Morphological Bionic Design Based on the Gill Structure

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ABSTRACT
Bionics, which is the study on the function of living systems, provides a scientific basis for expanding the study of modern design. In this study, the gill structure of the fruiting body of a fungus is studied in depth, and the structural properties and functional advantages of gill are summarized through a mathematical analysis of their intrinsic morphogenetic patterns. This study presents new insights into structural bionic design through the application of the bionic design principles in industrial, architectural and urban planning. Therefore, it provides new ideas and reference values for the future intervention of bionic design research into practical design applications with an open perspective.

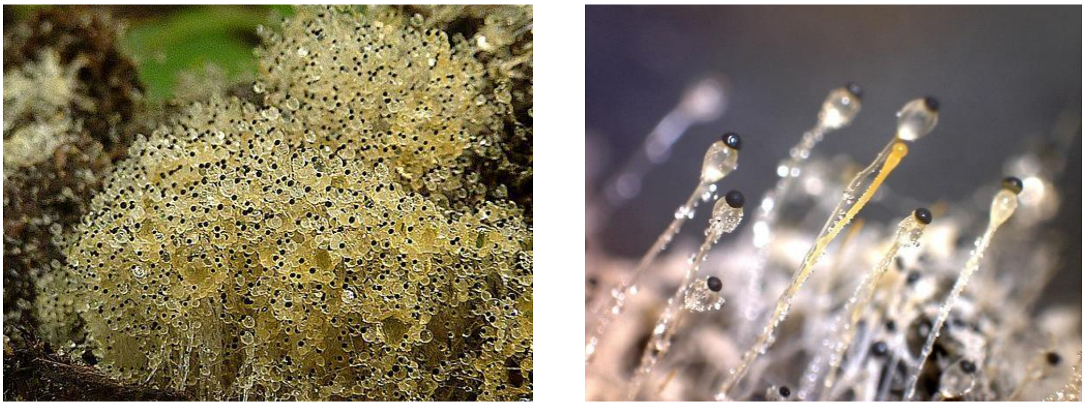
Keywords: *Gill, Structure, Bionic design, Morphological research.*

1. INTRODUCTION

Bionic design refers to the refinement of the laws of nature and an exploration of the mysteries of life and spirit. The functions of animals and plants in some aspects are far beyond the research results of human beings themselves. Based on the forms of living bodies and biological systems, people design scientific and technological products with powerful functions, vivid interfaces and easy operation, such as a glider made from the wings of a bird, and a streamlined structure with little resistance that mimics the spindle shape of a trout. It can be said that human development and progress is a process of constantly exploring nature and imitating natural creation. [1]

Morphological bionic design refers to the design of the biological form into the morphological characteristics of the product. With necessary abstraction, evolution, refinement and sublimation, the form not only breaks away from the pure natural form, but also retains its morphological essence, with a kind of association and emotional expression. [2]

In life, there are many bionic design cases based on the study of animal and plant morphology, but "fungi", such a biological group with a very rich diversity, has rarely become the object of mainstream attention. Although there are some product designs inspired by "mushrooms", most of them are based on the simple appearance imitation of mushrooms, and there are few in-depth studies and applications on the biological form of mushrooms.



(a) Pilobolus (b) Pilobolus in close

Figure 1 Pilobolus (a type of mold) of the mucor. Source: (a) https://commons.wikimedia.org/wiki/File:Pilobolus_sporangia.jpg (Eduardo A. Esquivel Rios); (b) https://commons.wikimedia.org/wiki/File:Pilobolus_sporangia_in_close_view.jpg (billyd)

Fungi belong to the eucaryon, and are separate from animals, plants and other eukaryotes. Hawksworth (1991) estimates that there are about 1.5 million fungal species worldwide. [3] There are very small microorganisms such as molds in the fungal kingdom (as shown in “Figure 1”) (they constitute the basic unit of mycelium, which is long tubular and 2~10μm wide). There are also the largest creature found in the world, such as armillaria mellea (covering an area of 965 hm^2, life span of 2400~8650 years, and estimated weight of 6800 t~31750 t) (as shown in “Figure 2”).

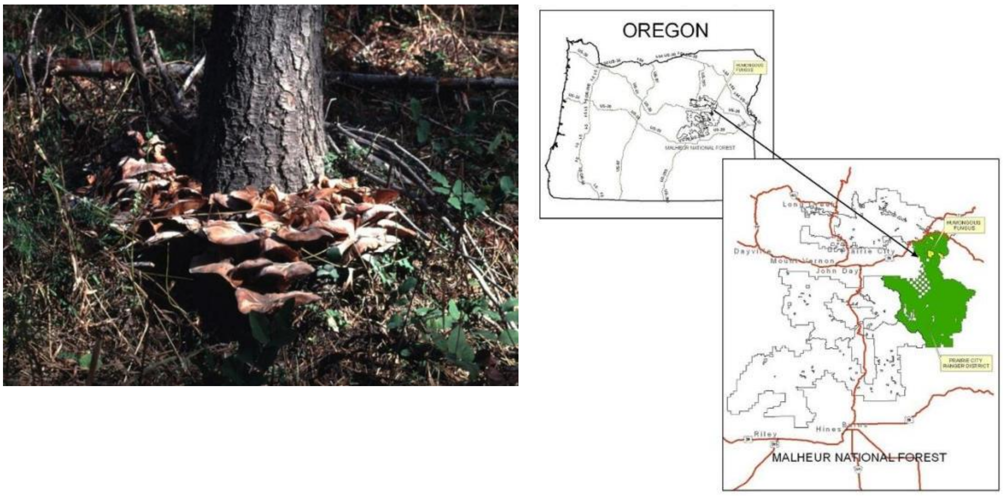


Figure 2 The World's Largest Living Organism (The Humongous Fungus) [4].

