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# NEXT GENERATION SERVICE MODELS OF MOBILE AUTONOMOUS ASSISTANTS

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In this paper, we present an evolution overview of the autonomous streaming-based services for mobile autonomous assistants in the human environment. In Section 1 we present the hypothesis that the technologies are in transition from fixed or portable and wearable devices to those in which the main function is based on independent and possibly self-initiated and remote-controlled movement of the devices. This transition is outlined and categorized in Section 2. Retrospectively, with the progress of the penetration and technologies of the fixed devices, they have evolved from those that function separately and in isolation to those that offer group services in networks of multiple devices known today as Internet of Things (IoT). Another point of our considerations is that consequently and analogously, mobile autonomous devices are also subject of evolution towards service models of multiple cooperating mobile devices. We propose a multidimensional and layered taxonomy for the basic case of isolated mobile autonomous systems for 1d-, 2d-, and 3d-movement models. Our classification covers both the functional and technological aspects of these systems as well as the possibility for grouping services. In Section 3 we consider the parameters of two exemplary platforms as use cases for the two movement modes. Although they represent different principles of movement (i.e. legged and wheeled movement) these examples clearly show a common pattern of service parameters. The movement pattern presented here includes space and time range, speed, range of sensory monitoring, as well as parameters characterizing obstacle surmountability. Finally, in the Conclusion we address the applicability of our parametrization for the purposes of standardization and interoperability the main conditions for the service implementation based on a scalable group of moving devices.

**Keywords:** Internet of Things (IoT), Autonomous and Intelligent Systems (AIS), mobile autonomous assistants, sensor networks, assistive technologies, wireless integrated network sensors

**CCS Concepts:**

• Computer systems organization~Embedded and cyber-physical systems~Robotics~Robotic autonomy

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## 1. The transition from fixed to mobile autonomous assistance

The monitoring of various context-specific parameters of the environment using appropriate sensors has passed through two stages and is about to enter a new third stage (or generation). In the first two stages, the devices are static unless their primary function involves passive relocation – typically when embedded in a vehicle or serving a wearer.

First stage is the generation of the Deeply Embedded Systems. These are the smart devices or all specialized devices that perform their limited functions autonomously or semi-autonomously. They do not use network connectivity, or if used, it is to provide a remote user or control interface. Example: an air conditioner that performs its functions according to a daily or weekly program, but with the possibility of distant control e.g. via WiFi protocol.

Second stage – Distributed Embedded Systems widely known as Internet of Things [4]. In it, smart devices, in addition to some local functionality, provide functionality for accumulating and processing sensor data from nodes that are connected to the Internet (or another network that may not be global, but private or limited in some appropriate range).

A major disadvantage of the autonomous assistants of the first and second stages is that the sources of observational sensor data are static or fixed. This has significant negative consequences, the most obvious of which are in two directions:

1. the need for expensive and, in most cases, incompatible and irreplaceable embedding of fixed devices with appropriate saturation in an already built infrastructure;

2. limited functionality – for example, limited possibilities for remote control due to the complex embedding of static systems with actuators for influencing the environment.

By the emerging new generation of autonomous assistants with surface or even airborne and submersible mobility, an important opportunity is created to monitor the environment and infrastructure without having to modify the already built infrastructure. Furthermore, there is no need to saturate the environment with numerous static devices. Instead, the autonomously moving devices can perform their services by moving from point to point and thus covering a wider area. A very obvious example of this transition is the possible replacement of the old-fashioned but widely spread C.C.T.V. (Closed Circuit TV cameras) with a single or several electronic "dogs". In this use case, the static cameras for an area surveillance are needed to be of enough number to cover the whole area with all the vulnerable spots. Another requirement in C.C.T.V. is that each camera has to be constantly monitored by another camera in the group. Replacement of the static cameras with the moving surveillance assistants may upgrade this functionality by dynamic context-driven repositioning of the registering cameras on and even off the ground.

Depending on the service context the mobile autonomous assistants may have to perform certain humanoid functions by robotic arm gestures in order to control rudimentary existing environment components such as electrical power or control switches or push-button devices. In other words, mobile autonomous assistants are platforms with good potential for adding appropriate actuator components such as a robotic hand for one- and two-finger gestures, which enables the control of various mechanical devices already existing in the environment, such as electrical and electronic switches, buttons, sliders, etc.

