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CESAR: A Lunar Crater Exploration and Sample Return Robot

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Abstract— **Suspicion of water ice deposits in the lunar south-polar region have sparked new interest into the earth's smaller companion, and robotic crater sample return missions are being considered by a number of space agencies. The difficult terrain with an inclination of over $30°$, eternal darkness and temperatures of less than $-173°C$ make this a difficult task. In this paper we present a novel, bio-inspired light-weight system design, which demonstrates a possible approach for such a mission. The robot managed to come first in the Lunar Robotic Challenge (LRC), organised by the European Space Agency (ESA) in October 2008. Using a remote operated robot, we demonstrated to climb into and out of a lunar-like crater with inclination of more than $35°$ on loose substrate, and performed the collection and delivery of a $100g$ soil sample without the aid of external illumination.**

I. INTRODUCTION

A. Background

It is very much in the human nature to explore the unknown, and this is especially true for unknown territory. With nearly every centimetre of the land surface of our home planet mapped, true mysteries lie beyond the boundaries of earth. An astonishing effort was made in the 60's, when the *Apollo Program* managed to engineer human space flight and was able to put a human on the moon and return him safely to earth. Back then, this amazing endeavour sparked the imagination of people, and it seemed only a matter of decades until the first colonisation of an extraterrestrial body would take place. Now nearly half a century later, this goal still seems to be some time in the future. The tremendous costs of human space flight, and the missing prospects of fast economic return on investment have lead to a more cautious approach. Robotic systems have moved into the centre of attention for the exploration of space. The first images from the surface of another planet, taken by the *Sojourner* Rover have changed the way humankind perceives the solar system and gave a glimpse into what might come. The *Mars Exploration Rovers* (MER) [6], which are still operational after 5 years on mars, showed that robotic systems have the ability and the robustness to perform these kinds of missions. With further missions planned for the exploration of Mars by NASA, ESA and other space agencies, the moon which has been studied well during the Apollo Missions is only now starting to receive new interest. Especially the lunar south pole, which in crater regions has the special situation of eternal darkness, is the target of various government and even private [7] interests. There is strong evidence, collected during the *SMART* [8] mission, that there is water ice in the dark regions of the *Aitken Basin*, near the lunar south-pole, which also contains the *Shackleton* crater. This is interesting for several reasons. Firstly, the moon could potentially act as a base for the further exploration of the solar system, since the escape velocity is far less than that of the earth, and there is no atmosphere which produces friction. Because of the extremely low temperatures that never rise above $-173°C$ in some places the area could be a potential candidate for a large infrared telescope as well. In order to verify the hypothesis of water ice in the dark regions, a sample needs to be collected and returned to a lab for analysis. This task is quite suited for a robotic mission, since most of the required technology is already available.

B. Problem Description

The findings of the *SMART* mission are a cause for the present developments of technologies to return and to verify the existence of water on the moon. The requirements for such a mission are more complex than for earlier missions to the equatorial region. The shape of the lunar surface in the south polar region is highly rough and unstructured. Also the lighting conditions in this area are complicated. The angle of incidence of the sunlight is very flat. Consequently the interior of the craters permanently stays dark and cold. There are few points of eternal light around the crater which are planar enough to allow for safe landings. Thus, the landing has to be controlled very precisely. Due to various reasons it is not feasible to land inside the crater. The lander must deliver a system with the capability to reach the interior of the crater and return a sample to the lander. The difficult environmental conditions, like temperature and lighting, as well as the requirement to negotiate rough and unknown terrain, make this a highly demanding task for the robotic system.

C. ESA Lunar Robotic Challenge

In the first quarter of 2008 *ESA* announced the first *Lunar Robotic Challenge*, where European universities were able to propose a concept for a robot, capable of retrieving samples from a lunar-like crater. Eight Teams from six different