2. GILL STRUCTURE

2.1 Generation of Gill Structure

Gill/Lamellae refers to the fruiting body of the Agaricales of basidiomycetes 1(commonly known as basidiocarps), or the structure developed from the trabecula.

The hymenium grows under the cap of the fungus. The hymenium consists of tightly arranged bbasidiomycetes and cystid and basidiole in some cases, which may be arranged on the inner side of a tubular structure (as in porcini) or on the sides of a gill under an overhanging cap. The gill is usually in

1. Fruiting body (fruiting body, sporocarp, fructification) is the spore-producing structure of a higher fungus, namely, the fruiting body, which consists of organized mycelium. Also, it is called the basidiocarps in basidiomycetes and the ascocarp in ascomycetes. Whether it is sexual or asexual reproduction, whether it is simple or complex, the sporulation structure is called fruiting body.

a thin ribbon, radiating from the edge of the cap to the stalk. [3]

Pleurotus djamor of Pleurotexpertae (as shown in “Figure 3”-a) and Flammulina velutipes (as shown in “Figure 3”-b) of Tricholomataceae, Gliophorus laetus of the Hygrophoraceae (“Figure 3”-c) were selected in this study.

(a) Pleurotus djamor (b) Flammulina velutipes (c) Gliophorus laetus

Figure 3 Photos of fungus gill structure of several Agaricales. Source: (a)https://commons.wikimedia.org/wiki/File:Pleurotus_djamor_(Pleurotaceae)_(19216460702).jpg (José Roberto Peruca from Araçatuba); (b)https://commons.wikimedia.org/wiki/File:Flammulina_velutipes_BS12.JPG (Jerzy Opioła); (c)https://mushroomobserver.org/image/show_image/1518416 (Betty Green)

2.2 Structural Similarity of Gill

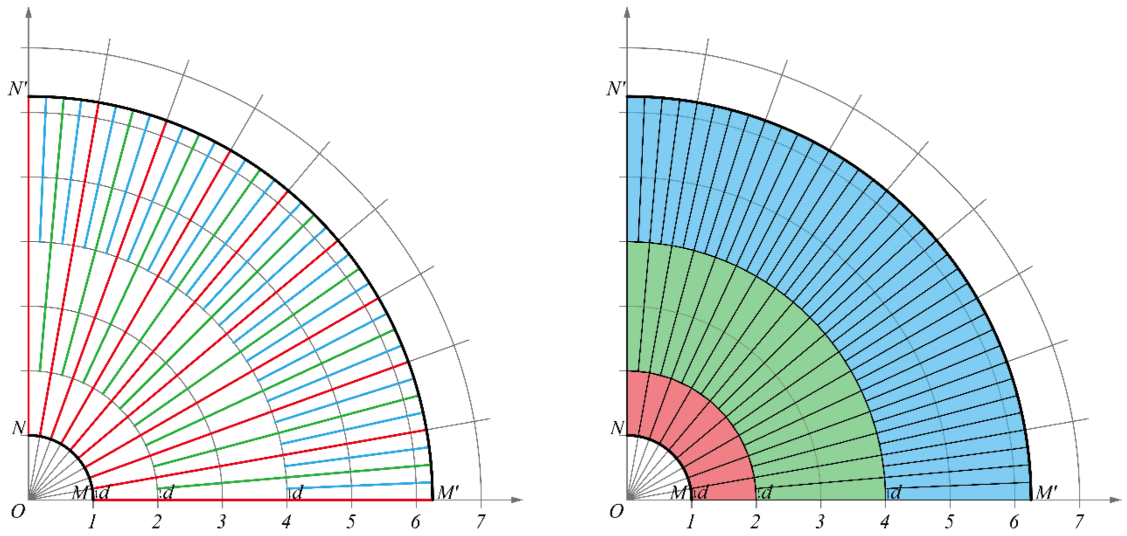
After observing the gill structure of the selected sample fungi, it is found that although fungi of different genera have great differences in the number of gill, the size of the cap, the length and the thickness of gill, they are highly similar in the arrangement and distribution morphology of gill.

- The gill structure is composed of several independent banded structures epiphytic under the fungal cap.
- All of these banded tissues are in the shape of radiating arrangement and distribution towards the stalk.
- Not all the gills are equal in length. In addition to the full-length gills that connect the edge of the cap and the stipe occupy the radial span of the distribution space, there are other short gills whose length decreases in turn.
- All the gills connected with the edge of the cap. However, only the full-length gill is connected with the boundary of the stipe, while the short gill is not connected with the boundary of the stipe. The shorter the gill is, the farther it is from the stipe.
- Although the density of gills of different fungi is different, their arrangement and distribution are very uniform, and the annular spacing between all adjacent gills at the same radius remains basically equal.