Our main objective is to study and analyze the approaches of mobile autonomous monitoring assistants in different application scenarios. The services supported by such groups of multiple moving sensors data monitors can be integrated with traditional and existing fixed monitoring infrastructure.

## 2. A taxonomy of mobile autonomous assistants

In our taxonomy, the main division of autonomous systems is whether they are fixed including portable or mobile by self-initiative. In mobile autonomous systems, it plays a major factor in the implementation of the assistant to be able to react to surrounding events including potential obstacles but also other context defined events. When the environment is un-urbanised, the moving assistant is expected to be able to navigate through any terrain in its context, while in an urbanized environment, which is more structured, it is expected to be able to handle sidewalks, stairs, doorways, etc. according to whether it is operated in open or closed space. Application in urban environments can be divided into two types – application in public spaces such as airports (indoor), offices, hospitals, museums, schools, etc. or used for private needs at homes. It is obvious that the moving assistants cannot provide logical and mechanical support for any type of terrain and obstacles. E.g. a home assistant can be easily implemented by upgrading a robotic vacuum cleaner if only its operation scenario is for single-floor premises or in buildings with available elevators. Climbing stairs option is more expensive at least in mechanical aspect. Same type of distinction between the types of moving devices can be made for outdoor scenarios.

On the other hand, despite of the vast variety of use cases and surface scenarios we have very limited movement models. Most obvious mechanical models of movement are based on some of the few options. Our taxonomy identifies four categories of several options each listed as follows. A visual representation of our taxonomy is shown in Figure 1.

A. Movement models:

1. “Legs” based walking
2. Wheels based: for plain surface
3. Stair climbing wheels triad: for stairs and stair walks of limited height
4. Track chains (typically of steel or plastic) or track belts: for any unstructured outdoor terrain with parameters reflecting limits of unevenness (fixed obstacles’ size and slope angle) and ground material instability (load capacity)

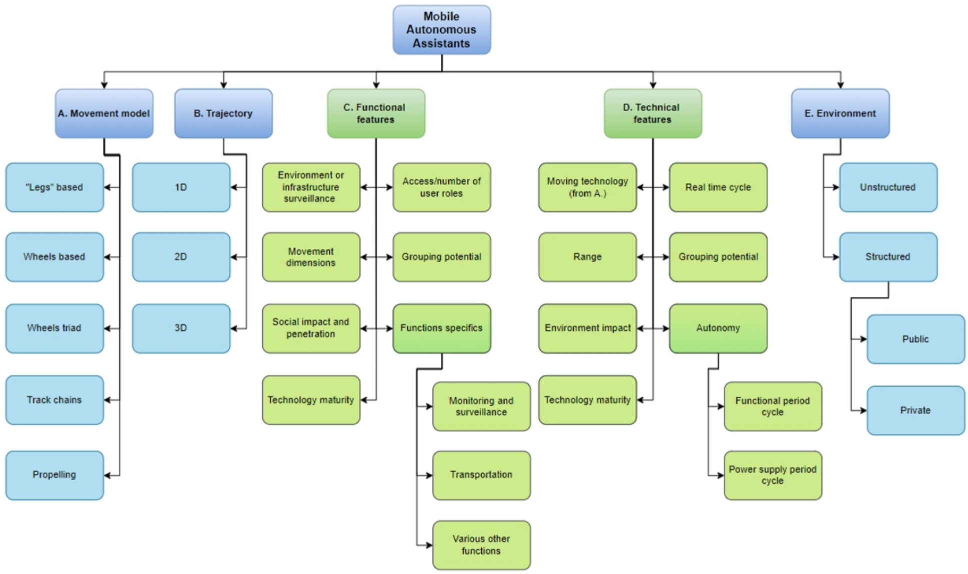


Figure 1. A mobile autonomous assistants

5. Propelling: for any type of 3d movement in fluids (water or air environments) with parameters reflecting limits of the currents and winds

B. Trajectory models:

1. 1d – borders or perimeters
2. 2d – surface
3. 3d – airborne or submerging environmental volumes

