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Experimental Results of a Novel Amphibian Solution for Aquatic Robot

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Abstract—**Water, recognized as one of the most important and endangered resources to mankind, is very difficult to monitor in real time using conventional methods. Thanks to recent advancements in technology, the use of robots, able to fulfill missions such as sampling from aquatic environments, becomes feasible and can increase dramatically the quality of water monitoring. Due to the complications for the robot's movement in some aquatic scenarios, for instance, shallow waters or dry banks of rivers and lakes, amphibian locomotion appears to be necessary to guarantee a satisfying coverage of the monitoring activities in such areas. In this paper, we focus on developing a practical amphibian solution by introducing a pair of screw rotors, which rotate in opposite directions to generate locomotion on the ground. The primitive idea of this novel design is to enhance the versatility of a marine robot with a terrestrial locomotion without undermining its performance during the movements in the water. In particular, we elaborate the principle of this novel design and present some test results of a prototype on selected terrain types, which are similar to the target aquatic environment. We conclude the paper with some preliminary conclusions based on the analysis of the test results about effectiveness and efficiency issues.**

I. INTRODUCTION

HAVING more convenient and economical solutions to collect samples and data in field with minimum expense of time and effort has always been a pursuit of aquatic environmental researchers. In the past, stationary equipments, research vessels and manually deployed devices have been used combined with a large human labor to achieve the goal. Due to the limit of equipments, coverage of samplers and difficulties of deployment both on scale of time and space, efficiency and effectiveness of such activities are compromised.

In the recent years, researchers have been trying to adapt robots as a promising alternative to substitute conventional methods, in order to tackle every shortage mentioned above, especially improving the spatial and temporal samplings coverage of an area of interest. In the framework of "HydroNet"[1], a European project aiming at developing a network of robots and buoys for environmental monitoring, one of the requirements is the capability for the robots to patrol in complicated fields, such as lagoons, rivers and lakes, to guarantee a comprehensive sampling and data collection. In these specific aquatic environments, some terrain types are necessary to be considered for the robots' locomotion such as shallow water, dry banks with sand, gravel, mud, and even grass, due to the seasonal change of water level and wet area. To cross these particular terrains, an amphibian locomotion has to be an important function of the robot. However, since aquatic locomotion is the usual condition during the monitoring mission, the additional mechanism for amphibian locomotion is expected to have a minimum counter-effect on that condition in terms of additional induced drag and ease of maneuverability. Moreover, the amphibian solution has to be designed to be ragged, adaptive and energy efficient, in order to deal with terrain variety and energy issues, while being suitable for long-term field operation without maintenance and support.

Fig. 1. Typical riverbank terrain types: gravels and sands (top), grassland and mixture (bottom).

Fig. 2. Types of amphibian solutions. amphibian vehicles with wheel and track (top); Lobster Robot[2] and RHex/AQUA robot[3] (bottom)

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So far, there are several conventional and unconventional amphibian solutions implemented on piloted and autonomous vehicles, for instance, legs, wheels, tracks, half wheels and so on (see Fig. 2). However, most of them either have insufficient adaptation to the objective field or fail on efficiency and roughness needed for fieldwork. For example, the wheel can easily fail on the mud and sand, the track is complicated in mechanism and exhibits a large drag when moving underwater, the legs are not energy-efficient, while they are complicated in mechanics and control as well.

To address this issue we propose to adopt a well-developed mechanism and to use that as a novel solution in the area of robot locomotion. The principle is similar to Archimedes' screw (see Fig. 3), which was originally invented by Archimedes of Syracuse in the 3rd century BC to pump bilge water out of ship hull. The screw was very effective because it got rid of the water and only required one person to operate it. Shortly after, it was also used to transport water from low-lying areas up to irrigation ditches. This design is so effective that is still being used in many modern-day applications. For instance, it has been used to drain water from the Alblasserwaard polders (lowlands reclaimed from the sea) into the Lek River in Kinderdijk, Netherlands, since 1972.