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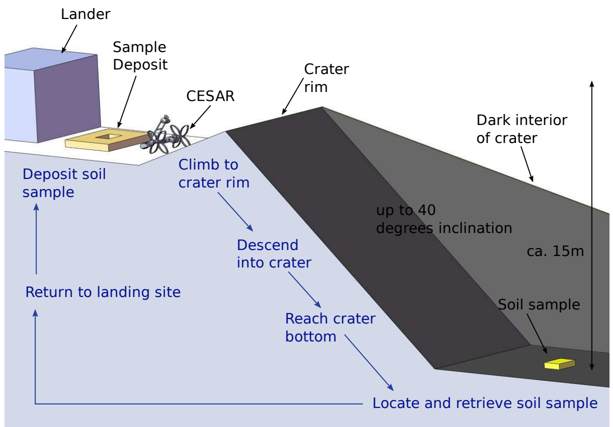
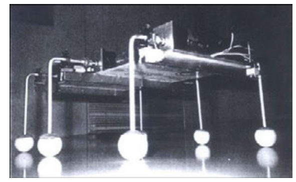


Fig. 1. Scenario of the ESA Lunar Robotic Challenge, where a robotic system is required to go into the dark interior of a lunar-like crater, retrieve a soil sample and return the sample to the lander.



(a) PROLERO robot (ESA)

(b) Whegs (Case Western Reserve University)

(c) Axel Rover (JPL)

(d) Asguard II (DFKI)

Fig. 2. Some of the design aspects for the CESAR robot are inspired by previous works of mobile robotic systems for space exploration.

countries were chosen [2] and given funding to proceed with the implementation of their designs.

The system constraints according to the statement of work and the mission specification, required to build a robot that can depart from a lander located at the simulated landing site, climb up the crater rim and descend the crater wall in order to search for a soil sample in the dark interior of the crater. After locating the sample the robot has to be able to collect at least $100g$ of the selected soil specimens, return them to the lander and deposit the sample in a collection container. Furthermore, the system to be built has to weigh less than $100kg$, consume not more than $2000W$ of power and should not occupy more than $0.5m^3$ of volume while stowed. Since the application for the system is in a lunar environment, it has to be designed and manufactured to withstand harsh outdoor environment conditions, work in extremely low as well as extremely bright illumination, and shall not take advantage of specific environmental conditions or capabilities which are available on earth, but not on the moon (e.g. no GPS or Compass).

II. STATE OF THE ART

The CESAR design is inspired by several highly mobile robots like ESA's PROLERO, the Whegs robot, the Axel Rover, and the Asguard robot.

The *PROLERO* [3] or PROtotype of LEgged ROver was developed in 1996 by the *ESA A&R group* (see Fig.2(a)). It consists of a small body and six actuators, each driving one L-shaped pole. This first leg-wheel hybrid already showed the main advantages of the concept. It combines the simplicity in mechanics and control, as well as low power consumption of the wheel, with the agility and the capability of negotiating difficult obstacles from the leg.

Whegs [5] from *Case Western Reserve University* uses a single motor to actuate its six leg-wheels and a tripod gate for locomotion. It also features an articulated body that helps to overcome obstacles. The use of more than one leg on each leg-wheel simplified control and makes the rover more robust in the sense of mobility.

The *Axel rover* [4] was developed by *NASA's Jet Propulsion Laboratory (JPL)* and consists of two motors driving the wheels and an additional motor to control the position of the trailing link. The trailing link provides a reaction lever arm against the wheel thrust.

The outdoor security robot *Asguard* [1] was developed at the DFKI in Bremen, and has four actuated wheels which are designed to enhance stair climbing and obstacle negotiation. A passive degree of freedom on the body helps to keep all four wheels on the ground at any time.

III. SYSTEM DESIGN

The CESAR system (see Fig. 3) has been specifically designed for the task of sample collection in a lunar crater-like environment. The main challenge is to trade-off the locomotion capabilities of negotiating a slope of over 30° in the presence of rocks and loose substrate, while still adhering to the boundary conditions set by the ESA LRC. Further, communications requirements have to be taken into account to control the robot and provide a situation awareness for the robot operator. Due to these requirements and the limited time-frame it was decided to opt for a simplistic design. By lowering the position of the sample collection unit a simple hatch design with only one degree of freedom could be used. This posed requirements on the body structure and locomotion system. These were solved by adopting a wheel/leg combination, which has shown promising results in previous projects, and reducing the number of main actuators to two, like in the case of the Axel rover. A passive reaction lever, which was planned initially caused too much friction, and the design was shifted to the currently employed active paddle wheel. Lightweight components where used throughout the design and simplicity and robustness was favoured over solutions with higher complexity.