3. ANALYSIS ON THE STRUCTURE AND MORPHOLOGY OF GILL

3.1 Analysis on Morphological Characteristics of Gill Structure

By observing and studying the geometric characteristics of the gill, each banded fold of the gill structure is regarded as a line dividing the spatial plane, and an abstract geometric schematic diagram of the gill distribution form can be drawn (as shown in “Figure 4”-a).



(a) Schematic diagram of distribution and morphology of gill (1/4). (b) Schematic diagram of the spatial distribution pattern of gill (1/4).

Figure 4 Schematic diagram of geometric abstract theoretical morphology of gill (drawn by the author).

Taking a quarter of the complete circular diagram, the outer boundary arc M'N' is the edge of the cap, and the inner boundary arc MN is the end face connecting the stipe and the cap. The thick straight lines in red, green and blue colors in the figure represent the gills hanging under the cap, and the space where they are distributed is generally circular, annular or fan-shaped.

3.1.1 Radial Arrangement

The linear segments of gill are arranged in a radial manner, extending outward and connecting to the edge of the cap, with the center point of the end face connecting the stipe and the cap as the center of the circle. (as shown in "Figure 4"-a)

The general radial linear pattern is different from the radial arrangement of gills. The farther the rays are from the center of the circle, the greater the spacing between rays, that is, the closer the rays are to the starting point, the denser the rays are; the farther away from the starting point, the more sparse the ray. However, the radial arrangement of gills is different. As shown in "Figure 4"-a, the density of radial linear segments is basically consistent from arc MN to arc M'N'.

3.1.2 Long-short Layering

The length of the linear segment of the gill is not consistent, and there is an obvious phenomenon of layering. (as shown in "Figure 4"-a)

As the gill itself has the thickness, the spores attach to both sides of the gill, and space is also needed to accommodate and spread the spores. Therefore, there must be a certain distance between the gills (the minimum distance), that is, the density of the gills is limited.

The minimum interval of the gills corresponds to the distance d (as shown in "Figure 4"-a). As the circumference of the inner boundary MN is limited, the number of line segments starting from the inner boundary is limited. The smaller the distance d is, the more the number of lines is, and the denser the line distribution is. The farther the inner boundary MN is from the outer boundary M'N', the more hierarchical the segment is.

According to "Figure 4"-a, there are three layers of line segments with different colors. The inner boundary MN and the outer boundary M'N' are in positive order: primary red line segments, secondary green line segments, and tertiary blue line segments. The starting distance of each layer of line segments is the minimum distance d.

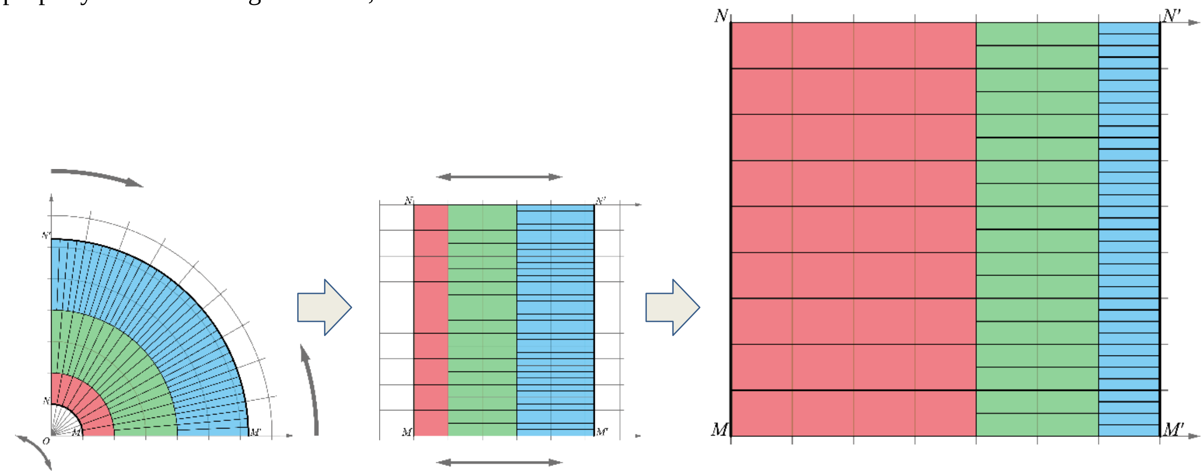
The primary red line segment starts from the inner boundary MN; the secondary green line segment is between the red line segments, and the number is the same as that of the primary red line segment; the starting point of the green line segment is at the position of MN after a radial offset of a distance. The third-level blue line segment is between the red line segment and the green line segment, and the number is twice that of the green line segment. The starting point of the blue line segment is at the position where the starting point of the green line segment is offset radially for a distance.

3.1.3 Circumferential Division and Radial Division of Space

There are spatial distribution characteristics of circular division and radial division between gills. The starting point of each line segment at each layer is perpendicular to the two sides of the line segment and intersects the adjacent two line segments (as shown in “Figure 4”-a). The lines are surrounded by quadrangles to obtain an abstract form diagram of the spatial distribution of gills (as shown in “Figure 4”-b).

The space between the gills not only has the property of circular segmentation, but also has the property of radial segmentation. The radial space is divided hierarchically, and the circular space is divided quantitatively (as shown in “Figure 4”-b).