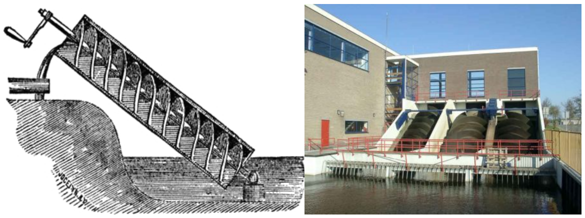
Fig. 3. Ancient (left) and modern (right) water-pumping application of Archimedes' screw

The Archimedes' screw is a positive-displacement pump**.** It is usually composed of a hollow cylinder shell and a cylindrical shaft sitting inside. Helical blades are attached along the shaft and are sealed tightly against the hollow cylinder, in order to create pockets between the shaft and the inner wall of the cylinder shell. To be functional as a pump, one end is placed in a low-lying fluid source and then tilted up into a discharge location. As its shaft rotates, it traps an amount of fluid in the first pocket from the source, and then pushes the fluid moving upwardly to the next pocket up to the discharge location, while new pockets of water keep entering the first one [4].

As the same principle of moving fluid through spinning a screw, also solid materials can be displaced by the same mechanism. In our case, the material we are trying to remove is attached to the ground and, the platform on which the screw is mounted is relatively free of locomotion. Hence, based on Newton's third theorem, the counter-force of the push, which is exerted on the ground material, gives the screw a source of axial movement, both forward and backward. To use this principle as a locomotion solution, two parallel positioned screws, which are identical except for the screw helical direction, are employed to compensate the transversal force the contact material gives when they rotate in opposite direction on the solid ground. Furthermore, providing different rotational speeds to the two screws, allows one of them to receive larger thrust force than the other making the vehicle turn to the desired direction.

II. BACKGROUND

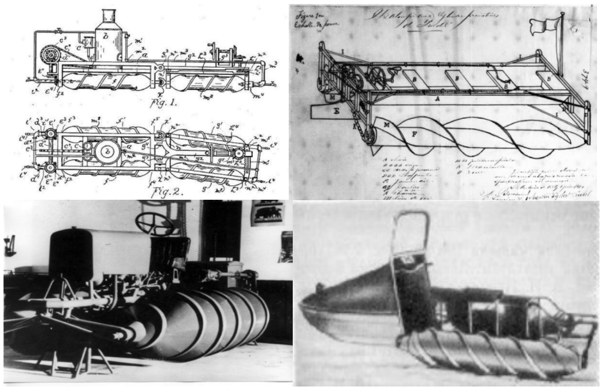

Fig. 4. Early screw-driven vehicles. "Snow locomotive", patented by Ira Peavey, US, in 1907[5] (top left). Propelling Barges, patented by Trudel, S. Augustin, St.Antoine De Tilly, Canada, in 1874[6] (top right). German screw propulsion vehicle, designed in 1944, during WWII, by Johannes Raedel (bottom left). one of Russian developed vehicles of this kind in 1960'[7] (bottom right).

A. Early screw-driven vehicles

From patents record, the earliest application of paired Archimedes' screws as ground locomotive actuator dates back to 1907 (see Fig. 4 top left): the idea is originated from the screw propeller for ships (see Figure 4 top right). A few types of vehicles based on this idea have been designed, prototyped and produced ever since. Most of them are dedicated to special requirements of transportation on extreme off-road conditions, such as thick loose snow, muddy swamp, and even grassland (see Fig. 4 bottom). By enlarging the cylindrical shaft, the screw gains more contact area allowing the vehicle to have a smaller pressure to the ground and making this locomotion system more efficient than tracks, wheels and legs, on thick loose terrain such as snow and swamp. Experiments of early types also showed that such kind of vehicles have extraordinary maneuverability and a high adaptability to different kinds of terrain making them able to overcome obstacles while holding their balance, and even move on bare ground and grassland. However, coming along with the advantages, there are also reports of distortions caused by uneven ground.

B. The Latest application: Snowbird 6

The most recent case of this kind of application is Snowbird 6 vehicle used by the British Ice Challenger exploration team to traverse the ice floes in the Bering Strait [8]. A pair of rotating screws used in the same way of the above-cited early examples allows Snowbird 6 to move over ice and to propel itself through water as well. The difference with respect to the early types is that while the early types operate on terrain by using the cylindrical shaft as a support and the screws for propulsion, Snowbird 6 also relies on the hollow shaft as a pontoon to float on water and uses the screw as an inferior alternative to propeller. However, the screw system was not considered suitable for long distance driving, and the screws can be raised so that the vehicle can run on conventional caterpillar tracks.

