Applying industry 4.0 concepts for monitoring spacecraft long term storage

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ABSTRACT

Satellite long term storage is expected to become a relevant issue in the near future, when for instance satellite batches can be produced and have to be kept inside specific containers before their launch. Pressurized and non-pressurized Transport & Storage Satellite containers equipped with vibration damping systems, thermal control and filtering systems protect the satellites during road and air transportation and long-term storage. In this paper, we explore the adoption of Industry 4.0 concepts and techniques for satellite monitoring and maintenance automation during their long-term storage.

INTRODUCTION

Satellite constellations play nowadays a predominant role in the design of many spaceborne applications and enable whole new class of space missions [1]. Even though some space science mission requirements can be fulfilled by monolithic spacecraft, other types of spaceborne applications, such as the satellite telecommunication systems or navigation systems, are implemented by batches of satellites. In this regard, we can mention the OneWeb satellite internet constellation. As reported in [2], the homonym company, authorised by the Federal Communications Commission to serve U.S. customers using a constellation of 720 satellites, asked in March 2018 the permission of adding further 1260 satellites. As a further example, in November 2018, SpaceX got the green light from US authorities to put a constellation of nearly 12,000 satellites into orbit in order to boost cheap, wireless internet access by the 2020s [3].

One of the main issues in the production of huge satellite constellations is their long-term storage, which can occur when satellite batches have to be kept inside specific containers before their launch [4]. Pressurized and non-pressurized Transport & Storage Satellite containers equipped with vibration damping systems, thermal control and filtering systems protect the satellites during road and air transportation and long-term storage [5]. In this paper, by analyzing different scenarios, we explore the adoption of Industry 4.0 concepts for satellite monitoring and maintenance automation during their Long Term Storage (LTS).

The paper has been organized as follows. Sect. 2 provides an overview on satellite long term storage needs and scenarios. Sect. 3 describes our vision on satellites LTS and Industry 4.0 approaches, Sect. 4 explores more specific guidelines for LTS implementation based on Intelligentia's experience, Sect. 5 concludes the paper and provides some future developments.

AN OVERVIEW OF SATELLITE LTS

During their long-term storage, satellites without their appendages are kept in storage containers, which consist of a base-frame, a thermally insulated tub, and a removable lid with external thermal insulation. The joint between the removable lid and container base is sealed by an inflatable seal [5]. From the perceptive of this paper, it is interesting to highlight the environmental requirements for long term storage, which are maintained by efficient passive thermal insulation, thermal control units with heating/cooling capability and air drying/filtering systems (for pressurized containers self-regulating nitrogen overpressure systems). A damping system attenuates shock and vibration, while a monitoring system is used for recording of shock, pressure, temperature and humidity.

During such long periods, satellites require periodical routine checks to address the issues that come from storage, such as lubricants settling in rotation wheel assembles. Testing has to be performed from time to time to ensure satellites remain in good health.

According to a study from the U.S. Government Accountability Office (GAO), the cost of storing satellites for various U.S. Department of Defence (DOD) programs is expected to raise, and that the reasons for such an increase are not fully understood [4]. Satellite long term storage can be due to e.g. changes in procurements methods, with satellites produced quicker than they are needed for launch. Satellites can be stored on the ground as part of the planned production of multiple satellite batches (e.g., in case of satellite constellation). Moreover, it could be possible to store back-up satellites in orbit to quickly react to any satellite failures that would otherwise result in an operability gap [6]. The risks for in-orbit spares are different, stemming mainly from the harsh environment of space.

The majority of storage costs can be attributed to personnel needed for maintenance and testing, along with preparations for launching. However, the granular information to accurately gauge these costs seems not to be clearly identified. In particular, cost data at a detailed level (such as the number of personnel and costs for each type of storage activity) and cost drivers have to be analysed and assessed so that they can be taken into account during the satellite procurement process (both from a technical and programmatic/budget standpoints).

Having more information from the space agencies or the major space industrial players on the main drivers for costs during satellite long-term storage could be beneficial in terms of cost planning, mitigation actions, and technical/programmatic decision-making processes. The industry 4.0 based approach described in this paper can support the understanding of such drivers, the overall decision-making process, while automatizing the monitoring and the maintenance of the different assets via the cloud infrastructure.

The main idea of this paper is to consider such container as an asset, and to connect the various local monitoring systems within a cloud infrastructure. This is meant to provide a global monitoring system, where parameters can be tracked and processed via more sophisticated approaches. This way, we could include relevant functionality such as data trend analysis, novel detection, and predictive maintenance. This way, the proposed solution becomes a knowledge management system, ready to support all the activities during the satellite long-term storage.

INDUSTRY 4.0 TECNOLOGIES AND SATELLITE LTS

Industry 4.0 is not a technology but a set of technologies and new methodologies for the pervasive introduction of software components into the industrial environment with the aim of improving the automation level of the manufacturing ecosystem, in particular by focusing on its productivity and quality in the direction of a “zero-defect” production cycle.
One of the most widely adopted definitions of Industry 4.0 ecosystem is the identification of the following technologies as its building blocks: Simulation, System Integration, Internet of Things, Cybersecurity, Cloud Computing, Additive Manufacturing, Augmented Reality, Big Data, and Autonomous Robots. We can also consider further topics such as Blockchain and Artificial Intelligence, that for sure can address further aspects, e.g. system integrations, autonomy, decision making support, and security.

In this paper, we are going to describe approaches related to the specific skills and experiences covered by the Intelligentia in the development and tailoring accordingly to customer needs of Industry 4.0 real applications (see).

