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A preliminary research to identify the biomimetic entities for generating novel wave energy converters

Hui Zhang [1], Wanan Sheng [2] , Zhimin Zha [1] and George Aggidis [2,*]

[1] Marine Engineering Equipment College, Zhejiang Ocean University, Zhoushan, Zhejiang, P. R. China, 316022; emails: H. Zhang: zhanghui@zjou.edu.cn; Z. Zha: zhazhimin96@126.com
[2] Lancaster University Renewable Energy Group and Fluid Machinery Group, Engineering Department, Lancaster LA1 4YW, United Kingdom; emails: W. Sheng, w.sheng@lancaster.ac.uk
* Correspondence: G.Aggidis@lancaster.ac.uk; Tel.: 0044 1524593052

Abstract: Biomimetics and creatures could contribute to novel design inspirations for wave energy converter as to other engineering branches since we have seen numerous examples in engineering applications. But how to obtain valuable biological entities or bionic design cases that could produce inspirations for novel designs may be challenging for the designers of wave energy converters (WECs). This research work carries out a preliminary research on acquiring the biological entities for designers, so to obtain the innovative bio-inspired ideas for designing novel WECs. In the proposed method, the first step is to draw out the engineering terminologies based on the functions, structures and energy extraction principles of existing WECs. Then by applying 'WordNet', the candidate biological terminologies can be obtained. Next, using 'AskNature' and through manual selection and filtering, the biological terminologies can be acquired. Lastly, to use the biological terminologies to establish the reference biological entities and the information and knowledge so for designing an innovative WEC. Using the proposed methodology, a novel WEC was conceived and verified.

Keywords: Design inspiration; biological entities; innovative designs; wave energy converters

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1. Introduction

Wave energy is a clean and sustainable energy source, with a huge potential to provide a continuous energy supply to the energy mix. To make use of the abundant ocean energy, WECs are the essential devices: they can extract the energy contained in waves and convert it into useful energy and eletricity. In order to convert ocean energy effectively, efficient wave energy converters must be developed. In principle, wave energy converter can use the different motions of the WEC, for instnace, surge, heave and pitch motions etc and using different energy conversion principles: point absorbers, attentuator, oscillating wave surge converter, overtopping, oscillating water column and bulge wave, etc. In deployment, different types of WECs may be deployed on the shoreline, nearshore or offshore, and can be also on the surface, in water or on seabed so to better extract the wave energy at different depths and different locations. Currently, the WECs have many disadvantages, such as high cost of energy production, low energy conversion efficiency, low survivability and reliablity, and so on. Therefore, it is very desirable to design the innovative wave energy converter or improve the existing WECs so to overcome all or some of the aforementioned disadvantages.

At same time, due to the nature of the ocean waves, wave energy generation generally takes place under large forces and low frequencies/speeds, which are challenging for an efficient and reliable wave energy production, and wave energy extraction becomes

even more challenging in the extreme weather conditions, in which waves could generate significantly larger forces, so to cause a significant damage to the wave energy converters.

In order to overcome the difficulties in wave energy generation and to improve the performances of WECs, a large number of researchers have conducted extensive research on different aspects of WEC devices, including the hydrodynamic performance of the WECs [1,2,3], Power Take Off (PTO) optimization [4, 5, 6], control for improving wave energy conversion [7], and so on. At the same time, developers have applied some characteristics of biology to the WEC design so for improving the performance and survivability in the WECs [8] as bio-WECs.

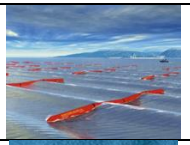
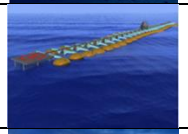
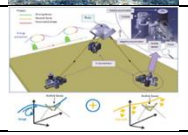
A bio-WEC refers to the bio-inspired wave energy converter. That is, the bio-WEC was designed with the biological inspiration triggered by the information and knowledge about function, shape, motion, behavior, strategy and other features of biological entities. Generally, a bio-WEC would have one or more features adopted from the biological entities. Good examples include: the Oyster [9] that swings back and forth like the opening and closing shells of an oyster; the Pelamis WEC [10] inspired by the shape and motion of the sea snakes; the Wave Dragon [11] that is inspired by the shape of a dragon's wings, while the Anaconda WEC [12] that by simulates the swallowing behavior of Anacondas; and more.

Generally, the existing bio-WECs (here a 'bio-WEC' refers that it has one or more biological features) have a good survivability [13], however, they have also disadvantages, including: low stability [15], low conversion efficiency [11] and high cost in energy production [16] (see Table 1). Although bio-WECs are not perfect, receiving inspiration from nature and from the creatures could still provide the inspiration to design innovative and practical WECs, similar to many other branches of engineering problems [17,18,19]. The use of biological knowledge, including biological attributes, biological functions or behaviors, biological principles and biological wisdom, could inspire designers to design products that meet performance requirements, so to achieve goals of efficient and reliable energy production [20]. Thus, there is an increasing number of researchers, who are investigating the relevant problems [21].

The methods of using biological knowledge to design innovative products can be divided into three different types, according to the design level [22]. The first one is to copy the biological attributes. This is the most widely used and direct method, for which a short time is only taken to complete the innovative design of a product, but requires advanced modelling techniques. The second method is to artificially simulate the biological functions, in which it is necessary to explore the behavioral representation model and function. The third approach is to develop a product based on biological prototype, which could be used for more complex design requirements. The biological working principles and intelligence could be used to optimize and improve engineering design. Regardless of which method is used, there is always a need to find the ideal biological entities first, and then to use their properties, functions, principles or wisdom to construct novel solutions, and to use them in the innovative design of WECs. Therefore, how to obtain suitable biological entities in order to assist WEC innovation is very desirable. This research presents a systematic methodology to identify the ideal biomimetic entities which can be used to assist to generate novel WECs.

In this paper, the rest of the contents is arranged as follows: The current methodologies of establishing the ideal biomimetic entities for innovative designs are summarized in Section 2. A novel method of finding the valuable creatures to assist WECs innovation is proposed in Section 3. In Section 4 the effects of using different engineering features of the WEC to retrieve biological entities are described. At the same time, an example of conceiving novel design ideas of WECs are illustrated using TALOS WECs as case studies. The advantages and disadvantages are discussed using AskNature to filter the candidate biological terminologies in Section 5. Finally, the features of the proposed method are analyzed. Then the insights and conclusions are drawn and synthesized.