Fig. 5. Snowbird 6 vehicles

C. *RC toy: Mattel's Terrain Twister*

Recently, a toy company Mattel® brought up an interesting RC model, called Tyco Terrain Twister, which was build to work at the same way as Snowbird 6 does. With Archimedes' screw propulsion, the toy is reported driving on various terrain types, such as mud, grass, sand, gravel and even on pavement, as well as in the water.

Fig. 6. Mattel's Terrain Twister

III. METHODOLOGY

The proposed solution in this paper is to combine Archimedes' screw as an amphibian solution during terrain overpassing and landing process, with a conventional propeller for propulsion in the water. The following design guidelines have been followed,

1) Since the aquatic locomotion is primitive to the robot operations, a conventional propeller is chosen to retain efficiency;
2) Screw is fixed under the body of robot, instead of being retrievable, to reduce mechanical complexity and the risk of leakage;
3) Screws must work effectively on various riverside terrain types, while exhibiting a low drag profile to save energy;

In the original application of Archimedes' screw as a pump, several parameters determine the effectiveness of this tool, such as the given torque, the outer radius and the length of the screw. On the other hand, the inner space (the distance from the surface of the shaft to the inner wall of the hollow cylinder), the number of blades, the pitch of the blades and the tilt angle (the slope) [9], determine the volume of water every scoop can contain, the consumed power, and the amount of water pumped in one unit height per time unit period: in general, the efficiency.

Pushing solid material instead of removing fluid, and setting the screw free instead of fixing it, are the key to transfer the pump to a terrain locomotion driver. However, the principle remains the same, so that the same parameters can be used to determine the performance of the locomotion system on the ground.

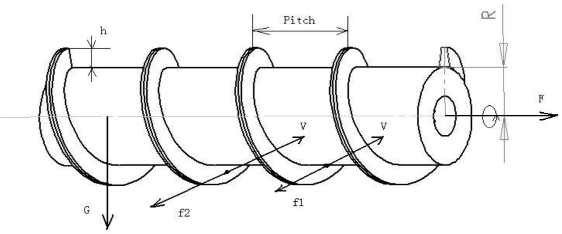

Fig. 7. Parameters of Archimedes' screw as terrain driver

As shown in Fig. 7, the following relations yield:

$$T = (f_1 + f_2) \times R \times \cos(\theta) + F \times \sin(\theta) \tag{1}$$

$$F = (f_1 + f_2) \times \tan(\theta) \tag{2}$$

$$f_1 = G \times u \tag{3}$$

$$f_2 = F \times u \tag{4}$$

$$A = (R + h)^2 \times \pi \tag{5}$$

TABLE I DENOTATIONS

Symbol	Quantity
T	Torque given by the shaft
G	Gravity force
R	Shaft radius
θ	Pitch angle
F	Traction
f_1	Friction on shaft surface
f_2	Friction on screw surface
h	Screw height
u	Friction coefficient
A	Frontal area

Considering one section of a screw as shown in Fig. 7.

In addition, taking into account the drag of the screw underwater, there are empirical formulas that can help to optimize the parameters.

$$D_p = C_d \rho V^2 \frac{A}{2} \tag{6}$$

$$D_v = \rho V^2 S \frac{C_f}{2} \tag{7}$$

TABLE II DENOTATIONS

Symbol	Quantity
D_p	Pressure drag
D_v	Viscous drag
C_d	Coefficient of shape
C_f	Coefficient of friction
S	Wetted surface area
V	Speed of vehicle
ρ	Density of water

From the above relations, trade-offs between drag and amphibian performance have to be achieved to decide the critical parameters, such as the pitch and the height of the screw and the length and the radius of shaft.

IV. PROTOTYPE AND EXPERIMENTAL SET-UP

Based on the guidelines mentioned above and target field situations, a prototype has been fabricated to validate the proposed robotic amphibian solution and as a platform for aquatic monitoring.