C. Functional features:

1. Environment or infrastructure surveillance
2. Access/number of user roles
3. Movement dimensions
4. Functions specifics
   4.1. Monitoring and surveillance
   4.2. Transportation
   4.3. Various other functions (e.g. vac, lawnmower)
5. Social impact and penetration (including useful and harmful)
6. Grouping potential – measured by the scalability (1 for single operating devices)
7. Technology maturity in sense of functionality support, QoS, user experience, user perception and social penetration

D. Technical features:

1. Moving technology – walking, wheeled, propelling, jet, etc. – from A.
2. Autonomy
   - 2.1. Functional period cycle – time complexity of tasks to perform without user interface
   - 2.2. Power supply period cycle
3. Range – dimensional range and time to leave (power)
4. Real time cycle – human capacity of perception is 10 Hz. The mobile assistants of course may perform at much higher rates.
5. Environment impact – mechanical impact/digital streaming
6. Grouping options
7. Technology maturity in sense of availability including Price

## 3. Implementations of mobile autonomous assistants

Here we present just two of the possible use cases of moving autonomous assistants in order to consider their major taxonomy feature A. – the movement model on solid surfaces. By these two cases, we justify the usage of a wheel-based drive (of the cases A1, A2, and A3) to that of the walking "legs"-based robots.

### 3.1. ANYmal

Robots using legs have an advantage in flexibility and mobility over those using chains and wheels. Despite these advantages, human-like robots are still very far from achieving natural movements. These robots are slow, and require a lot of energy and computing power. Much greater efficiency can be achieved by using multiple legs. The biggest example is Boston Dynamics' Big Dog and Spot. Similar examples in terms of mobility, dynamics and maneuverability can also be seen in the development of the IIT's four-legged hydraulic drive HyQ and the next HyQ2max, MIT's electric cheetah and the ETH's StarlETH serial elastic robot [1].

Developed by Swedish company ANYbotics, ANYmal is a four-legged robot designed for use in an industrial environment to perform inspection and maintenance tasks. It can operate in challenging environments such as stairs, uneven surfaces and confined spaces. The robot is equipped with a set of sensors for navigation and perception [5]. Unlike the examples in the previous paragraph, which were mostly considered in a laboratory environment, ANYmal is one of the first robots used in a real environment [1]. Figure 2 shows the main features of ANYmal.

ANYmal is fully protected against dust and water (IP67), which allows it to operate in humid and dusty environments, saving people from unnecessary exposure to dangerous situations, for example, areas with a high probability of an explosion.

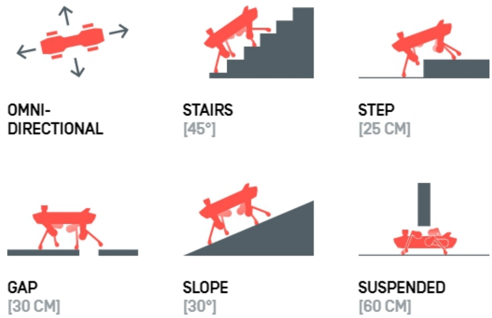


Figure 2. ANYmal characteristics [1]

For this case, ANYbotics also develops Ex-proof ANYmal for potentially explosive environments. Additional protection from water allows it to be easily washed.

It autonomously navigates in a complex environment by having prior information about the environment and finding the most direct way to complete the task. There are built-in depth sensors for precise obstacle avoidance for smoother navigation. Accuracy up to 1cm in both closed and open spaces [1].

Once taught where to go and what to do, he repeats regular inspections on his own. If manual intervention is required, ANYmal allows manual control and viewing from the robot's front and rear cameras. The camera is capable of up to 20× optical zoom to capture clear images and video at long distances in 2K resolution. The user interface allows showing the location of the robot, mission progress and more. At any time, the mission can be interrupted, live camera data can be transmitted, movements can be controlled and additional measurements can be taken for greater precision [1].

After completing a mission, it returns to the charging station. The battery capacity is 90 min. It takes 100 min to quickly charge up to 70%, and 3 hours to fully charge. To extend the range of operation, several charging stations can be installed in different locations. When it runs out of power, it will autonomously go to the nearest docking station to recharge, then the mission will continue [1].