Table1. Features of existing bio-WECs

Bio-WEC examples	Types of WEC	Mimicked types	Mimicked objects	Methods of power extraction	Advantages	Disadvantages	Images of bio-WEC
Pelamis [10]	Attenuator	Shape, Motion	Sea Snake	Pitch, Yaw	High conversion efficiency when the wavelength matches the pitch.	Low adaptability, the pitch is fixed and cannot adjust the sea conditions.	
Wave Dragon [11]	Overtopping/Terminator	Shape	Dragon	Overtopping	High flexibility, freely up-scale and adjust to varying wave heights.	Low conversion efficiency, optimization of the power production is required.	
BioWAVE [13]	Oscillating Wave Surge Converter	Function, Motion	Kelp	Surge	High survivability, protected on the seabed during storm conditions.	Low adaptability, appropriate water depths required to be selected.	
Centipod [14]	Attenuator	Structure	Centipod	Heave	Low environment impact.	Low cost-effectiveness, the loads and stresses on the structure require reduction.	
Oyster [9]	Oscillating Wave Surge Converter	Behavior	Oyster	Surge	High survivability.	Low conversion efficiency, need to form cluster arrays and unit field.	
Sea Heart [15]	Point Absorber	Principle	Human Heart	Heave, Surge	High flexibility, hybridization of marine waves and sea current energy sources.	Low stability, the stability of electrical energy requires solving.	
Anaconda [12]	Bulge Wave	Shape, Principle	Anaconda& Human Heart	Bulge Wave	High cost-effectiveness owing to simple structure and durable material.	Low conversion efficiency, the parameters and the performance require improvement.	

2. Current methodologies

Currently, the retrieved objects mainly include two types: One of the retrieved objects is a bionic design case. That is, a prototype or product that has been developed according to the characteristics of a certain creature. For example, the mechanical arm is designed by imitating the nose of an elephant [23]. Next, after obtaining a bionic design case, other features of the bionic object, such as function, shape, structure, and behavior, can be attained. These features can also be used to get inspiration and propose new applications, such as using the elephant's ear as an example to stimulate a design inspiration. Other uses can also be developed based on the existing features of the bionic object. For example, the elephant's nose can be sprayed with water in addition to taking a heavy object, so this water spray function can be used to inspire another new design idea.

Another type of object retrieved is a biological entity. Usually, we do not tend to pay attention to some characteristics of the biological entity. Thus, there are no design cases, which are stimulated by such biological entities. Design inspiration can often be obtained by analyzing the function, structure, morphology, and manner of the creature. When the obtained biological entity is used to assist the product design, the special features of the creature make the product more innovative.

Whether a biological entity or a bionic design case, it can provide designers with inspiration to create novel solutions. Now the lack of biological entities and bionic design examples hinders the designers' innovative design process. In order to retrieve valuable biological entities and biomimetic design cases and acquire relevant biological knowledge, researchers have carried out a large volume of research that could be categorized under three commonly used methods.

(1) Obtaining biological entities and cases by the functional model.

Goel et al. [24] used the SBF (Structure-Behavior-Function) model to acquire the functions of biological systems. They developed the DANE (for Design by Analogy to Nature Engine) [25-27] database that includes some design case libraries of biological and engineering systems. The database can be accessed and used for conceptual design of products. Chakrabarti et al. [28] used the SAPPhIRE functional model of biological and engineering systems to acquire functions of the biological system and constructed an IDEAINSPIRE database containing biological systems and engineering systems to support innovative product design. Sartori et al. [29] used the function and structure in the FBS (Function-Behavior-Structure) model to retrieve examples of biological analogies. FBS model was provided by Gero [30] to describe the physical phenomena related to the function in the engineering problem.

(2) Obtaining biological entities and cases by natural language process.

Chiu, I. and Shu, L.H., 2007 [31,32] provided some methods to search biological information from books and papers with the help of the natural language processing techniques. These methods use part-of-speech tags, typed-dependency parsing and syntactic patterns to identify and extract the functional keywords. These functional keywords are usually some verbs and describe some engineering problems. At the same time, the natural language format can be used to directly retrieve related biological phenomena with the help of a variety of biological information. Cheong, H. et al. [33] used the terms of the Functional Basis [34] and the search strategies [34] to search for biological cases in books and papers to identify words of biological significance.

(3) Obtaining biological entities and cases by the biomimicry taxonomies.

This method uses biomimicry taxonomy as functional keyword to retrieve biological cases. Some biology websites, such as AskNature [35], Biology Online [36] and BIOPS [37]

can be used to retrieve the biological cases and entities. AskNature website is an online database with a wealth of biological information that can be used to inspire the design process in a multidisciplinary field. The user can retrieve information according to the desired function, but not all keywords and queries can get satisfactory results, which depend mainly on the ability of the database to recognize keywords and the amount of information stored in the database. Biology Online is one of the largest bio-sites, with biodictionaries and bioinformatics, providing knowledge about biological phenomena and links to design ideas and applications. Fraunhofer BIOPS is an online tool that assists with the retrieval of biological entities using functional keywords. The number of the retrieved results directly relates to the number of available data in these databases.

Stroble, J.K., et al. [38] used a list of collocated verbs in the same sentence as the keyword to retrieve biological textbooks. Spiliopoulou, E., et al. [39] constructed the functional taxonomy table according to the functional basis and the biomimicry institute. These controlled, functional taxonomies are used to directly search for biological papers to obtain biological entities or biological cases. The search results of these two methods are closely related to the selected data source. Because the keywords are selected from a specific database, so the amount of data in the database will affect the determination of keywords.

Jahau Lewis Chen and Chang-Lin Lee [40] analyzed the description of the invention principle in TRIZ according to the functions that require to be implemented. They selected the verbs with similar meanings to the invention principle as keywords to retrieve related biological cases from the biological book. The vocabulary in TRIZ is relatively abstract and the number of inventive principles is limited, thus not all functions or principles that need to find biological objects can obtain corresponding vocabulary in TRIZ.

Following from the above analysis, the search that is carried out includes mainly books, papers, notebooks, online and other professional databases. There are a few studies directly searching related biological cases and entities on the public domain. In the selection of engineering keywords, most methods use the function of the design object as a keyword, and less involve other attributes of the design object, such as structure and motion mode. In addition, many methods use some special database or principle library to obtain keywords, which limits the number of keywords obtained. Therefore, there is a need to explore a method to obtain more valuable biological entities.

3. Novel methodology

According to the above analysis, this paper proposes a method for obtaining an ideal biological entity with the specific steps being shown in Figure1. And in the following subsections, the relevant information would be given for each step.

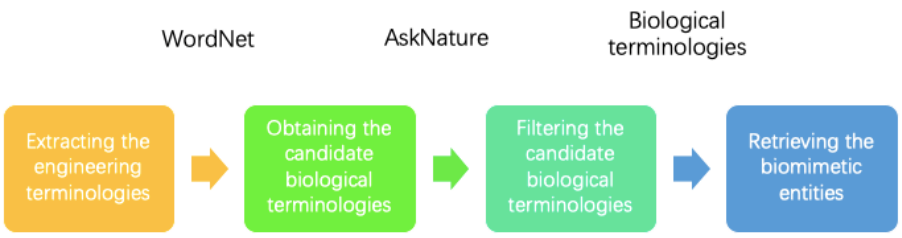


Figure 1. Flow chart of the proposed method

3.1 Extracting the useful engineering terminologies

When designing a WEC, it is usual to consider the functions of the WEC, including the system composition of the WEC, the method to extract energy of the WEC and the related movement behaviors, amongst other more specific functions. Therefore, the useful engineering terminologies may be established for these aspects.