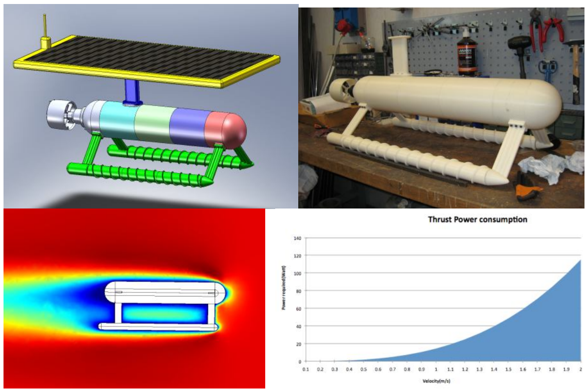

Fig. 8. Modular designed 3d model and prototype (top); Drag analysis in COMSOL® and power vs. speed curve (bottom).

This prototype's basic features (without solar panel) are described in the following table,

TABLE III SPECIFICATIONS

Parameters	Quantity
Dimensions	111 cm x 42 cm x 46.4 cm
Weight of the robot	15 Kg
Reserved payload	10 Kg
Cylindrical main body	Radius 0.08 m, Length 0.75 m
Screw shaft	Radius 0.025 m, Length 0.65 m
Screw height	0.5 cm
Screw pitch	5 cm
Designated cruise Speed	0.5 m/s
Wet Surface Area	0.7 m^2
Drag at cruising Speed	1.8 N
Screw actuator power	8.7 W
Screw Maximum rotary speed	55 rpm
Nominal maximum torque	1 Nm

As showed in Fig. 8, the main body (made by ABS) is built torpedo-shaped and presents a modular design to facilitate the device housing and the process of reconfiguration and quick add-ons, whereas retaining a low drag profile. From bow to stern, there are five modules dedicated respectively to the housing of vehicle sensors, payload sensors, batteries, control electronics and propulsion, as well as their supporting electronics. The size of main body is chosen to be portable, with a sufficient volume to provide buoyancy for the expected payload, without exhibiting a large drag. A solar panel of about 7 Kg is installed on the top of the main body through a support with electrical connections hiding in. The waterline will stay between the lower surface of solar panel and the top of main body. Such a design minimizes the waterline area, hence providing better stability to the platform in the case of ripples, which covers the surface of most river and offshore context. A pair of rotary-screw drivers is installed, under the main body. The shaft radius is chosen as a trade-off between the following two facts. In order to minimize drag in water, the shaft radius should be kept as small as possible. This can also help handling larger friction on the shaft surface when rotating on ground at the same torque. On the other hand, the "screw drivers'" adaptability on different terrain types is highly relative to the shaft radius, which characterizes the contact area of the shaft surface and ground. In general, the adaptability increases along with the shaft radius. Other trade-offs are also used to decide the height and pitch of screw thread. Larger height provides better interaction of the screw over the ground material, hence better performance in the locomotion. This can increase dramatically the frontal area of the screw deteriorating the hydrodynamic profile and giving large drag. Longer pitch offers less drag in water and more material to interact on ground, but also causes lower efficiency in ground locomotion.

Based on these considerations the parametes of the screws were decided and are reported in Table III. The screw shaft is slenderer, comparing to those of the piloted examples mentioned above, because in this case terrain adaptability is sacrificed to achieve a lower drag for a better efficiency in water.

Fig. 9. Test configuration (top left) and test sites: muddy sand (top right), gravel (bottom left) and grassland (bottom right).

Regarding the aquatic locomotion, a shrouded thruster mounted at the stern provides major actuation for retaining maximum efficiency [1].

Several experimental sites have been chosen as representatives for real field contexts, while to be relatively simple to ease the identification and evaluation of the amphibian performance. As shown in Fig. 9, three types of terrain were chosen to perform the trail: muddy sand, gravel and grassland. To evaluate the performances, we used a National Instrument's DAQ device to log the voltage charged on both driving motors and currents absorbed during the trail, in order to have an idea about the power consumption over different terrain types and ground situations. Some preliminary results are presented and analyzed in the following section.

V. EXPERIMENTAL RESULTS

The experiment was designed for two purposes, the first one was to evaluate the performances directly through observation, and the second one was to study the power efficiency of this locomotion solution. A video clip recorded during one of the tests is released for public review [10]. In addition, there is another short video clip attached to this paper as a demo.