Local data processing (Edge Computing) reduces response time and saves network load. It also eliminates the need for continuous network connectivity. ANYmal has a built-in option to connect to Wi-Fi if available or build his own local network. Through an additional module, it enables 4G/LTE telecommunication. The robot collects and stores the verification data and when the network is available, it will encrypt and feed the information to the ANYmal API and other systems [1]:

- Results can be integrated into Enterprise Asset Management (EAM) or Maintenance Management System (CMMS) management and maintenance systems. Inspection data and analysis reports are transmitted.
- Provide complete reports in PDF or XML format for quick decision making.
- Time and geographic inspection observations.

- Track patterns and historical issues.
- Access to necessary inspection data for further analysis.

The ANYmal data workflow diagram is shown in Figure 3.

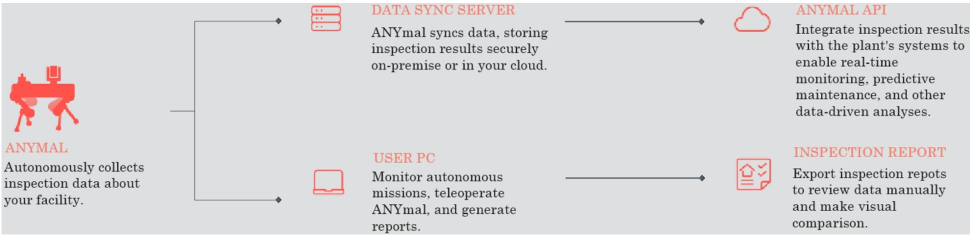


Figure 3. ANYmal workflow [1]

During an inspection, ANYmal provides visual, thermal and acoustic information about the condition of the equipment and the environment. The Pan-tilt module is used to scan the surrounding environment and precisely position the built-in survey sensors to the target point, which helps when it is far away or in a hard-to-reach place. Algorithms based on artificial intelligence analyze the data from the sensors, interpret the values, classify the result and detect anomalies. Unforeseen technical events can lead to dangerous situations – through sensitive sensors it can detect dangerous conditions in the environment and trigger a warning when necessary. Early signs of operational problems are caught by examining the general condition of the equipment. During inspections, ANYmal checks critical points for anomalies and immediately reports serious problems. Industrial environments require continuous monitoring for structural changes. ANYmal scans and documents the data from the 3D environment as a digital twin. All inspection data is linked to accurate temporal and 3D spatial information [1].

Some of Animal's components are: thermal camera provides precise measurements in the range from $-20$ to $500\,^{\circ}\mathrm{C}$ without the need for physical contact; LED spotlight aids visual inspections in low- or no-light environments; microphone for recording acoustic measurements in the sonic and ultrasonic frequency range [1].

A wide range of analog instruments and indicators can be digitized. Once trained on a given tool type, the value or state is reliably identified. In case the object is moved to a different angle, the robot can be programmed to take a new position to accurately capture the data [1].

ANYmal allows it to be programmed with additional modules to extend its capabilities through ROS (Robot Operating System) APIs and an open-source ecosystem. A simulation environment that provides a realistic simulation of the physical environment and access to all sensors and APIs facilitates development and testing. For example, a CAD model of the real environment can be loaded and realistic simulations of inspection missions, operating in hard-to-reach places and software integration can be performed before the robot is released into a real environment.

Another option is to walk the robot through the facilities and photograph the inspection points, thereby planning a mission on site. The robot will remember the tasks and independently repeat the inspections [1].

Pharos is a proprietary 3D SLAM software that provides [1]:

- Mapping accuracy of 1–3 cm by fusion of Lidar and depth camera data.
- Full coverage of large facilities with the ability to build maps with up to 4 km range at once.
- Continuous operation without the need for navigation markers, QR codes and GPS connectivity.

Trekker is an artificial intelligence-based deep learning algorithm for navigating complex environments. It allows the robot to access hard-to-reach places without the need to change the environment. Allows ANYmal to climb stairs, scale steps, and crawl over obstacles. Provides performance and reliability. Optimizes the path of routine monitoring tasks [1].

ANYmal constantly checks for people and objects in its surroundings to avoid collisions. It can also move moving obstacles, wait for a path to clear, or find an alternate path to its final destination. There is an option to work together with a fleet of ANYmals to more easily expand coverage and scan frequency [1].