The functions of WECs

The wave energy converter is a device that can convert the energy produced by capturing or extracting wave energy into the useful mechanical energy and finally electricity generation by employing different methods. These methods include the production of air or liquid flows to drive a turbine, the high-pressure liquid for a hydraulic motor to drive a generator and driving directly a generator to generate electricity. Regardless of which method is employed in the WECs, most of the devices contain some similar functions and the relevant terminologies related to the functions are given as follows: capturing energy, extracting energy, absorbing energy and storing energy.

The structure of WECs

According to the analysis by Salter S. H. [41], the wave devices employed to produce electricity are usually composed of the following subsystems: 1) the elements to interact with the waves and transmit the required forces, 2) The means to increasing velocity, rectifying direction and/or moving in the opposite direction, 3) the parts driving an electrical machine and 4) The connections for combining and transmitting the power to shore. Therefore, the abstract terminologies about the structure of WEC can be obtained, including: displacing element, linkage element, adjusting means, rotating part, reaction means, and transforming means.

The methods of power extraction of WECs

Power extraction of the WEC from waves is a key problem in designing a wave energy device. The different devices may use different motion modes of the WECs for extracting wave energy. For different WECs, the terminologies related to the methods for energy extraction mainly include: surge [9], sway [10], heave [42], roll [43], pitch [41], yaw [44], oscillating water column [45], overtopping [11], bulge wave [12] and others.

3.2 Obtaining the candidate biological terminologies

From the above analysis of engineering terminologies, it can be seen that the terminologies associated with the structure and energy extraction method of the WEC are the terminologies that represent the state of the movement or behavior. Therefore, candidate biological terminologies can be obtained by finding their respective synonyms.

The candidate biological terminologies can be obtained using the lexical dictionary WordNet [46]. WordNet is the large lexical database of English based on cognitive linguistics designed by researchers at Princeton University. It has the characteristics of a traditional dictionary and a synonym word database, which make up a "word network" according to the meaning of words. WordNet uses synonym sets (i.e., 'synsets') to list concepts. The 'synsets' are interlinked with the help of conceptual-semantic and lexical relations. Its structure makes it a useful tool for retrieving the biological terminology. In order to obtain more synonym words of extracted engineering terminologies, these engineering terminologies are simplified in this paper, as seen in Table 2.

Table 2. Engineering Terminologies of the WEC

Types of terminologies	Simplified engineering terminologies
The functions of WECs	Capture, extract, absorb, store
The structure of WECs	Displace, linkage, adjust, rotate, transform
	Reaction
The methods of power extraction of WECs	Surge, sway, heave, roll, pitch, yaw, oscillating, overtopping, bulge…

3.3 Filtering the candidate biological terminologies

The terminologies obtained need to be filtered before retrieving biological entities, as some candidate terminologies may not be biological terminologies. The currently commonly used method for filtering biological terminologies is to use biological dictionaries to identify biological terms [47], such as the Oxford American dictionary [48], Henderson's dictionary of biological terms [49], the Oxford Dictionary of Biology [50] and many other. However, these methods could be very inefficient in filtering candidate biological terminologies, if only the meanings of biological terminologies can be obtained.

In this paper, a combination method is used for filtering. First, synonyms obtained by using WordNet are selected, with an aim to obtain valuable animals or plants, which have the specific behaviors or working principles. Then AskNature is used for the secondary filtering and the words displayed for the related items are the biological terminologies.

Tables 3, 4, and 5 show the filtering methods and the selected results of the candidate biological terminologies according to the functions of WECs, the structures of the WECs and the energy extraction method, respectively. These have been retrieved from the AskNature website.

Table 3. Filtering of the candidate biological terminologies related to the functions of WECs

	Words with synset (semantic) relation	**Deleted words**	
		Manual selecting	Website filtering
Capture	Trance, catch, captivate, charm, fascinate, entrance		Enamour, becharm, enamor, beguile, bewitch, enchant
	Get, catch		
	Appropriate, seize		Conquer
Extract	Pull, pull out, pull up, take out, draw out, evoke, draw out; Press out…		
	Extract	Distill, distil	
	Express	Excerpt	
Absorb	Ingest, take in, take over, suck, suck up, draw, take up		
	Steep, immerse, engulf, plunge, soak up		Engross
Store	Hive away, lay in, put in, stack away, stash away	Salt away	

Table 4. Filtering of the candidate biological terminologies related to the structures of WECs

	Words with synset (semantic) relation	**Deleted words**	
		Manual selecting	Website filtering
Displace			Pre-empt
	Give notice, can, send away, force out, terminate	Fire, dismiss, give the axe, sack, give the sack	
	Move		
Linkage	Gene linkage		
Adjust	Set, correct, align, aline, line up, conform, adapt		

Rotate	Revolve, go around, turn out, splay, spread out		
			Circumvolve
Reaction	Chemical reaction, response		
Transform	Transmute		Transubstantiate
	Metamorphose		
	Transform	Translate	

Table 5. Filtering of the candidate biological terminologies related to the energy extraction method of WECs

		Deleted words	
	Words with synset (semantic) relation	Manual selecting	Website filtering
Surge	blow up, reflate, soar, soar up, flush, gush, circulate, run off, run down, pour, spill, run out…		
Sway	Shake, swag, move back and forth, swing, waver, flitter …		Nutate
	Carry	persuade	
Heave	Inflate, blow up, heave up, heft, heft up, pant, puff, gasp…		
Roll	Turnover, roll out, roll up, wrap, flap, revolve, seethe		
	Roll	Hustle, pluck	
	Wander, stray, cast, rove…		Vagabond
	Rock, shake, swag, totter		Nutate
Pitch	Toss, incline, cant, tilt,		
	Move, stretch out, move over, reciprocate, move back and forth, cant over, tilt, waver, linger, turn…		Wrestle, wobble, fidget, dawdle, squinch
	Pitch	Peddle, monger, vend…	
	Pitch	Gear	
Yaw	Swerve, sheer, veer, peel off…		
	Divert, detour, depart, straggle…		Sidetrack
Oscillating	Vibrate, waver, dwell on, linger over…		Waffle
	Swing, waver, weave…		
Overtopping	Overlook, top, ride, lap, focalize, cap, crest, look across…		Overshadow
Bulge	Pouch, protrude, bulk, change shape, deform, flatten out, twist, distort, bend, stretch out, extend…		

3.4 Retrieving the biomimetic entities by the biological terminologies

When the biological terminologies are used to search for the biological entities, the keywords are usually the phrases containing biological terminologies to improve the searching accuracy. The keywords, such as the function-related biological terminologies + food/prey, structure-related biological terminologies + mode, energy extraction methods-related terminologies + motion mode, can be used to retrieve the biological entities. By using these keywords, a number of the interesting biological entities could be obtained.

- Retrieving by the biological terminology related to the functions of WECs shown in Figure 2.