During several trials on various types of terrain mentioned above, we found out the following features,

1) Wide range off-road adaptability except hard, smooth ground.
2) Locomotion on ground, such as gravel and sand, with no or minor slippage.
3) Easy turning/Small turning radius; in ideal case turning at one point (zero turning radius).
4) Climbing over slope (with limited angle) and obstacles, while maintaining its balance and heading. In the test, we found out that it can climb up to about 30 degrees on gravel.

Shortages are as well spotted,

1) On uneven ground, especially when the size of uneven area is comparable to the length of the screw shaft or smaller, distortion happens in extent depending on the geometry of the unevenness.
2) "Drum action" appears when the path presents undulating surfaces. "Drum action" is to describe the swinging movement of the head of vehicle between left and right side along the forwarding direction.
3) When climbing up a slope, serious slippage may happen, which depends on the slope angle, weight and how loose the ground is.

Power consumption is one of the critical features to evaluate the efficiency of this new locomotion solution. During the test, current and voltage of both motors are sampled and the power consumptions for each terrain types are illustrated in the following charts. The samples are filtered using a Butterworth filter of order 3 and cut-off frequency 0.1.

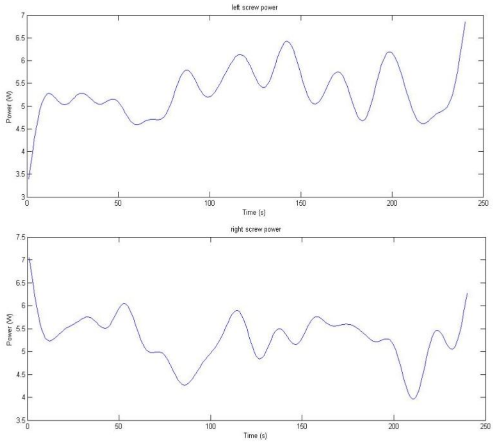

Fig. 10. Power consumption when testing on sand, left screw (top), right screw (bottom).

On sand:

As shown in Fig. 10, the average power consumption is about 5.5 Watts, despite of some fluctuations, which are the result of the changing resistance on the screw during locomotion. Based on the observation, there is a drop of consumed power when the screws meet softer sand, since less torque is required to cope with the resistance on looser material. However, slippage may appear also in this case. To the extreme case, slippage may be so serious when the supporting material is so loose that cannot produce any grip on the screw. In this case, that side of screw will spin at the same position without pushing the robot forward, and the other screw will make the robot turning, or stopping moving at all if it loses grip as well. In this case, we can see a smoother power consumption curve lower than average value. The peaks in the curve appear when the screws hit firmer sand, which gives larger resistance to the screw and less probability to have slippage on it.

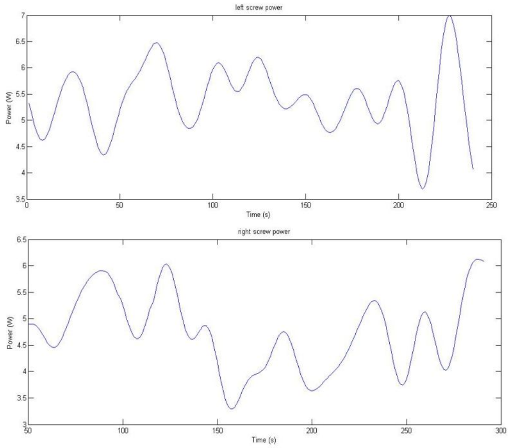

Fig. 11. Power consumption when testing on gravel, left screw (top), right screw (bottom).

On gravel:

As shown in Fig. 11, the average power consumption when moving on gravel is about 5 Watts, which is lower than that on the sand because the friction coefficient (formula(3), (4)) is lower in general. However, the rocks with various shape, offer the screws a very uneven surface to interact with. Hence, comparing Fig.11 to Fig.10, we can notice a more dynamic curve, due to the more variable power consumption as the robot moves on a more uneven terrain.