The inner boundary MN and the outer boundary M'N' are in positive order, and the radial length and circumferential length of each layer of quadrilateral are twice as long as those of the upper layer, that is, the radial and circumferential length of each layer of space are exponential, and the exponent is 2. However, each layer of space is divided at circumferential direction, and the number of quadrangles in each layer is 1/2 of that in the next layer, that is, the number of space partitions in each layer is also exponential, and the exponent is 2. This is also the reason why the density of the gill is consistent from the stipe to the edge of the cap.



(a) (b) (c)

Figure 5 The figure obtained through continuous changes (rotation, expansion, scaling) of the spatial distribution form of gill (drawn by the author).

3.1.4 Fractal Geometric Properties

The spatial distribution of gills also has the fractal characteristics[2]. From the perspective of topology, regardless of the shape and size of the quadrangle in “Figure 4”-b, only the position relationship of the quadrangle is considered. “Figure 4”-b can be changed into a new graph (as shown in “Figure 5”-c) through continuous changes, which is very similar to the famous self-similar fractal set "Cantor Set"[3].

The most common structure of Cantor Set is Cantor Ternary Set (as shown in “Figure 6”). Taking a straight line segment with length of 1, it is suggested to divide it into three equal segments, remove the middle segment, leave two segments, and then divide the remaining two segments into three equal segments, remove the middle segment

2. With the morphological characteristic of filling space in non-integer dimensions, the fractal is usually defined as "a rough or fragmentary geometric shape that can be divided into several parts, each of which is (at least approximately) the reduced shape of the whole", i.e. it is self-similar in nature.

3. Cantor Set, introduced by the German mathematician Georg Cantor in 1883 (but discovered by Henry John Stephen Smith in 1875), is a collection of points on a line segment, with many remarkable and profound properties. Although Cantor himself defined this set in a general, abstract way, the most common structure is the Cantor tripartite set, obtained by removing the middle third of a line segment.

respectively, and retain four shorter segments. By analogy, this operation will continue until infinity. As the number of segments formed is increasing and the length is decreasing in the process of continuous segmentation and discarding, the set of these segments is Cantor Ternary Set. If the ratio of the length of the line segment obtained after each operation to the length of the previous one is equal to 1/3, the similarity ratio is 1/3.

As shown in “Figure 5”-c, quadrilaterals at each level are self-similar, and the figure area ratio of each level is 1/4, that is, “Figure 5”-c is the deformation of Cantor Set with a similarity ratio of 1/4.

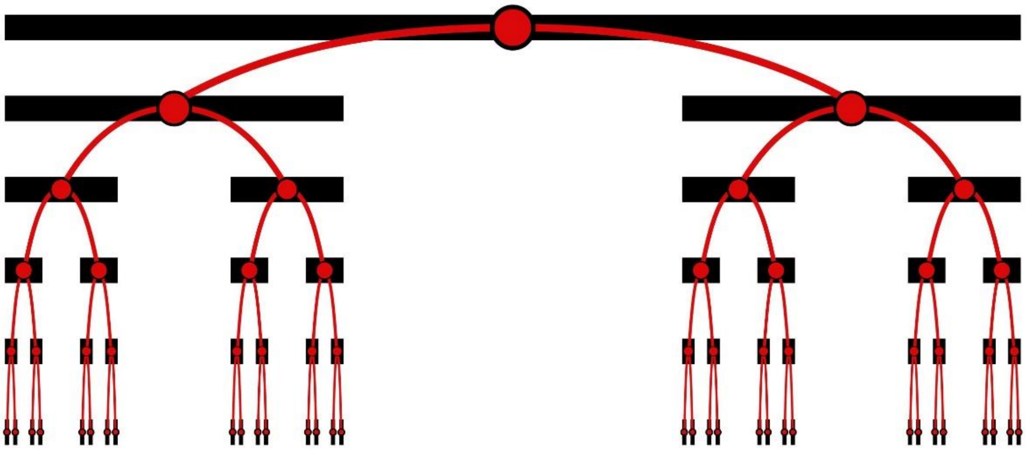


Figure 6 Diagram of Cantor Ternary Set (Cantor set). Source: https://commons.m.wikimedia.org/wiki/File:Cantor_set_binary_tree.svg (Sam_Derbyshire).

3.2 Analysis on the Morphological Law of Gill

3.2.1 Morphological Formation Law of Gill Structure

According to the above discussion, the morphological formation law of the gill structure can be clearly concluded.

As shown in “Figure 4”-a, primary gills (the first-level gills) are first generated according to the minimum distance between gills. The quantity Q_1 is equal to the perimeter of the inner boundary C_{MN} divided by the minimum distance d, that is, $Q_1=C_{MN}/d$ (the calculation result is non-zero natural number).

According to the arc length formula (as shown in Table 1), the radius $R_2 = d \times \frac{Q_1}{2\pi}$ of the second-level gill at the starting point can be deduced. As the number of space divisions in each layer is exponential, and the exponent is 2, the number of the second-level gills is $Q_2 = Q_1 \times 2^0$. The radius of the third-level gills at the starting-point position is $R_3 = d \times \frac{Q_2}{2\pi}$ and the number is $Q_3 = Q_1 \times 2^1$.