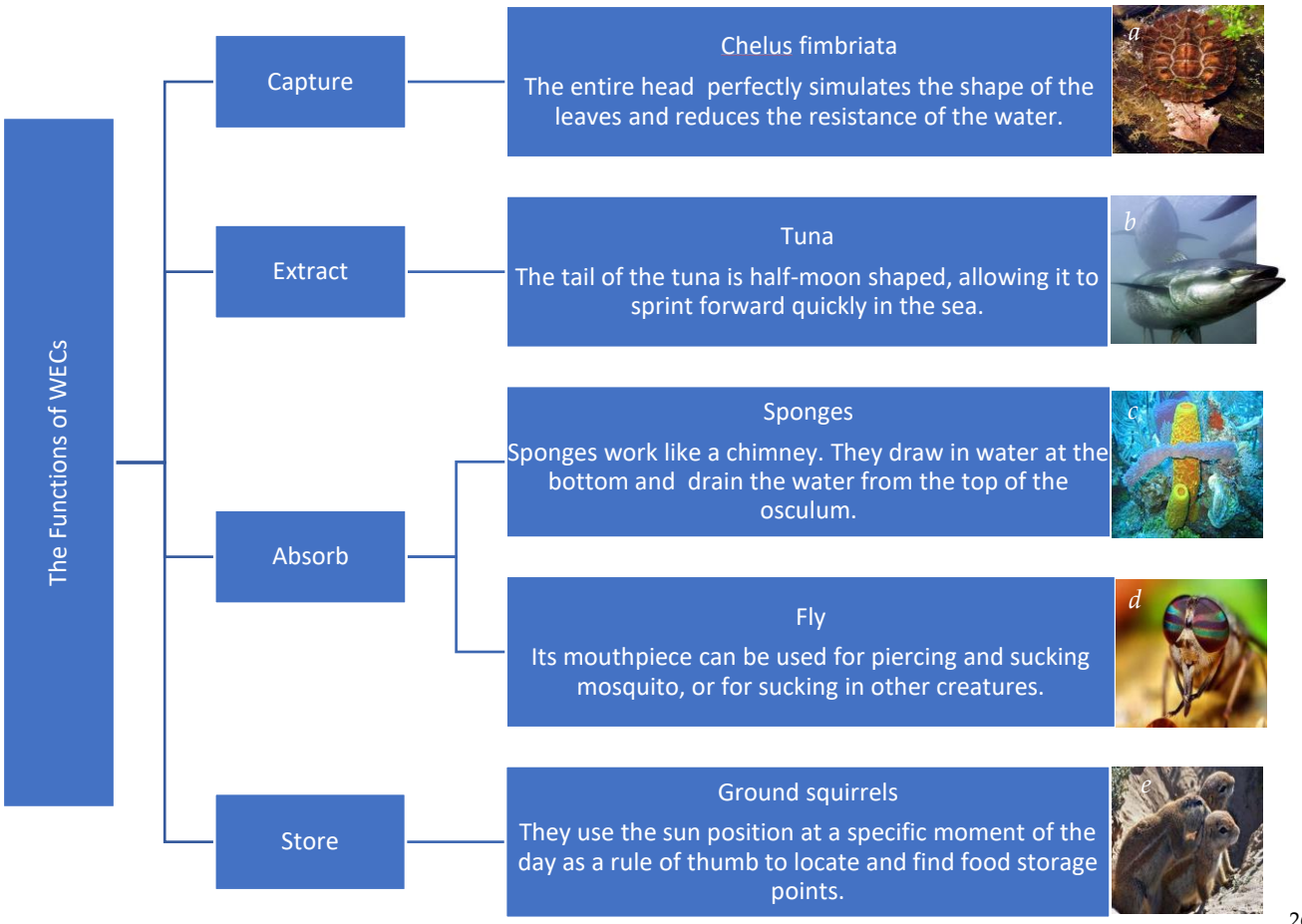


Figure 2. Retrieved biological entities by the biological terminology related to the functions of WECs, a. Chelus fimbriata [51]; b. Tuna [52]; c. Sponges [53]; d. Fly[54]; e. Ground squirrels[55].

- Retrieving by the biological terminology related to the structures of WECs shown in Figure 3.