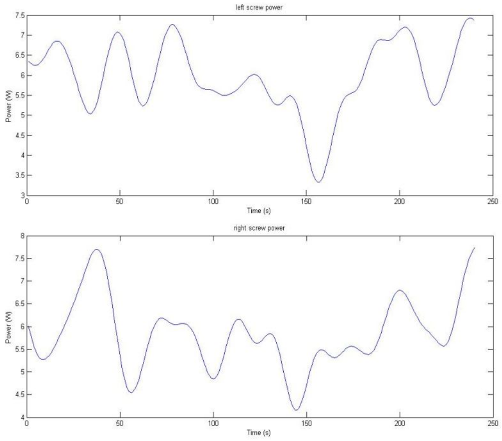

Fig. 12. Power consumption when testing on grassland, left screw (top), right screw (bottom).

On grassland:

As shown in Fig. 12, the average power consumption on grassland is about 6 Watts, the highest among all the three types. Besides, the intensity and period of single fluctuation is also larger with respect to the other ground types. All these are result of a more complicated and worse surface situation in this case. The grassland is composed by, on the top, different kinds of herb species that can have different effects on the screws; on the bottom, mixture of mud, sand, rock and others. Such a complex ground material explains the most unstable power consumption and the highest average value. The slippage is also speculated to be the highest, due to the drastic changes shown on the power curve and the obvious uneven surface and very loose supporting material such as grass.

Furthermore, the actual forwarding speed is recorded as a reference to note slippage under certain rotational speed. The screws rotate at about 55rpm; the robot moves at about 2.75m/min with a pitch of 0.05m. The average speeds for gravel, sand and grassland are 2.5m/min, 2.2m/min and 2m/min separately, which indicate the robot presents the lowest slippage on gravel, while the largest on grassland.

VI. DISCUSSION

The analysis on the shortages shown during the tests suggests us the drawbacks of this first prototype and gives important clues to further improvements in the future development.

Fig. 13. Suspended positions on concave ground.

We found out the screw shaft is too long to be well adaptive to uneven ground, which results in the so-called “drum action”, that occurs also on piloted screw-driven vehicle. The shaft supports on both tips of screw suspend the robot when it encounters concave ground (see Fig.13). The screw height is too small to interact with enough soil material which fills in the space composed by shaft surface and screws, and serious abrasion of screw fringe during trials make this situation worse. One of the reasons is the softness of the plastic material used in fabrication. We also noticed the need of more torque, when dealing with occasional large friction, such as climbing steep slopes.

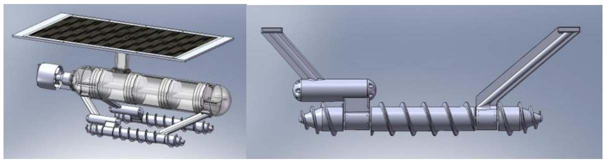

Fig. 14. Model with improved screws.

Based on this analysis, an improved screw design is presented to tackle the drawbacks (see Fig.14). In the new design, the shaft is about 20 cm shorter to improve adaptability on uneven ground. The shaft bearing supports are relocated from the both tips of the previous single-pieced shaft to between three sections of a new separated shaft, to deal with concave ground suspension problem. As a new feature, cone-shaped screw tips are introduced to help coping with the same problem as well. A more powerful motor is chosen to actuate, and is mounted in a position between main body and the screw shafts, with belt transmissions, to guarantee enough torque. The screw height is augmented from 0.5 cm to 1 cm to enhance performance particularly on soft ground, while metal-powder reinforced silicone material can be a harder alternative to the previous plastic material to ease abrasion.

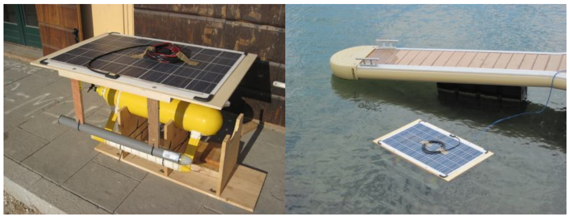

Fig. 15. Water trial

Furthermore, the water trail is undergoing as shown in Fig. 15, and the remote controlled maneuvering test will follow. In the final stage, the landing process will be performed to demonstrate the amphibian ability by connecting locomotion on both water and land.

VII. CONCLUSION

In this paper, an unconventional amphibian locomotion solution for aquatic robot is illustrated and the preliminary test results on a prototype are presented. The results are encouraging and demonstrate practicality and some exclusive features. In the next stage of investigation and development, we will work on the prototype improvement, aquatic maneuvering and landing trails.

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