Table 1. Arc length formula

$l = \alpha \times r$

Character	l	α	r
Coreference	arc length	Central Angle (radian system)	radius

By analogy, the formula for the number of gills at the nth level can be derived. (as shown in “Table 2”)

Table 2. Formula for the number of gills at each level

$$Q_n = \frac{C_{MN}}{d} \times 2^{n-2}$$

Character	n	Q_n	C_{MN}	d
Coreference	Series of gill	Number of the nth-level gill	MN perimeter	Minimum-spacing arc length

Radius formula of the nth-level gill at the starting-point position is shown in “Table 3”.

Table 3. Formula of radius of each-level gill at the starting point

$$R_n = d \times \frac{Q_n}{2\pi}$$

Character	n	Q_n	R_n	d
Coreference	Series of gills	Number of the nth-level gill	radius of the nth-level gill at the starting point	Minimum-spacing arc length

For different kinds of fungal fruiting bodies with gill structure, the gill shape is the same, but the spacing density and the gill shape will be different depending on the species. For the same species but different individuals of fungal fruiting bodies, the gill shape is basically the same, but the gill level and length are different. In the same fungal fruiting body, the gill shape at different growth stages is completely consistent, but the gills increase with time and extend in length.

3.2.2 Inherent Growth Law of Forming Gill Structure

"Biological forms" have their own inherent morphological characteristics and reproduce, grow and die according to the existing growth laws. It is generally believed that the "form" of organisms is closely related to their habits and growth environment, and is constantly improved in the process of evolution [5].

The inherent growth law and function of mushroom gill structure are closely related to their habits and growth environment, and are constantly improved in the process of evolution. The spores of Agaricales fungi with gill structure grow and attach to both sides of the gill. In order to accommodate more spores, the gill structure needs to increase its surface area as much as possible in a limited space, and the structural morphology of the gill is the evolution result of increasing the surface area.

The distribution form of the gills grows according to the hierarchical state, and the radial span of the hierarchy and the number of spatial divisions of each hierarchy are exponentially increasing, which is related to cell division. It is assumed that cell division occurs once every unit of time, and the relationship between the number of cells generated by cell division (dependent variable) and the elapsed unit time (independent variable) (division occurs once per unit of time) is an exponential function (as shown in “Figure 7”).

Therefore, this exponential relationship can be seen everywhere in biological morphology, such as the shells, teeth, horns, claws, etc. of many animals.

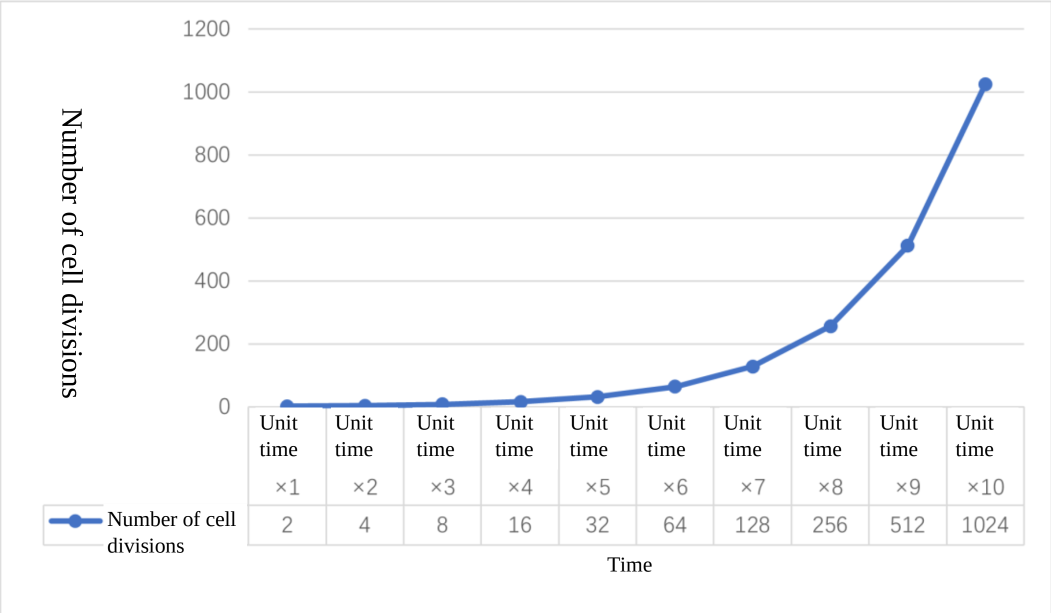


Figure 7 The relationship between the number of cell divisions and unit time (drawn by the author).

3.2.3 Advantages of Gill Morphology

- Increasing specific surface area[4]

The gill is to contain more spores in the limited space. The basic function of the gills is to increase the surface area that spores can attach to. Especially in round, fan-shaped, circular or other spaces with radial expansion properties, the distribution and arrangement of gills have obvious advantages in specific surface area.

- Unlimited extension

The gill shape has the advantage of infinite extension. In theory, the gill has only a starting point but no end point. The larger the area and radius of the cap, the longer the gill, and the more gill levels.

Theoretically, the larger the fruiting body of the fungus is, the more the original gill of the fungus will continue to extend outwards. When the distance between the gills expands to more than twice the minimum distance, the new level of gills will also begin to grow, and so on.

- Space bisection for radial expansion

The gill structure reasonably divides the space at the bottom of the cap where the gill is located. As it has the characteristics of circumferential and radial spatial segmentation, the spacing between the banded tissues of each gill is almost uniform and consistent.