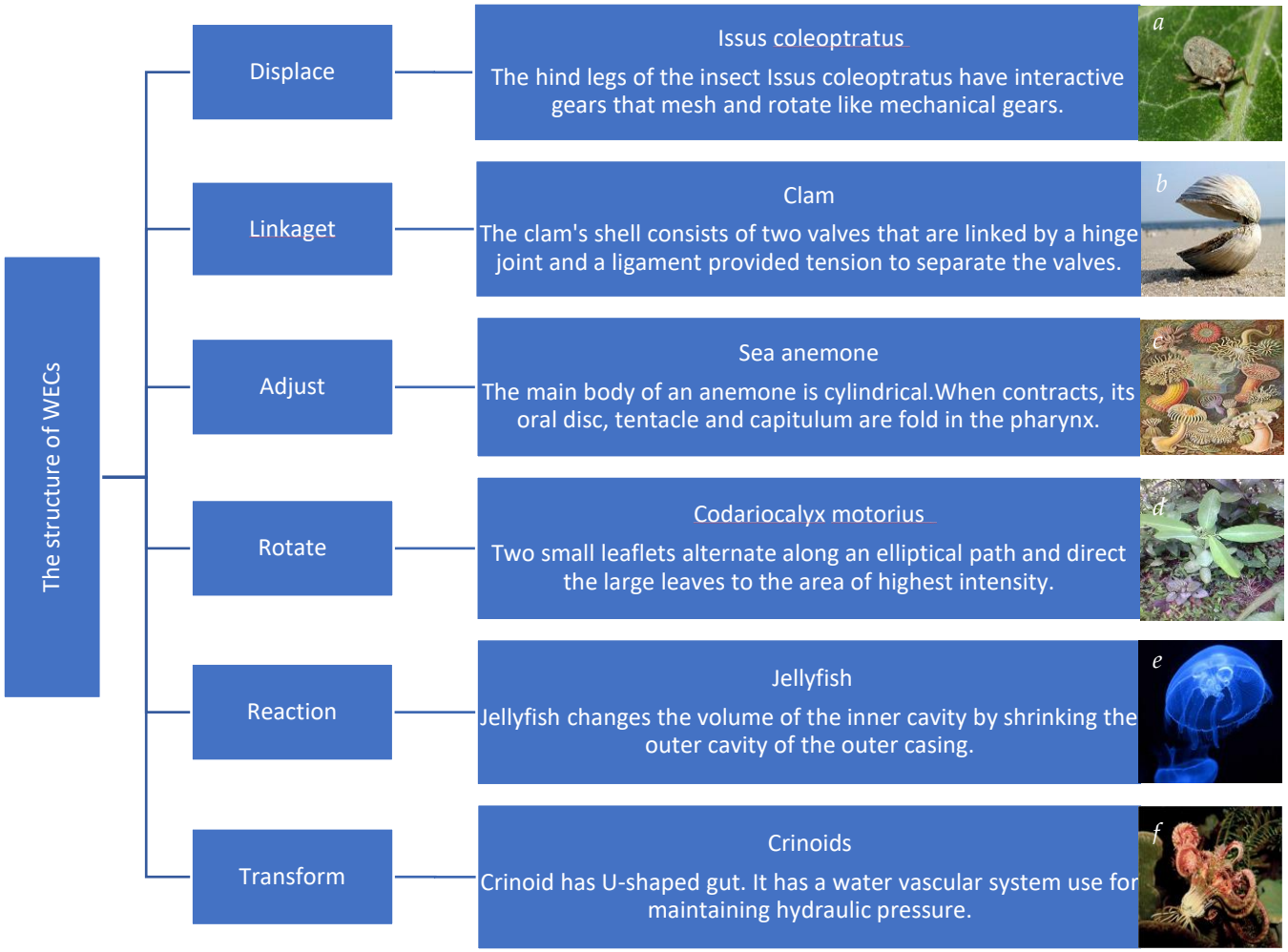


Figure 3. Retrieved biological entities by the biological terminology related to the structures of WECs, a. Issus coleoptratus [56]; b. Clam [57]; c. Sea anemone [58]; d. Codariocalyx motorius [59]; e. Jellyfish [60]; f. Crinoids [61]

- Retrieving by the biological terminology related to the methods of power extraction of WECs shown in Figure 4.

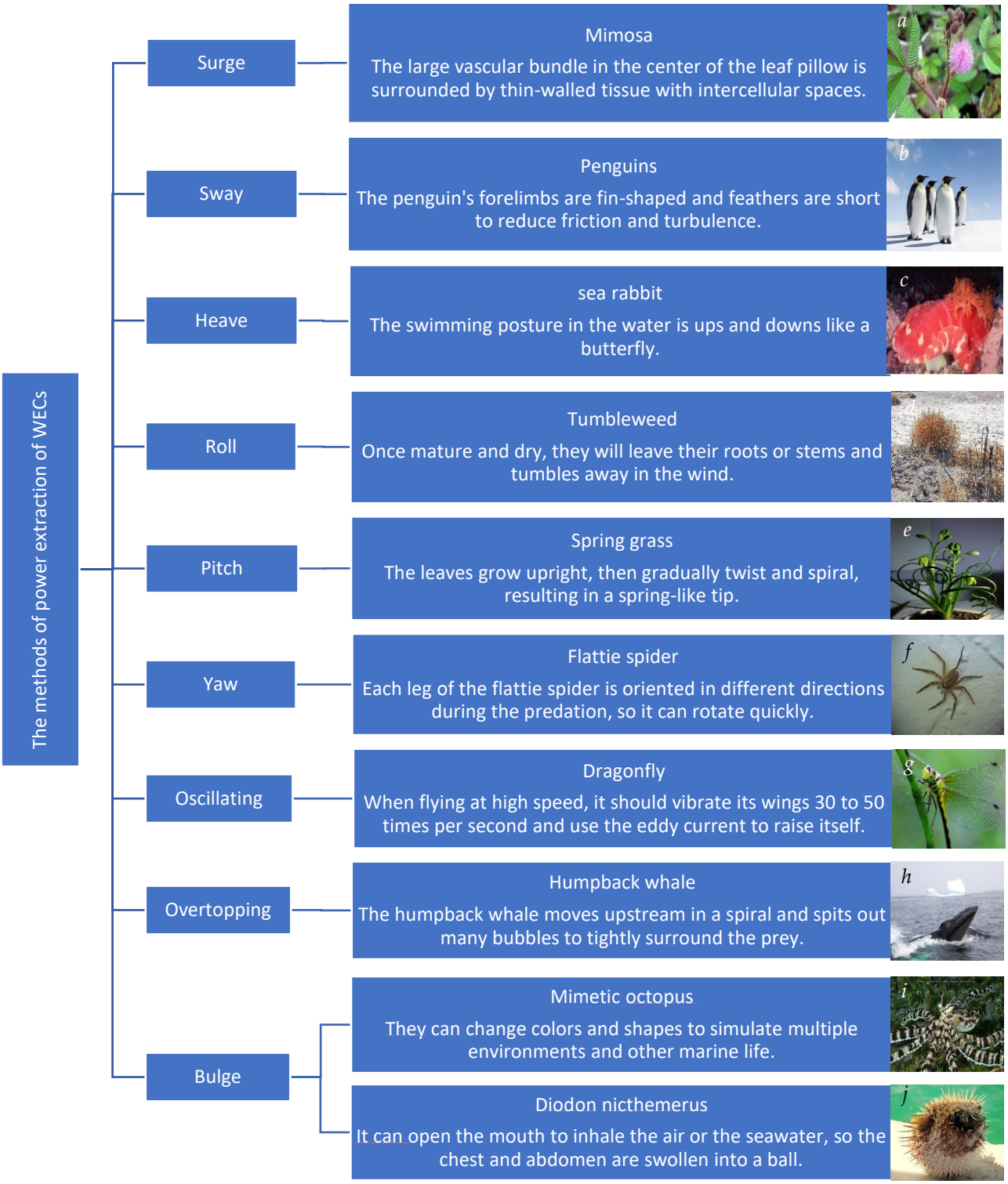


Figure 4. Retrieved biological entities by the biological terminology related to the methods of power extraction of WECs. a. Mimosa[62]; b. Penguins[63]; c. Sea rabbit[64]; d. Tumbleweed[65]; e. Spring grass[66]; f. Flattie spider[67]; g. Dragonfly[68]; h. Humpback whale[69]; i. Mimetic octopus[70]; j. Diodon nicthemerus[71]

The retrieval is performed using the biological terminologies related to the engineering features of wave energy converters. These biological terminologies can be selected from Table 6, together with the used keywords and the obtained biological entities.

Table 6. Biological entities

Features	Engineering terminology	Biological terminology	Key words	Biological entities
Functions of WECs	Captures energy	Capture	Bewitch+ pray	Chelus fimbriata
	Extract energy	Extract	Draw out+ food	Tuna
	Absorb energy	Absorb	Take in+ food	Sponges
			Suck in+ food	Fly
	Store energy	Store	Store+ food	Ground squirrels
Structure of WECs	Displacing element	Displace	Move+ mode	Issus coleoptratus
	Linkage element	Linkage	Linkage+ mode	Clam
	Adjusting means	Adjust	Adjust+ mode	Sea anemone
	Rotate part	Rotate	Rotate+ mode	Codariocalyx motorius
	Reaction means	Reaction	Chemical reaction	Jellyfish
	Transforming means	Transform	Transform+ mode	Crinoids
Methods of power extraction	Surge	Surge	Inflate+ mode	Mimosa
	Sway	Sway	Totter+ motion	Penguins
	Heave	Heave	Heave+ motion	Sea rabbit
	Roll	Roll	Roll+ motion	Tumbleweed
	Pitch	Pitch	Twist+ mode	Spring grass
	Yaw	Yaw	Slew+ motion	Flattie spider
	Oscillating	Oscillating	Vibrate+ mode	Dragonfly
	Overtopping	Overtopping	Overtopping+ mode	Humpback whale
	Bulge	Bulge	Change shape	Mimetic octopus
			Bag+ mode	Diodon nicthemerus

4. Steps of generating design ideas

Obtaining the biological entities in the first instance, then the new concept of WEC can be conceived by using the function, structure or principle of the biological entities. The following flow chart illustrates how to use the method proposed in this paper to search for valuable biological entities which could trigger design inspiration.

