers and gyroscopes, two sensors that work together to tell the direction and motion of a subject by tracking readings of activity and applying the theory of conversation of angular momentum. IMU returns information about where the subject is based on the estimations of the subject's velocity and orientation after moving away from the last known position. It helps with both navigation and tracking of subjects, which are two fundamental problems faced in designing intelligent robots, making it to be widely used in robots. For instance, IMU is responsible for measuring the robot's body orientation and acceleration [11]. Similarly, it is used for assisting altitude measurement in Bat Bot and eMotionButterflies during flight, and "Phoenix" also uses a combination of accelerometers and gyroscopes [3, 5, 7].

3.3. Others

Despite those listed above, the fish-like robot also uses micro sonars to clarify obstacles in the surroundings, a liquid conductive sensor that speacialises for guaranteeing the robot's safety (no leaking) in an underwater environment, and sensors to monitor voltage and current in order to know the amount of power consumed [11]. Prevalent sensors also include infra-red sensors, barometers, pressure sensors, magnetometer and lidar.

4. Control method

4.1. PID and PD

PID, which is the abbreviation for Proportional Integral Derivative, is a classical method used for automatic control. It involves three algorithms: proportional, after giving a suitable coefficient to the current error applying plus or minus algorithm to approach the set value; integral, improving output by decreasing offset; and derivative, adjusting the output using derivative of error when unexpected changes occur. The benefits of using PID controller include easy operation and maintenance. As a result, many robots including a non-biorobot used PID for control [15]. PD, similarly, stands for Proportional Derivative. Different from PID controller, it suits better on robots requiring quick response instead of those having strict requirements on accuracy and stability. Bat Bot is an example of a robot using PD control [5].

4.2. ILC

Iterative learning control *(ILC)*adjusts the input based on previous trials. It is called iterative because the output from the last turn will be used as the input of the next cycle. By continuous revising, input will be adjusted to approach the desired value. It is asserted that ILC surpasses PID controller in accuracy of tracking so that it is more suitable for repeated situations [16]. Research illustrates robots utilising ILC and PID type iterative learning control can be found and are inspiring [17, 18].

4.3. Machine learning

Several bionic robots including flapping-wing bird-like robot and fish-like robot can use techniques under machine learning to control their motion. For example, the fish-like robot utilises a neural network algorithm [18]. Another fish-inspired bionic robot employs reinforcement learning [19].

4.4. Others

Alternative control methods include bionic learning control mentioned and the use of fuzzy logic (using models to process data to achieve an effect similar to the performance of human's brain) [17]. Compared to other controllers like PID, fuzzy logic is more flexible but complex whereas it is simpler to construct compared to those model-based controller.

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5. Comparison with classical vehicles with aerial vehicles as an example

5.1. Structure design

5.1.1. Degrees of freedom. Due to the fact that bionic vehicles aim to imitate the flight altitudes of real natural creatures, which are far more complex than simply allowing robots to stay in the air by providing sufficient and appropriate amount of forces, Degrees of freedom (DOF) is made a large difference between bionic vehicles and conventional ones. Taking BionicOpter as an example, it has a DOF of 13, including the wings' flapping frequency, angles twisted by each of four wings, amplitudes achieved by each wing, and the horizontal/vertical movement of head and tail, whereas multirotors, non-bio-inspired vehicles, actuate in 6 DOF to work in three-dimensional environments [6]. As a result, those bionic robots are more likely to manage to achieve a higher degree of independent control and the flight altitude is more vivid and flexible.

5.1.2. Wing system. Aerial robots have several different types based on flight mechanisms. Typically, some aerial robots employ wing systems, including fixed wing, rotary wing, and flapping wing whereas others working in the air use propellers for support, especially for quadrotors, a kind of common aerial vehicle. As for bionic aerial vehicles, in order to better mimic flying altitude of natural creatures like birds, bats, butterflies, most of them employ flapping wing system. "Phoenix", Bat Botand eMotionButterfliesare evidences [3, 5, 7]. For this kind of robot, they use special materials to build the wings and use servo rotors to make the wings flap at certain frequencies. Conventional aerial robots utilise tilting propellers [15]. The advantage of using propellers is that less complex control is required and higher stability can be achieved. It also requires less consideration of the material of wings and specific wings design as the flapping-wing system usually has flaws in the handle of disturbances due to the tiny weight of their wings [20]. However, using propellers makes those robots have less manifold flying altitudes and taking-off postures compared to flapping-wing designed bionic vehicles. They usually take off vertically so less unique.

5.1.3. Parameters and performances. Data about some bionic aerial robots introduced in previous chapters and some conventional vehicles are summarised in the following Table 1.

Table 1. Parameters and performances of different robots.