The distribution pattern of gills has the property of uniform division for round, fan-shaped, circular or other spaces with radial expansion.

- Diversion

The spaces at all levels between the gills are connected in radial direction, while each layer of space is divided at the circumferential direction, and the number of divisions in each layer is exponential. Therefore, when the fluid passes through the space channel formed between each layer of the gills from the center to the outside, the fluid will be diverted and continue to spread. The more the morphological levels of the gills, the more the number of shunts.

As long as the distribution of the gill maintains a relative position relationship, it will not affect the nature of its shunt with the rotation, distortion, extension and other deformation in gill shape.

4. Specific surface area (m^2/g) is the total area of a unit mass material. Usually, it refers to the specific surface area of solid materials such as powders, fibres, granules, flakes, blocks, etc. Specific surface area has another definition: area/volume (m^2/m^3).

Table 4. Calculation formula of heat dissipation

$$Q = K \times \Delta T \times F$$

Character	Q	K	ΔT	F
Coreference	Heat dissipation	Combined heat transfer coefficient	Heat dissipation surface temperature — ambient temperature	Area of heat dissipation
Unit	W	W/(m2·℃)	℃	m2

3.3 *Morphologic Bionic Design and Application of Gill Structure*

3.3.1 Radiator Fins

The heat dissipation calculation formula of radiator is as shown in Table 4. It can be seen from the formula in Table 4 that the heat dissipation capacity is positively related to the heat dissipation area. When the heat dissipation coefficient, heat dissipation surface temperature and ambient temperature remain unchanged, the larger the heat dissipation area is, the greater the heat dissipation capacity is. In other words, increasing the heat dissipation area can improve the heat dissipation efficiency of the radiator.

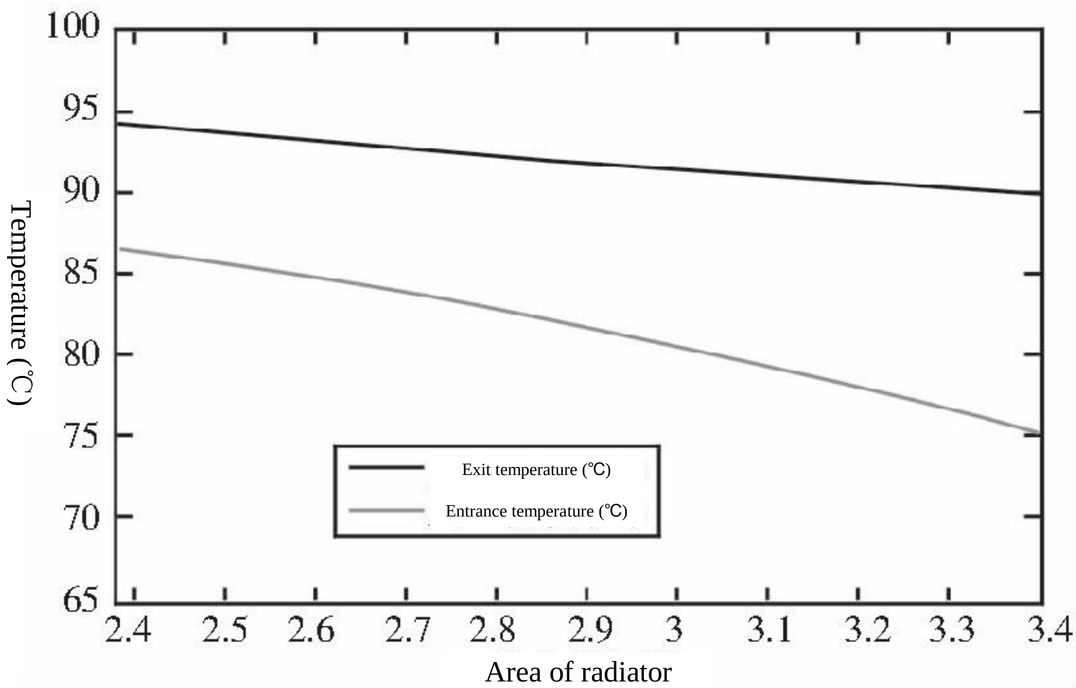


Figure 8 Effect of the windward area of radiator on heat dissipation performance [6].

Yang Ying and others from the School of Vehicle Engineering of Chongqing University of Technology establish the thermal management simulation calculation model of the whole system based on AMESim. By comparing the temperature changes of the cooling medium under two common working conditions, the temperature changes at the inlet and outlet of the water-cooled radiator and the intercooled radiator are obtained. [6] It is found that when the heat dissipation area increases, the temperature at the inlet and outlet of the radiator decreases significantly, and the temperature difference at the inlet and outlet of the radiator also increases significantly, indicating that the heat dissipation capacity of the radiator increases. [6] (As shown in "Figure 8")

The structural form of the heat sink on the fan clutch is the same as the distribution form of the gill in some essential characteristics, which is mainly used in the cooling system of automobile engine (as shown in "Figure 9"). In the 1960s, BorgWarner manufactured the first silicone oil fan clutch in the world. With the continuous innovation of technology, silicone oil fan clutch has become an important component of modern high-performance cooling system of automotive engine (especially diesel engine). [7] After installing silicon oil fan clutch, it has the advantages of noise reduction, low emission and ground wear.