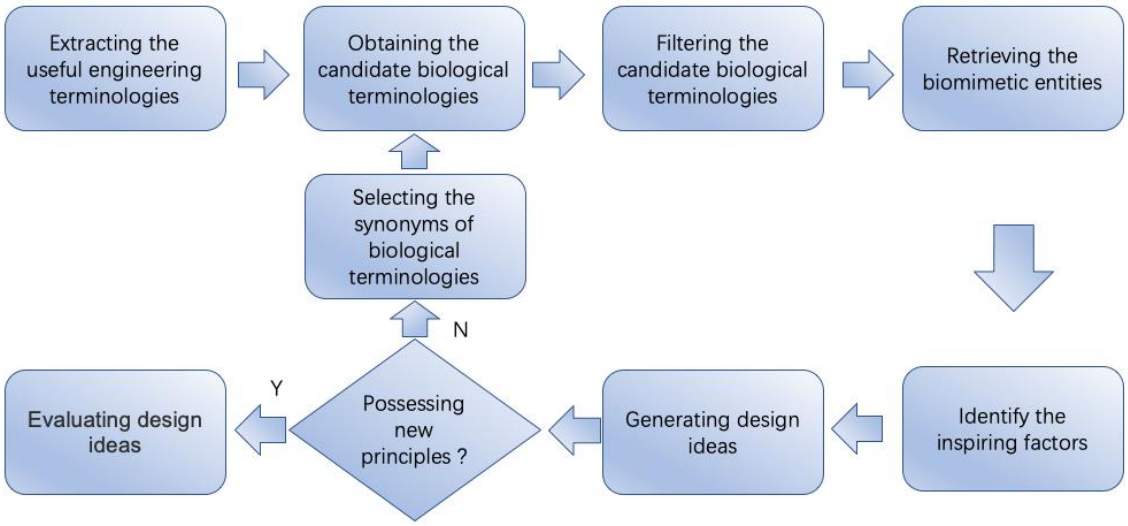


Figure 5. The guideline of generating design ideas

4.1 Extracting the useful engineering terminologies

The useful engineering terminologies have been given in Section 3, and the remaining step is to select a terminology based on the engineering terminologies set of function, structure and energy extraction method of the WEC. For instance, the widely used energy extraction methods "surge" can be chosen as an engineering terminology.

4.2 Obtaining the candidate biological terminologies

With the help of lexical dictionary WordNet, the candidate biological terminologies can be obtained, for instance, for 'Surge', as:

'Surge'

billow, surge, heave, inflate, blow up, reflate

soar, soar up, soar upwards, surge, zoom

tide, surge, run, run off, run down, run out, flow, feed, course, flush, jet, gush, tide, surge, circulate, eddy, purl, whirlpool, swirl, whirl, waste pour, spill, stream, well out …

4.3 Filtering the candidate biological terminologies

Many of the candidate biological terminologies for "surge" are related to human behavior, thus those terminologies that are not related to animals and plants need to be deleted by manual method and then a further filtering using AskNature. Some of the biological terminologies after filtering are shown on Table 7.

Table 7. Filtered biological terminologies

	Words with synset (semantic) relation word
Surge	Billow, inflate, blow up, reflate, blow up, reflate
	Soar, soar up, soar upwards, surge, zoom
	tide, surge, run, run off, run down, run out, flow, feed…
	Scend

4.4 Retrieving the biomimetic entities

According to the filtered biological terminologies about the "surge", some keywords composed by the "biological terminologies & animal" or "biological terminologies & mode" can be obtained. With the help of these keywords, a variety of biological entities can be retrieved, such as sea rabbit, mimosa, tuna, sponges, clam, chelus fimbriata, jellyfish, crinoids, dragonfly, humpback whale, ramshorn snail, etc., as shown on the Table 8.

Table 8. Retrieved biological entities

Biological terminologies	Biological entities
Billow	Big-eared octopus, feather stars
Heave	Sea rabbit
Inflate	Mimosa
Tide	Hermit crab, sea anemone, jellyfish, bat star, limpet, sea lettuce
Run	Bubble snail
Flow	Chelus finbriata, tuna, sponges, jellyfish
Feed	Fly, jellyfish, crinoids, sea rabbit
Circulate	Sponges
Eddy	Dragonfly
Whirlpool	Ramshorn snail
Waste	Sponges, crinoids
Stream	Humpback whale
Filter	Humpback whale
Drain	Tuna, sponges, clam

4.5 Generating design ideas

In order to trigger design inspiration and generate design ideas, it is critical to identify the inspiring factors. Inspiring factors are closely related to the stimulus. These stimuli can be perceived by the senses, usually existing in many forms including videos, pictures and texts [72,73]. Inspiration factors include the working principle, shape, structure, function, behavior, motion, material, texture and color characteristics hidden in the stimulus [74]. Therefore, the terminologies describing these features can be extracted and used for stimulating design inspiration and conceiving new design ideas. Some biological entities are listed in Table 9.

Table 9. The information of biological entities

Index	Biological entities	Stimuli	Inspiring factors
1	Big-eared octopus [75]	Body	Shape: a circus tent Motion: inflate, billow
2	Feather stars [76]	Arms	Structure: feathery fringes Function: swim
3	Sea rabbit [64]	Outer shell	Structure: unfolded Motion: ups and downs like a butterfly
4	Bat star [77]	Body	Structure: webbing between arms
		Arm	Shape: triangular
5	Bubble-rafting snails [78]	Body	Function: rafting Principle/Structure: trap air inside quick-setting mucus to make bubbles that glom together and form rafts
6	Tuna [52]	Body	Shape: streamlined
		Breastplate	Function: keep balance

		Tail	Shape: half-moon shaped Function: sprint forward quickly
7	Crinoids [61]	Water vascular system	Principle: maintains hydraulic pressure Structure: connected to the body cavity, not to the external sea-water
8	Dragonfly [68]	Wings	Shape: long and narrow Function: vibrate Behavior: vibrate wings 30 to 50 times per second
		Wing eye	Function: eliminate the hazard of the flutter and make safe under high-frequency vibration
9	Ramshorn snail [79]	Shell	Shape: planispiral coiled shells
10	Humpback whale [69]	Mouth	Structure: the special ligament structure between the upper and lower Function: open Behavior: open the mouth at an angle of 90 degrees

It can be found from Table 9 that most of the biological entities obtained have some interesting characteristics. In order to quickly generate new design ideas, we can use the analogy method to conceive. For example, the shape of Big-eared octopus likes a circus tent, it can billow in the water. According to its shape and motion features, a design idea of WEC can be conceived. This WEC is a floating WEC. It can roll over the sea with waves like a Big-eared octopus. There is a big ball inside the shell. The ball can jump freely with the rolling of the shell. Some piezoelectric elements or hydraulic cylinders can be mounted on the inner wall of the shell. When the ball moves, it will generate pressure on the piezoelectric elements, thereby directly convert the kinetic energy generated by the waves into electrical energy. Alternatively, the ball will push the hydraulic cylinder to generate high pressure liquid to drive the hydraulic motor, and finally drive the generator to generate electricity.