A. Locomotion Subsystem

Legged locomotion is an attractive alternative to wheels or tracks for mobile robots. Legged animals have the ability

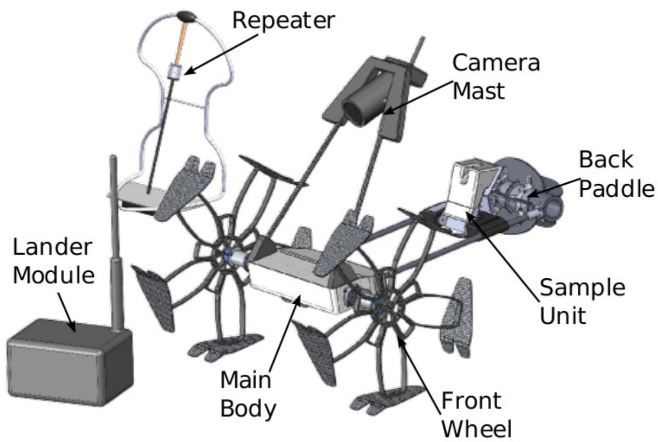


Fig. 3. CESAR consists of three subsystems. The robot, the repeater (back left) and the lander module (front left). Both repeater and lander module primarily act as communication relays.

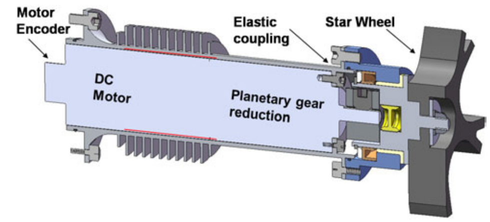


Fig. 4. The motor module houses a DC brushed motor and gearbox and is passively cooled, which allows the motor to be used over specification for short bursts. Further, the elastic coupling increases the flexibility of the wheel/leg construction.

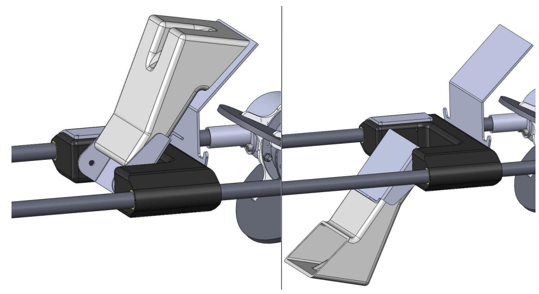


Fig. 5. A simple one degree of freedom shovel is used for picking up soil samples. The unit is constructed in such a way that the sample gets stored inside the shovel (left) for transport and can be released at a later stage (right).

to negotiate rough terrain and obstacles more easily than wheeled systems. However, current legged robots enjoy neither the simplicity of wheels nor the versatility of legged animals. A major difficulty in achieving legged locomotion is to coordinate and control the legs to produce efficient and robust movement of the body. This problem is exacerbated in unstructured environments. By utilizing statically stable locomotion, the complexity of operating the legs can be reduced because of much simpler system dynamics.

The key factor of CESARs locomotion concept is the special design of the drive subsystem, the wheels and the feet. A number of elasticities make the overall system adaptive to difficult terrain and reduce the requirement for complex control. They also act as a suspension system, which absorbs loads, and allows a more favourable scaling of the frame and drive components. Moreover, the wheel's shape provides high ground clearance and a very low centre of mass while traversing obstacles. The flexible, spread out and spiked feet provide a suitable grip for good locomotion on loose soil.