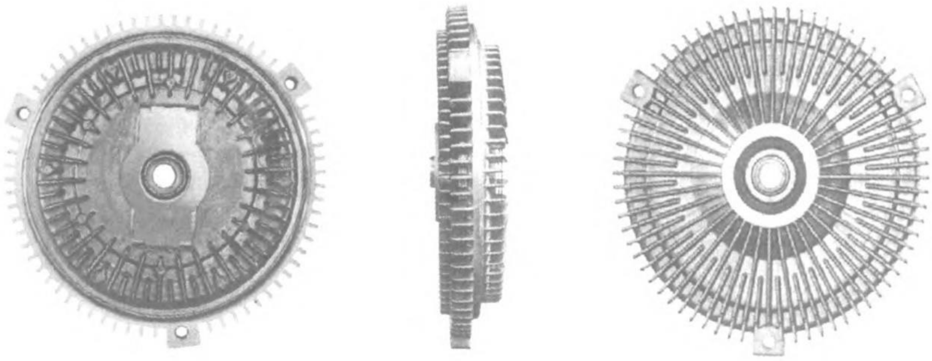


Figure 9 Central-hole mounted fan clutch [7].

3.3.2 Building Structural Support

The gill structure divides the space distributed by the gill, and the architectural support structure not only supports the building but also plays the role of dividing the architectural space, both of which have the same role in spatial distribution.

In addition, the form of uniform division of space by the gill structure can also be used for force transmission. The plane spatial distribution form of gill is stretched in the Z-axis direction to become a three-dimensional gill form supporting structure.

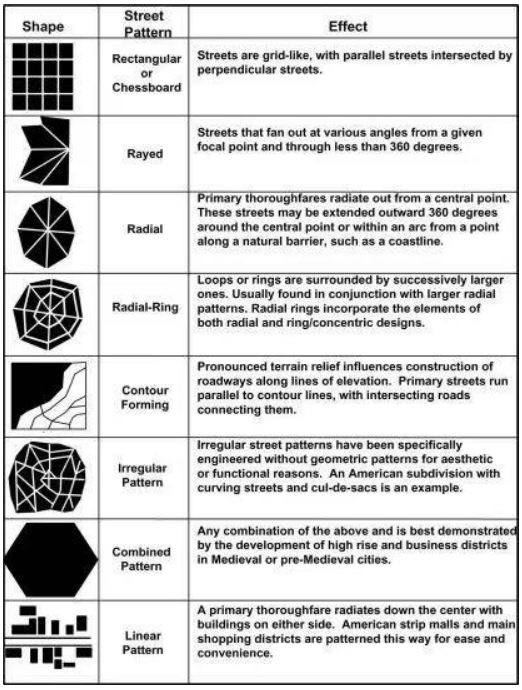
Figure 10 Fan vault of the gateway of the Corpus Christi College, Cambridge. Source: https://commons.m.wikimedia.org/wiki/File:Fan_vault_of_the_Gatehouse_at_Corpus_Christi_College,_Cambridge.jpg

The fan vault structure of British Gothic architecture is very similar to it (as shown in "Figure 10"). This form of supporting structure can transfer the load of the superstructure to the support of columns or walls through the structure. At the same time, it has the property of outward expansion on the XY axis plane, which can expand the small bearing area of the superstructure to a larger range.

3.3.3 *Urban Form Model Design*

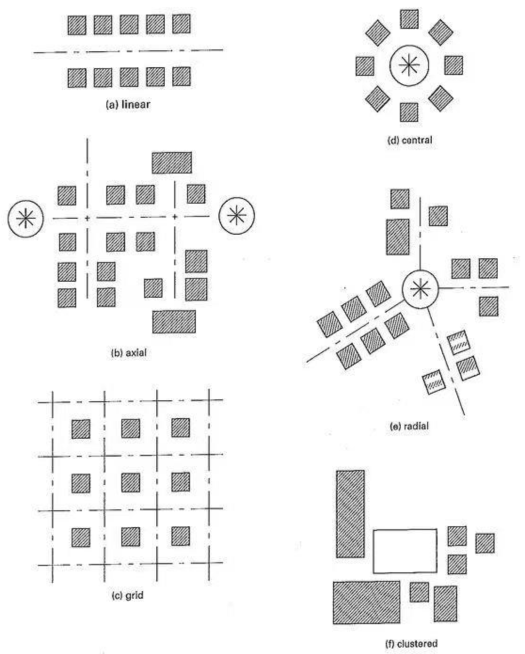
There have been many types of studies on urban layout form. Based on different research results, according to urban land use form and road skeleton form, it can be generally summarized into two categories: centralized and decentralized urban layout form. [8]

The centralized urban layout can be further divided into grid type, circular radial type, etc. [8] The most important feature of decentralized layout is that urban space presents a non-clustered distribution, including clusters, belts, stars, rings, satellites, multi-center and group cities. [8] (As shown in “Figure 11”)



Shape	Street Pattern	Effect
	Rectangular or Chessboard	Streets are grid-like, with parallel streets intersected by perpendicular streets.
	Rayed	Streets that fan out at various angles from a given focal point and through less than 360 degrees.
	Radial	Primary thoroughfares radiate out from a central point. These streets may be extended outward 360 degrees around the central point or within an arc from a point along a natural barrier, such as a coastline.
	Radial-Ring	Loops or rings are surrounded by successively larger ones. Usually found in conjunction with larger radial patterns. Radial rings incorporate the elements of both radial and ring/concentric designs.
	Contour Forming	Pronounced terrain relief influences construction of roadways along lines of elevation. Primary streets run parallel to contour lines, with intersecting roads connecting them.
	Irregular Pattern	Irregular street patterns have been specifically engineered without geometric patterns for aesthetic or functional reasons. An American subdivision with curving streets and cul-de-sacs is an example.
	Combined Pattern	Any combination of the above and is best demonstrated by the development of high rise and business districts in Medieval or pre-Medieval cities.
	Linear Pattern	A primary thoroughfare radiates down the center with buildings on either side. American strip malls and main shopping districts are patterned this way for ease and convenience.