In summary, ANYmalis used for inspection and maintenance in challenging environments. Its main features are quadrupedal design, range of sensors and cameras, and ability to traverse stairs and uneven terrain. As advantages can be marked as high mobility, the ability to operate in challenging environments and a range of sensing capabilities. Some of the ANYmalis limitations are that it has limited load capacity and it is specially designed for inspection and maintenance.

### 3.2. Jackal

Jackal is a four-wheeled robot developed by Clearpath Robotics for use in research and industrial environments. It can operate both indoors and outdoors. It has a modular design and it is equipped with sensors for precision and control [2].

The Jackal robot is equipped with an integrated onboard computer, GPS, and IMU that work together with ROS to provide a wide range of autonomy options. It can connect via Bluetooth and Wi-Fi and has options for adding various types of sensors with power supply options of 5 V, 12 V, and 24 V. The robot has a sturdy aluminium chassis with a high-torque $4 \times 4$ drive that makes it suitable for all-terrain operation. It is weatherproof with an IP62 rating and can operate within a temperature range of $-20\,^{\circ}$C to $45\,^{\circ}$C. Figure 4 shows Jackal human-machine interface [2].

Clearpath Robotics partnered with NVIDIA to develop the Jackal robot, which is built around the Jetson AGX Xavier computing device. The Jetson platform is ideal for robot development with its powerful and compact GPU, making it suitable

Figure 4. Jackal HMI [2]

for VSLAM, 3D imaging, and machine learning applications. The robot is configured for basic autonomous operations in both indoor and outdoor environments, from GPS waypoint navigation with laser scanning for collision avoidance to indoor mapping and route planning. It comes with a pre-installed Linux and ROS system [2].

The visual survey setup of the Jackal robot includes two front-facing FLIR Blackfly cameras for stereo vision and is fully compatible with ROS, RViz, and Gazebo. It also has a pre-installed CUDA toolkit, making it suitable for machine vision, human-machine interaction, and Visual SLAM applications [2]. Gazebo simulation packages enable testing of the robot's capabilities in a virtual environment, enabling early detection of problems and gaps. Gazebo provided an almost identical configuration to the actual Jackal, and various packages, services, nodes, and themes were available in the simulation [5].

The navigation package of the Jackal robot combines a SMART-7 RTK GPS with a wide-range station, achieving an accuracy of less than 2 cm and remote communication up to 1 km. This package is used for outdoor navigation, multi-robot systems, and remote environmental sensing [2].

Many additional extensions such as lidars, cameras, GPS systems and many more can be added. For example [2]:

- SICK TIM551 LiDAR
- 3DM-GX3-25 IMU
- TIM551 laser range finder
- SwiftNav Duro GPS
- IP65 FLIR Camera Enclosure
- SMART-6 RTK
- HDL-32e 3D laser scanner

In summary, Clearpath Jackal is used for research and industrial applications. Its main features are a four-wheeled design, the ability to operate in outdoor and indoor environments, a modular design, and a range of sensors and cameras. As advantages can be marked as high mobility, the ability to operate in challenging environments, a range of sensing capabilities and modular design. Some of Jackal his limitations are that it has limited load capacity and it is specially designed for research and industrial tasks.

### 3.3. Comparison

Table 1 compares some of the technical characteristics of ANYmal and its components with those of Jackal. Comparison is divided into different categories – ANYmal and Jackal, Payload, Perception Sensors, Communication, Environment, Battery and Battery Charger.

Table 1. Comparison of technical characteristics [1, 2]