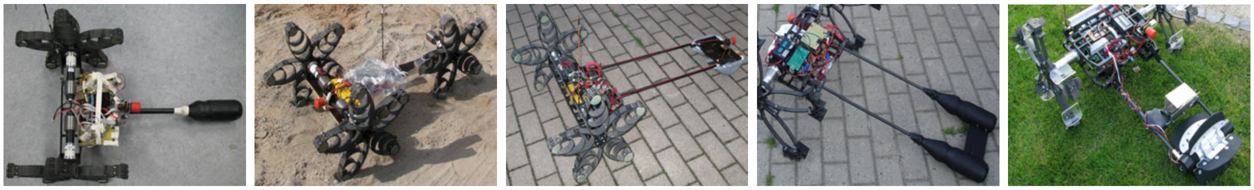
The wheel concept was improved during the development and adapted for sandy terrain. Each wheel consists of an assembly of five modular spokes which is manufactured by water jet cutting a 15*mm* polyoxymethylene (DELRIN) board. The feet are a sandwich construction of fibreglass and aluminium and have been inspired by Lizards mode of locomotion on loose sand (see Fig. 7(a)). The Lizard uses his feet as an active paddle when loose substrate starts behaving like a liquid. CESARs feet express similar hybrid properties since they provide a flexible structure which adapts to the ground shape and provides a large ground contact area which can also act as a paddle. A number of different foot morphologies (see Fig. 6(b)) have been tried in an iterative design approach, to optimise performance on loose soil.

Another important point of the mobility of CESAR is the active wheel paddle on its back part. It also consists of an assembly of five modular paddles, an actuator in the centre, composed of a DC-motor, and an elastic coupling. The shape of the wheel was inspired by a star fruit. The geometry provides a large contact surface for traction, but is also able to slide sideways with a very low resistance on the ground. A number of different iterations have been tried until settling for the final solution (Fig. 6(a)).

Both front and back actuators are powered by an 80*W* 24*V* DC-motor with a planetary gear reduction of $169:1$. To protect the motor and gears from internal and external destructive effects, a flexible coupling, a sand shield and a passive system for heat dissipation were added (See Fig. 4).

B. Sample Acquisition

Tests indicated that $100cm^3$ should be sufficient to hold the required 100*g* of soil sample. Fig. 5 shows the implemented sampling unit. The u-shaped carrier plate (black part, $270 \times 90 \times 50mm$) is attached between the open frame structure of the rover with two aluminium guides. The compact lightweight laminated sandwich structure houses the actuator/servo-motor, the drive section and the strut mount. The aluminium shovel compartment is connected with the drive section. The shovel is 140*mm* long, 100*mm* wide and can safely contain $120mm^3$ of soil sample. While the shovel is closed, the shovel-compartment is sealed by a mounted aluminium back-plate with an integrated rubber sealing. On the back of the shovel a small plate is used to transfer the tangential ground contact forces during the sampling process from the shovel-compartment to the carrier plate. The plate also prevents damage to the drive-section by restricting the backward movement of the shovel. Furthermore the shovel compartment can be used as hook for the transponder release. The transponder unit is attached on the housing of the active



(a) Various concepts of active and passive structures on the back of the robot have been evaluated.

(b) The progression of the foot design shows a tendency towards a flat structure with a large surface area.

Fig. 6. An iterative design strategy with regular testing intervals was driving the optimisation of the CESAR design towards improved mobility on an inclination with loose substrate.

(a) Lizard using feet as paddles for locomotion on loose sand. (Goldmann, Koeff and Full, 2005)

(b) CESAR on loose substrate at an inclination of around 30°.

Fig. 7. CESARs mode of locomotion on loose substrate was designed to have similar properties to that of a Lizard on sand.

paddle wheel and fixed between the shovel compartment and the backplate. Opening the shovel on the crater rim will release the transponder. Since the unit is designed to be off-balance without the clamp to the shovel, it will tip over the back and position itself in an upright state.

C. Avionics and Communications

The main body of the avionics system is a custom electronics board, which hosts an ARM based 32bit CORTEX-M3 micro-controller with 72 MHZ clock frequency, power regulation, level converters, interface modules and connectors to the other subsystems. The processing power of this micro-controller is sufficient for the given task since the robot is remote operated with only simple local control.

The communication subsystem is split into the command and control channel and the video channel (See Fig. 8). The communication of the command signals is realized using a 500mW data modem, transmitting on the free 868MHz ISM band. The modem is operated at a channel bandwidth of 25kHz with a transmission baud rate of $4.8kbps$. The video transmission is designed using two different analog transmission channels. Analog transmission was mainly chosen because of the graceful degradation of the transmitted video signal. The poor ground penetrating performance of the video link was the main driver for the introduction of the repeater module. The lander module hosts a pc, which converts incoming network traffic into control packets on the 868MHz channel, and also digitizes and streams the incoming video transmission over the network to the simulated Ground Station.