In addition, in order to generate more new design ideas, we can use the combination method to conceive. The characteristics of the structure and shape of each biological entities in Table 9 and some characteristics of WECs can be composed of the following Table 10. Through the combination of various characteristics, we can get a lot of WEC design solutions, including some novel WEC design ideas, such as: M2-S2-T3-I1-E3. Namely, Billow- Triangular- Webbing between arms- Ocean surface- Electromagnetic induction. According to this information about the features of the new WEC, we can conceive a WEC that floats and rolls on the water surface. It is a polyhedron composed of triangles, which can be tetrahedron, octahedron or icosahedron. The surface of each triangle is covered with light material. Each rod composing the triangle is designed as an energy convert device. When the polyhedron is billowing in the waves, the coils in the rod move back and forth in magnetic field, which can convert wave energy into electrical energy.

With the continuous addition of new biological features, novel WEC design ideas will continue to increase. Of course, the transformation of each group of combined features into a WEC concept requires designers to have strong knowledge background and innovation ability.

Table 10. Features Table

Features	Information					
	1	2	3	4	5	6

Motion(M)	Inflate	Billow	Ups and downs			
Shape(S)	Circus tent	Triangular	Streamlined	Half-moon shaped	Long and narrow	Planispiral coiled shells
Structure(T)	Feathery fringes	Unfolded	Webbing between arms	Connected to the body cavity	The ligament between the upper and lower	Bubbles glommed together
WEC Installation position(I)	Ocean surface	Under the ocean surface	Seabed	Onshore		
WEC Energy conversion method(E)	Air pressure energy-electrical energy	Hydraulic energy-electrical energy	Electromagnetic induction	Piezoelectric effect	Photoelectric effect	Thermoelectric effect

4.6 Validation of design idea

According to the proposed method, a piezoelectric-electromagnetic wave energy conversion device used for piers of sea-crossing bridges is designed by using the feature combination M3-S5-T6-I1-E3E4. As shown in Figure 10, the WEC has Simple structure and strong environmental adaptability. Thus, this design has been patented.

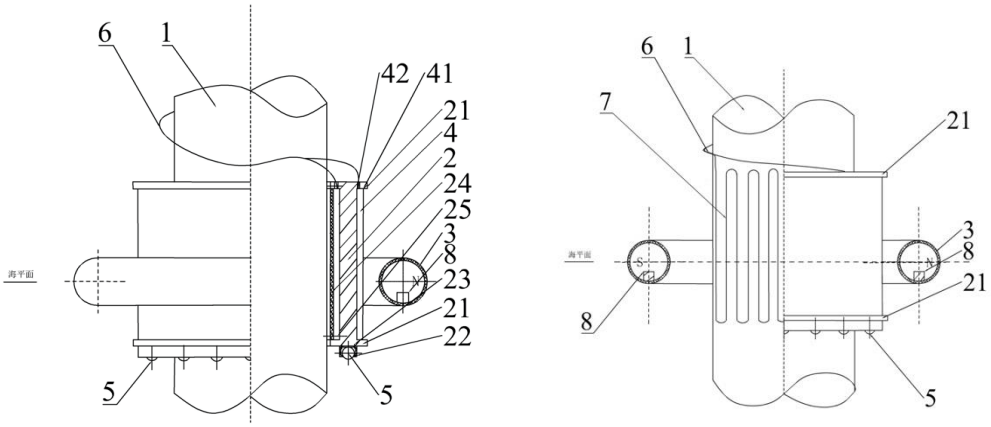


Figure 6. A piezoelectric-electromagnetic wave energy conversion device used for bridge piers [82]

1-Bridge pier, 2-Buoyancy sleeve, 21-Protrusion, 22-Fixing bracket, 23-Fastening screw, 24-Bottom plate, 25-Fixing screw, 3-Annular floating body, 4-Piezoelectric film, 41-Signal Electrode, 42-Ground electrode, 5-Buoyancy ball, 6-Wire, 7-Serpentine wire, 8-Heteropolar magnet.

In order to verify the feasibility of the idea, The TALOS WEC was conceived by big-eared octopus obtained using the approach in Figure 7. Some modelling, simulation and testing work has been carried out at Lancaster University, UK [6]. The TALOS multi-axis WEC can be seen in Figure 8, in which a heavy ball inside the TALOS device is supported by a plurality of hydraulic cylinders (or dampers) and springs connected to the wall of the

hull. When the hull is pushed by waves in the motions of all directions, the heavy ball is supposed to be stationary, such that the relative motion between the hull and the heavy ball could drive the hydraulic cylinders to pump the hydraulic fluid, which can be used to drive a hydraulic motor to generate electricity. Some initial studies have been made on the TALOS WEC at Lancaster University, including the wave tank testing of a scale model of 1:100 as well as the PTO test using the test rig (the details can be found in [6]).