(a) Urban form classification



(b) Linear, axial, grid, central, radial, clustered.

Figure 11 Type of urban space form. Source: (a) https://www.pinterest.com/pin/492649939644605/ (b) https://www.pinterest.com/pin/196329483484555555/

However, the infinite extension characteristic of the gill form and its space equal division of circular, fan-shaped, circular or other radial expansion characteristics are highly consistent with several types of urban form. The gill is regarded as the interval between the traffic route and the single building, and the space divided by the gill is regarded as the building area. The morphological distribution of the gill has reference value for the design of urban spatial morphology.

Sun City, located in Arizona, USA, at the northwest corner of Phoenix, is a world-famous pension real estate project. It is a typical layout of multi-center, circular and radial urban form, with multiple circular and fan-shaped building areas. The overall layout of its houses is similar to the spatial distribution of gills. The buildings in Sun City also have the characteristics of radial expansion and hierarchical level, but the distance between the levels is a quantitative constant, and the number of single buildings in each level is not an exponential but linear. (As shown in “Figure 12”)

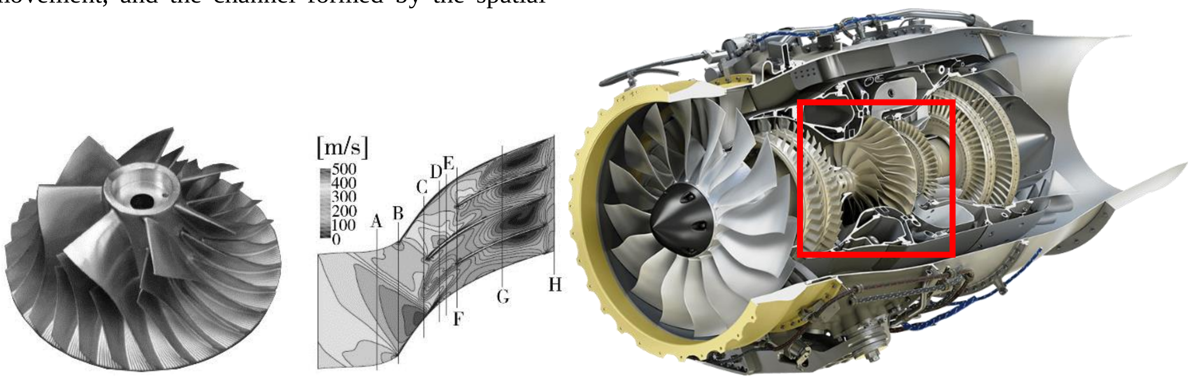
(a) (b)

Figure 12 Figure 16 Aerial View of Sun City, Arizona. Source:
(a)https://www.pinterest.com/pin/1047509194552697247/
(b)https://www.pinterest.com/pin/185914290857838473/

3.3.4 Radial Shunt

As the fluid is divided in the process of radial flow from the inner boundary to the outer boundary of the gill shape, the direction of this fluid movement is consistent with the centrifugal movement, and the channel formed by the spatial distribution of the gill can act on the separation in the process of centrifugal movement.

Compressors, such as compressors and water pumps, work on the principle of centrifugal motion, and the radial split flow property of gills can be used for this centrifugal compression device.



(a) Centrifugal compressor with double splitter blades and its simulation results [9] (left). (b) HF120 engine/manufacturer GE Honda Aero Engines (GHAE) (right).

Figure 13 Impeller with splitter blade and centrifugal space engine. Source: (b) https://www.kindpng.com/imgv/iJbThwx_hf120-engine-full-color-autodesk-inventor-jet-engine

The impeller with splitter blades is mainly used for the high-pressure ratio centrifugal impeller components of the centrifugal engine on small spacecraft (as shown in “Figure 13”). The design method of splitter blade (also known as short blade or small blade) adopts long and short blade spacing arrangement, which can effectively improve the flow field distribution in the impeller, improve the impeller pressure ratio, and improve the operation stability. It is an effective way to improve the comprehensive performance of centrifugal turbomachinery. [9]

4. CONCLUSION

Considering the randomness of the forms of natural creatures, there are no two identical individuals, but they all have a rule to follow, that is, the "algorithm" of the creatures themselves.

In this study, the gill structure of agaricus fungi are observed and studied, and the homogeneous characteristics of the biological structure of the gill is summarized. Also, the growth law and algorithm behind the shape of the gills are explored through geometric analysis and pure mathematical theoretical derivation. Through the output of mathematical model, the characteristics and advantages of the gill structure can be applied to the related fields in the way of bionic design. Also, it provides reference value for future research on bionic design and practical application from an open perspective.

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