D. Control

The CESAR robot is remote operated and has no autonomous capabilities. Steering of the Robot is based on differential wheel speeds. The layout of the robot, with the two main front wheels and the actuated shovel-wheel at the back is chosen in such a way, that the centre of rotation is between the two front wheels. Any rotation around this point will translate the back shovel in a transversal direction. The design of the back wheel favours such a passive movement and provides little resistance. Further, the given forward speed is translated to both front wheels and the back shovel by a ratio, which is also operator controllable.

E. Navigation

Different navigational means have been implemented in the CESAR system, in order to assist the task of finding the

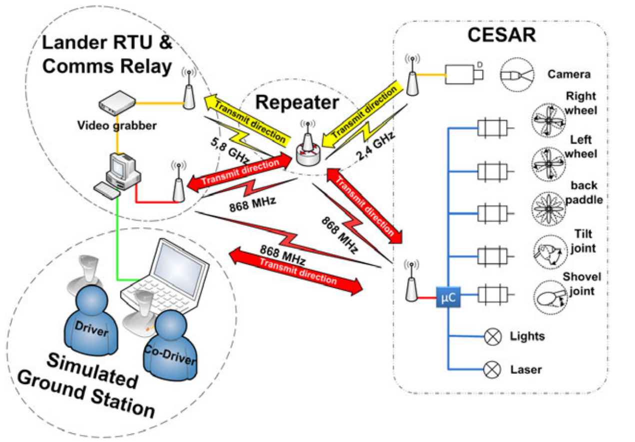


Fig. 8. Control signals are generated at the operator station which simulates the Ground Station of a real mission. Both the lander module and the repeater act as communication relays for the control and video channels.

Fig. 9. CESAR at the Teide Volcano on Tenerife, the location for the ESA Lunar Robotic Challenge.

soil sample and returning back to the lander without the help of external positioning information.

The camera features a Sony 1/3" DSP CCD and an infrared LED ring with 28 LEDs and a denoted lighting range of 30 meters, and an opening angle of 78°. The off-the-shelf design was modified so that the original camera and LED boards were integrated into a custom built encasing which also holds a digital servo. This degree of freedom makes it possible to use the main camera for both navigation, inspection of the robot and monitoring of the sample acquisition process.

The interior of the crater was expected to be almost void of any lighting. The on-board camera has built in night vision capability, as well as active IR illumination. Since the soil sample is colour marked, additional illumination in the visible spectrum is added on both the front and back. Two orthogonal red LED line lasers were used to project a cross onto the ground in front of the robot. The laser cross showed to be sufficient to estimate the distance, shape and bearing of obstacles by the operator.

The repeater module which is dropped at the crater rim features flashing high-power IR and red light LEDs. This provides a landmark for navigation and a cue for the return trip. In addition to the landmark, one of the operators kept track of the robot's estimated position and the crater's topography on a hand-drawn map.

IV. RESULTS

A. Challenge Event

In October 2008, the eight European teams took part in the ESA Lunar Robotic challenge. The CESAR robot was able to accomplish all the given tasks of climbing up the crater rim, go down into the dark interior of the crater, locate and pick up the soil sample, drive up the crater, return to the lander and deliver the sample in the sample deposit box. Exactly $100g$ of soil sample were delivered, and two interventions were required to accomplish this task. CESAR was the only robot among the competitors to fulfil all the tasks and was ranked first by the organizers. The challenge took place at night-time to ensure dark operating conditions within the crater. The transition between the lander and the crater was approx. $50m$, the depth of the crater ca. $15m$, with up to 40° of inclination on the descent and ascent. Soil properties consisted of loose granulate of volcanic origin with an average size of $5-8mm$. The crater wall also contained rocks of up to $1m$ diameter with an uneven distribution. The most challenging task of climbing up the crater was successfully repeated on the next day.

B. Performance Data

In order to asses the general performance of the system a number of different tests have been performed after the challenge event. Of prime interest where power consumption (planar/climbing), maximum speed, dynamic stability, climbing capabilities for different substrates and the performance of the communication subsystem. General System Parameters are given in Table I. With 13.3Kg the system was the lightest competitor for the LRC. In Table II, some experiments on the speed of the system have been performed on flat sandy terrain. The table also extrapolates potential range based on the capacity of the battery. In Table III some experiments on an inclination with different substrates where performed. The temperature at which these tests were performed has been around $-4°C$, so the soil was partly frozen. Tests for the video transmission showed that the 5.8GHz link at 25mW provides usable results up to 80m, the 2.4GHz link at 40mW up to 200m. We did not experience any degradation of quality of the control channel over the distances relevant to the application to the rover.