Name	Type	Properties			Performance	
		Weight/g	Length/cm	Wingspan/cm	Speed/ms^{-1}	Endurance/min
iBird-bot [4]	BAV: bird-like	12				
Smartbird [4]	BAV: bird-like	450	106	196		
Dove [4]	BAV: bird-like	220	60		6~10	
Humming bird [4]	BAV: bird-like	10	16	16	2.5	10~20
Phoenix [3]	BAV: bird-like	680		220	6.2	60
Black Hornet [4]	BAV: bird-like	16	10		5	25
Microbat [4]	BAV: bat-like	10		23		25
Bat Bot [5]	BAV: bat-like	93		47		

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Table 1. (continued).

Bionic Opter [6]	BAV: insect-like	175	44	63	almost as fast as natural dragonfly(maximum speed of natural dragonfly: 15)	
eMotion Butterflies [7]	BAV: insect-like	32		50	1~2.5	3~4
Novel quadcopter [21]	UAV	5500	56.3 (arm length)			23~24
table tennis aerial robot player [15]	UAV	1255				
A custom UAV prototype [14]	UAV	3200	62			12

It is obvious that bionic robots usually have a smaller mass than conventional ones. A possible explanation for this is that bionic robots listed in Table 1 currently do not carry specific tasks in real life whereas the robots in literature are designed for specialised missions including freight carrying and playing table tennis [14, 15, 21]. In order to load those extra masses of freight or other objects, conventional robots usually have the weight that is large enough for them to support. It can be seen that from the table all non-biological inspired vehicles possess weights larger than 1000 grams whereas the bionic robots with maximum mass in those listed only weigh half of that of the lightest conventional vehicle listed [15]. In addition, the working time of those light bionic vehicles are not significantly shorter compared with large UAVs. Although the data on speed and endurance for those bionic robots may only consider the robot itself, in other words, speed and endurance without fulfilling pragmatic tasks still show the possibility that using principles from natural creatures will help robots become more efficient.

5.2. Sensor

After analysis, it is found that both bionic and conventional aerial robots employ sensors like accelerometers, gyroscopes, and IMU modules. This is in the expectation as they all require those sensors to understand their current state hence helping make adjustments and decisions next. Although for different aims and working conditions, they tend to use different sensors to understand the surroundings. For instance, non-biological inspired vehicles favours the use of lidar, Hokuyo UTM-30LX specifically, while eMotionButterflies employ a system of infra-red camera (infra-red wave detection) to clarify the obstacles [14].

5.3. Control method

Instead of employing high-level controllers, the quadrotor gets some values involved in its dynamic equations from human input [15]. However, as for bionic robots, they often need to make decisions by themselves as they face a dynamic environment and even may work in an environment that is unreachable and unknown to humans. Consequently, many bionic robots apply more mathematic-based models or techniques relative to artificial intelligence including neural networks and reinforcement learning [18, 19]. Those control methods allow robots to “study” from the massive amount of data and make improvements by themselves, hence they can move and act closer to that planned by humans after a certain amount of time trying and adjusting.

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6. Conclusion

The design of bionic robots is manifold. They draw experiences and mechanisms from all types of real creatures in nature hence are capable of working in various environments including on the ground, in the water or both. This review includes a summarisation of existing designs of bionic robots and groups them into types according to their different working environments. Up to now, bionic aerial vehicles include bird-like, bat-like and insect-like designs such as "Phoenix", iBird-bot, and Smartbird. Bio-inspired robots working underwater usually draw experiences from fish and other marine creatures. As for amphibian vehicles, frogs and snakes are examples of their inspirations.

A comparison between conventional aerial robots and bionic ones shows they use similar sensors. The reason is that for all robots, functional sensors are essential in order to get information from surroundings to carry out analysis and decision-making. To be specific, from 17 bionic examples, this review concludes that cameras, accelerators, gyroscopes and inertial measurement unit are widely and commonly used in both type of robots. According to their different designs, those sensors are placed in different parts and the exact type of sensors may vary.

However, the conceptional difference that bionic vehicles aim to mimic whereas those are conventional focus on fulfilling pragmatic tasks results in differences in their DOF, structures and control method. Since bionic vehicles are more flexible and vivid, they involve more variables on the structure to change the state of different parts, so more DOF. Taking the bionic aerial robot BionicOpter as an example, it allows its head, tail and every wing to move independently. Also, to reconstruct the elegant and vivid flying motion of natural creatures, bionic aerial vehicles usually employ flapping-wing system instead of using propellers or other wing structures like fixed-wing and rotational-wing.

Moreover, many bionic vehicles need to make decisions and control by themselves during the motion, so they reject to rely on human's input and control completely. As a result, they employ techniques including neural networks and reinforcement learning to improve and correct the errors.

This review summarises different designs in bionic robots and some existing methods of controlling. This may provide helpful information when doing future designs of bionic robots. Other important value includes giving the public an introduction to this new type of robot and suggesting possible improvement and changes need to be made on structures or internal algorithm designs in order to give ability of realistic task performing to bionic robots.

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