| | ANYmal | Jackal |
|---|---|---|
| Dimensions<br>L × W × H | 930 × 530 mm (default walking) × 890 mm (default walking) / 470 mm (lying on the ground) | 508 × 430 × 250 mm |
| Weight | 50 kg / 55.7 kg with Inspection Payload | 17 kg |
| Speed | 1.3 m/s maximum, rough or slippery terrain may reduce the walking speed, 0.75 m/s recommended for safe and efficient operation | 2.0 m/s |
| Number of limbs/ wheels | 4 | 4 × 190 mm diameter |
| Degrees of freedom | 12 | |
| Payload | | |
| Weight | 5.7 kg | all terrain: 10 kg<br>maximum: 20 kg |
| Perception Sensors | | |
| LIDAR | 16 channels, 300 000 points/s, full sweep at 10 Hz<br>0.4–100 m range, 3 cm accuracy (typical)<br>360 × 15.0 to −15.0° FOV (Horizontal × Vertical)<br>905 nm, Class 1 Eye-safe per IEC 60825-1:2007 & 2014 | SICK TIM551 LiDAR |
| Depth camera | 0.3–3 m range, 87.3 × 58.1 × 95.3° depth FOV (Horizontal / Vertical / Diagonal), Class 1 Laser Product under the EN/IEC 60825-1, Edition 3 [2014] | IP65 FLIR Camera Enclosure |
| Tele-operation cameras | 1440 × 1080 px<br>110 × 76.5 × 117.7° FOV<br>(Horizontal / Vertical / Diagonal) | |
| Internal Sensing | | Battery Status, Wheel Odometry, Motor Currents, Onboard IMU, Onboard GPS |
| Communication | | |
| Communication | Wi-Fi: Built-in module 2.4/5 GHz, 802.11 ac wave2<br>Access point or client mode<br>4G LTE: Add-on module, LTE Cat.12 | Ethernet, USB 3.0,<br>RS232, IEEE 1394 avail. |
| Environment | | |
| Temperature | Specified: 0–40 °C<br>Typical: −10–50 °C | −19 to 45 °C |
| Water & dust ingress protection | Fully protected against water and dust (IP67) and able to operate in humid and dusty conditions. | Designed for IP62 |

| | | |
|---|---|---|
| Battery | | |
| Battery & capacity | Swappable Li-ion battery, UN 38.3 certified 932.4 Wh | Lithium, 270 Wh |
| Running time & range | 90–120 minutes on a full charge 4 km range on a full charge, up to 2 km for a typical inspection mission depending on payload weight and number of inspection points. | 2 hrs maximum<br>8 hrs typical |
| Recharge time | 3 h for a full charge, 100 min for a 70% quick charge | 4 hours |
| Weight | 5.5 kg | |
| Battery charger | | |
| Power supply | 110–240 V/50–60 Hz | 110–220 VAC |

As can be seen from the overview above and Table 1, one of the main differences is that the battery capacity of the first use case (ANYmal) is about 3.5 times that of the second use case (Jackal) and yet the time the ANYmal's operation time is 90–120 minutes, while the Jackal's is 8 hours in typical use. There is also a difference in speed between the two examples – Jackal's speed is 2.0 m/s, while ANYmal's is 1.2 m/s, but the recommended 0.75 m/s for safe and efficient operation is most likely influenced by a more complex motion model of ANYmal and its 12 degrees of freedom. Another factor in the result above is the big difference in weight, where the ANYmal weighs 50 kg without Inspection Payload, and the Jackal weighs 17 kg. The time to fully charge the first use case and the second is approximately the same – 3 hours and 4 hours, respectively.

Due to their roughly the same application areas (indoor and outdoor inspection), the two examples have fairly similar location and environmental analysis components – GPS, remote controller (via Wi-Fi or Bluetooth), depth sensors and cameras. Both use cases allow to be programmed with additional modules to extend their capabilities through ROS APIs and an open-source ecosystem and both have simulation environments for easier and better development.

## 4. Conclusion

This paper presents a taxonomy of the autonomous streaming-based services based on self-initiative moving devices. We are focusing on the transition from fixed or portable and wearable devices to those with independent and self-initiated movement. The taxonomy provides a multidimensional and layered classification (movement, environment and functionality) for isolated mobile autonomous systems with 1d-, 2d-, and 3d-movement models, covering both functional and technological aspects. The paper also considers two exemplary ground moving platforms as use cases for the movement models based on walking and wheels – ANYmal and Jackal. Our concept which is reflected in the taxonomy is that the usage of a wheel-based drive (of the cases A1, A2, and A3) has very important advantages to that of the walking "legs"-based robots. Overall, this paper contributes to the understanding of the evolution of autonomous streaming-based services and provides a framework for further research and development. In a more general point of view currently the artificial moving assistants mimic in their evolution that of the living creatures but only with some important differences. Wheel drive is one of the most important among them. Of course, in the end, this reflects the difference between a proteins-based civilization and the artificial one based on silicon, metals and mathematics.

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