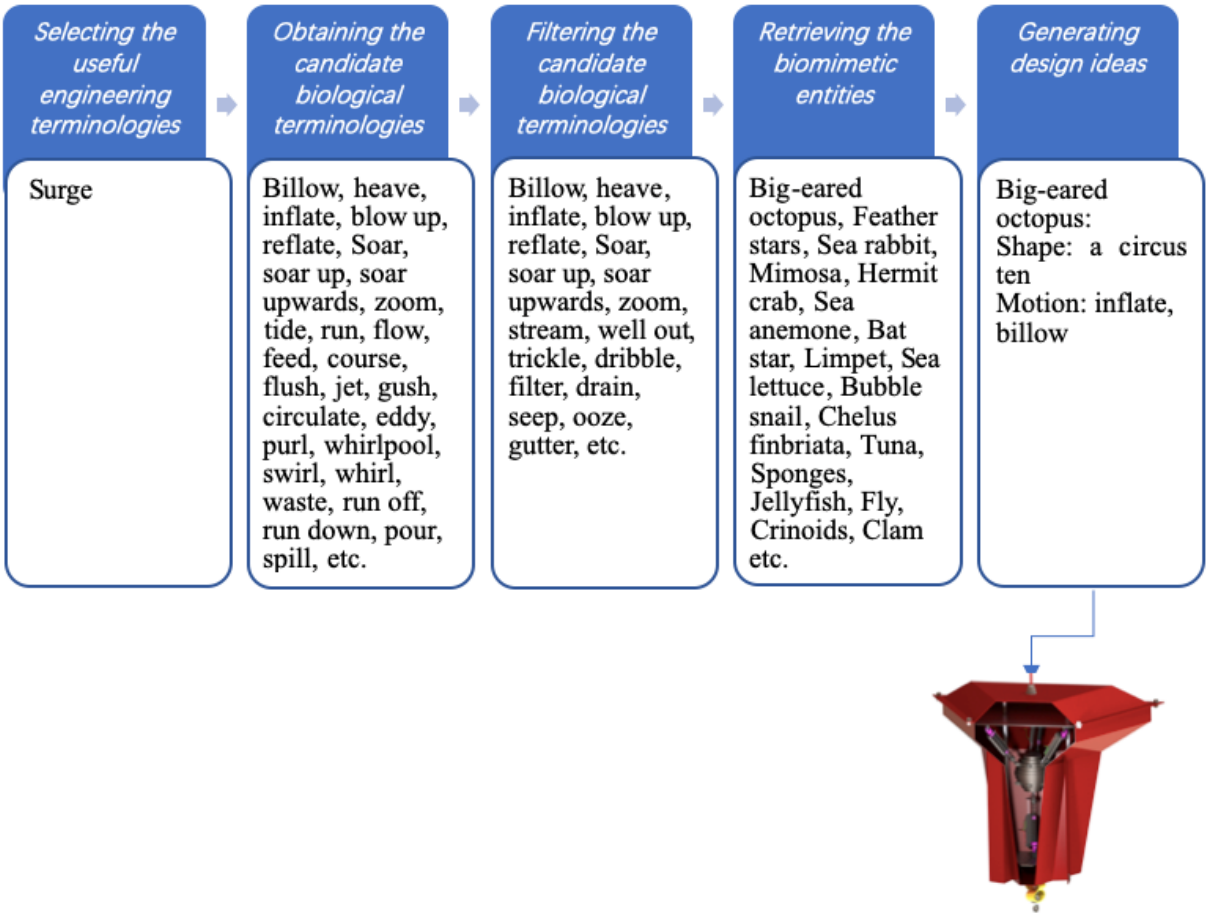
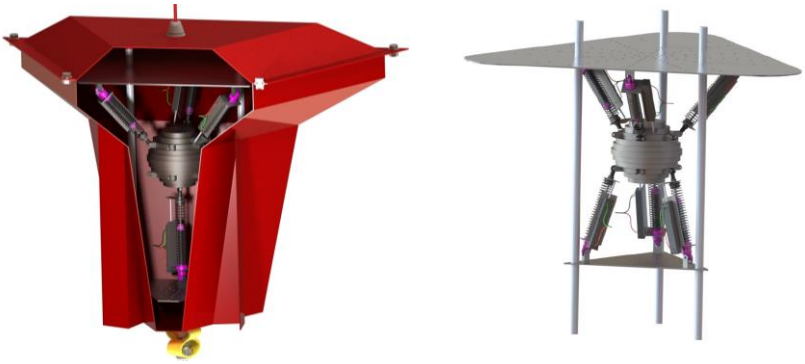


Figure 7. Flow chart of obtaining the biological entities by "Surge"



(a) The TALOS WEC (b) the hydraulic test rig

Figure 8. The prototype of the WEC [6]

Recently, UK Research and Innovation (UKRI) has announced to financially support 8 projects [80], aiming to unlock the potential of marine wave energy. The NHP-WEC for TALOS multi-axis WEC is one of the supported projects. The main objectives of the project are to optimize the TALOS WEC, the relevant PTO system and control technologies in order to advance the TALOS WEC technology.

The ongoing research focus is on advancing the TALOS WEC, including the hydrodynamic optimization of the TALOS WEC, as well as the relevant PTO system. In addition, the project will also advance WEC's technology by developing essential device control and monitoring systems that are integrated with high-fidelity sea state forecasting using the SmartWave toolset [81]. This joint approach of TALOS and SmartWave would facilitate methodological synergies within these two areas of investigation, so to bring the TALOS wave energy technology forward.

5. Discussions

In the process of searching for biological terminologies, it is found that the number of biological terminologies obtained by the different engineering terminologies can be different. For example, the number of biological terminologies related to the energy extraction methods is large, but the number of biological terminologies related to the structure is small, as shown in Table 11.

Table 11. Comparison of the number of candidate biological terminologies by the different engineering features

Features		Number of biological terminologies	Total number of biological terminologies
Functions of WECs	Capture	10	45
	Extract	13	
	Absorb	17	
	Store	5	
Structure of WECs	Displace	6	29
	Linkage	1	
	Adjust	12	
	Rotate	5	
	Reaction	2	
	Transform	3	
Methods of power extraction	Surge	38	437
	Sway	14	
	Heave	15	
	Roll	28	
	Pitch	203	
	Yaw	18	
	Oscillating	20	
	Overtopping	36	
	Bulge	45	

In the process of retrieving biological entities, AskNature is a good bio-retrieval site because it contains a large number of biological cases and biological entities and a good tool for filtering biological terminologies via its very useful retrieving mode. When the candidate biological terminologies composed of phrases is retrieved in AskNature, a large amount of irrelevant information can be generated. For example, when a biological entity is retrieved using the word "educa", search results will relate to education and educator which include the word "educa". When searching with the phrase "take in", the system

displays information about all words containing the word "in", such as “inspired” and “Bio-industrial” containing the word “in”, so Asknature is suitable as a filtering tool for the biological terminologies, but if AskNature's search results are used for statistical analysis, it is possible to get inaccurate conclusions. In addition, when using AskNature to filter candidate biological terminologies, it will be found that manually filtered words will still be displayed in related cases. Therefore, AskNature can be used to check the manually filtered biological terminologies to reduce the error filtering of biological terminologies.

6. Concluding remarks

This paper illustrates how to obtain the valuable biological entities so for designing novel WECs. The proposed method could provide a large number of biological inspiration resources and valuable biological entities related to the principles and goals for a novel WEC, and from which the useful biological identity may be obtained to inspire the innovation and design of a wave energy converter. In the proposed method, following steps are made:

1) By using WordNet, a large number of candidate biological terminologies can be generated.
2) Using manual filtering and the filtering and AskNature, the candidate biological terminologies can be acquired.
3) Using the engineers' understanding to the candidate biological terminologies so to remove the deviations in the filtering process.
4) In the cases of a large number of filtered biological terminologies, it is necessary to develop a computer-aided tool for filtering the candidate biological terminologies, including how to select the appropriate biological terminology in order to obtain the ideal biological entity.
5) Selecting a candidate biological terminology with a small amount of information that can be retrieved, may be a shortcut to obtain a novel biological entity for this new and novel design process.

A utilization of the present method demonstrates how to obtain the ideal biological entities. It should be noted that finding the relevant biological entities may provide the inspirations for designing the innovative devices but would not solve all the WEC design questions. After all, the improvements and optimizations must be carried out during the development stages of wave energy converters, similar to other bionic engineering problems.

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