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusion

We have presented a design for a robot, which is able to perform the task of sample acquisition and return in a lunar-like crater environment. The benchmark for the operation was set by the ESA Lunar Robotic Challenge, in which

Dimensions	
Weight	13.3kg
Bounding box (w/l/h)	820mm/980mm/690mm
Wheel diameter	498mm
Ground clearence	205mm
Distance main axle to back wheel center	660mm
Drives	
Power Supply Motors	2x 14.8V=29.6V @ 4Ah
Power Supply Electronics	14.8V @ 4Ah
Drives	
Drives	3x Faulhaber 24V 169:1 DC 80W
Max. Wheel Torque	ca. 20Nm
Power Consumption	
Light	0.75W
Laser	0.3W
servos	2W (up to 15W peak)
Microcontroller Board	0.75W
868 MHZ communication	0.75W (receive only)
2,4 GHZ video	1.9W
Drive Electronics	0.3W
Total Standby Power	6.6W

TABLE I

SYSTEM SPECIFICATION

run time (in s)	consumption (in Wh)	speed (in m/s)	system range (in km)
85	1.33	0.59	4.5
88	1.33	0.57	4.5
83	1.21	0.6	4.8

TABLE II

SPEED AND POWER CONSUMPTION ON 50M PLANAR SAND TEST TRACK

our design was competing against seven other designs from Europe. Several new design concepts were introduced, which assisted the system in successfully fulfilling the required tasks. A novel bio-inspired foot design for a hybrid wheel/leg improved the climbing performance in steep terrain and loose soil, while keeping the complexity down. Another aspect is the application of a shovel-wheel, which has very little resistance in the transversal direction to aid turning, but provides significant support for forward locomotion. The design of the system allows further, the application of a simple and robust sample collection mechanism.

B. Lessons Learned

The tests carried out, and the experiences at the challenge event, showed certain limits of the system. Without an inclinometer it was very difficult to assume the attitude of the system, which proved to be crucial for example while dropping the repeater. While descending into the crater the system's dynamics might cause the robot to flip when going backwards which limits manoeuvrability. Usage of 2.4 GHz video might conflict with WLAN in the area. The simple hatch allows taking samples only from the surface of a local plane. Samples from holes, between rocks or deeper layers are excluded. Being able to relocate the repeater would optimise the performance of the robot within the crater.

Substrate	Inclination	Distance (in m)	Power (in Wh)	Peak Power (in W)
Chippings	$30° - 34°$	5,1	0.49	67
Gravel	$31° - 32°$	4,5	0.47	66
Gravel	$33° - 34°$	5,2	0.67	50
Gravel	$33° - 34°$	5,2	0.65	62
Gravel (Descent)	$33° - 34°$	5,2	0.04	21

TABLE III

POWER CONSUMPTION FOR CLIMBING ON DIFFERENT SUBSTRATES AND INCLINATIONS

C. Future Work

Because of the limited time frame that was given for the construction of the robot, several design aspects, that were initially foreseen could not be implemented in the final system. Up/down symmetry with the additional ability to shift the centre of gravity could be achieved by using an actuated camera mast, which is able to swing through the centre structure. Further, currently the CESAR system is remote operated, so additional work for autonomous behaviour is foreseen for future development. One interesting aspect here is the use of inertial sensors in order to coordinate and improve the climbing behaviour.

The system acts as a proof-of concept, and further modifications are necessary to advance towards the goal of a real lunar exploration mission. The casing has to be rugged and lightened where possible, the structural design improved to withstand launch conditions. Materials and electronics that degrade or malfunction in an environment with vacuum, large temperature changes and high radiation must be replaced by space qualified components. Further, a thermal control system has to be added. To improve reliability, crucial subsystems need to be made redundant or designed more robust. Finally, the sampling unit has to be sealed and temperature controlled, to preserve the soil sample.

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