Figure 1 Industry 4.0 ecosystem and technologies

During the past months, Intelligentia has collected requirements for investigating in detail the main issues related to a satellite long-term storage use case. The assumption we do in this paper is to look at a satellite as a complex industrial plant and the long-term storage as an application of production line monitoring and maintenance. We also assume that satellites delivered for the long-term storage are not stored in “top class” Clean Rooms but in a sort of monitored and secured warehouse that have basic environmental constraints (e.g. climatized room, restricted access granted to operators for surveillance and maintenance, low restrictions on dust, electronics, and human presence).

It is clear that decades of storage for satellites involves not only the need of identifying a tool for supporting some data analysis, but is a complex process that starts with the main focus on know-how digitalization, personnel competences, trusted data sharing, procedures, best practices, and finally the grant of having such a huge amount of incremental information available for decades to several groups of people (e.g. customer, Original Equipment Manufacturing (OEM), suppliers, external experts)

In our vision, the basic brick in building an effective LTS strategy is to have a strict integration between several information systems such as document management, QA/PA procedure repositories, System Engineering procedures, scripting/code repositories, log books of performed activities, FDIR procedures, calendars and notification systems to remind activities and tasks to perform, etc. A relevant aspect is that the information systems itself where the information is stored and classified are affected by the LTS issues. The integration between all of them is fundamental for preserving baselines at each stage of the LTS history where all the data treated by different and not correlated tools need to be “frozen” in a central information repository for future access by personnel that were not present at the time of the baseline creation.

What is currently clear to the industrial applications is that the technology advances are so rapid that at a certain point in the future, the systems itself that generate or hold the information of previous years, can evolve in something different from the initial one. This evolution shall preserve the overall data and information persistent and coherent with the rules defined decades before. We assume that standards in documentation, coding, procedures writing and language will be kept during the lifecycle of the project, but one of the point we would like to analyse in this paper is that the technology of the information systems can evolve and that this point can be beneficial also for the final customer that is not forced to keep updated and maintained an old tool just for the purpose of the LTS.

One of the most important concepts that is leading the industrial forth revolution is the goal to have software systems and in general information systems that can cooperate and that are able to migrate their data to external or complementary tools. For addressing such a need, in addition to the definition of standards that will cover the formalism of how the information shall be represented, the data storage layer is moving into cloud infrastructures because of their intrinsic security, scalability, replicability, availability, and reliability requirements. By its mean, cloud is not related to specific hardware components (e.g. servers) but are often synonym of virtual environments having the capabilities to replicate and migrate their content from one geographical node into another in few seconds in response to disasters, or just for business reasons (cheaper cost of a potential new cloud provider). Because the information is critical and its availability over the time is even more critical for the specific activities such as LTS, the cloud architectures implement natively replication of data and, for mission critical application, usually the low-level infrastructures implement strict and reliable disaster recovery procedures.

Because of the need in adopting cloud architectures, the data portability takes a fundamental role. This is a necessary asset for such a system in case of update of the basic technologies or just migration for business purposes to another equivalent or concurrent environment. With such a definition of the information, cloud ecosystem for LTS shall grant shared and tailored virtual control room applications to each stakeholder involved. A private cloud or a secured cloud access shall give the possibility for each stakeholder to monitor their produced assets for example:

- EGSE suppliers can monitor the current status of their asset in dedicated dashboards where is reported only the information of their interest;
- Payload integrators can l keep trace of the current status of their components and if the recurrent procedures have been performed, on which date, and analysing the result of the data generated;
- Customer can have dedicated KPIs for alarms or video logs analysis of the experiments and routine maintenance performed, access to each PA/QA document, and so on;
- Space Agencies or Primes can have the complete status of the asset monitored, data generated by EGSE/SCOEs during periodic and recurrent maintenance activities;
- The LTS responsible can have the complete overview of the information and the possibility to manage any kind of request from the external partners in a central tailored application.

The cloud concept is also opening in the industrial market the need for security and privacy of the information. Cybersecurity is one of the emerging trends in Industry 4.0 application when related to Internet of Things and distributed cloud applications.

Another aspect for Satellite LTS is the periodical and recurrent activities that can be performed by qualified and unqualified personnel in activities such as:

- Unpacking satellite components from their storage containers;
- Execute trivial or complex inspection activities;
- Execute trivial or complex integration activities such as plug harness to multiple EGSE/SCOE for the preparation of a test campaign;
- Execute a periodical test campaign;
- Analyse the result of the test campaign and prepare reports or analyse a misbehaviour of the element under review, and execute the required activities suggested to restore the normal status;
- Restore the LTS status of the component at the end of the task and report all data to the central knowledge management system.

The activities mentioned before can be expanded for specific cases in thousands of details, but this is out of the scope of this paper. The message that we would like to point out, is that most of these activities are involving automatic procedures where data are the main driver for assessing the status of a certain component. If we assume that each EGSE, SCOE, Transport Container can be monitored by a software agent that is able to record and store in a central cloud each telemetry or in general data log that is produced during an experiment, this repository can be analysed by Artificial Intelligence components to detect any kind of deviation from the normal and expected behaviour. This is involving model-based approach for teach the AI about the expected behaviour that the component should have, and this teaching can be performed by the use of any-kind of software/hardware simulator used during the production of the satellite at the acceptance (e.g. reference test execution logs) and activation of the LTS stage of the project.

As a consequence, we are clearly targetting Big Data and System Integration. In the context of Big Data is not only relevant how to store and preserve a huge amount of data. It is referred to a Big Data application if are matched the four "V's" properties:

- Volume: the telemetry and raw sensor data points and all the contextual information that will flow through central application will be related to a potentially huge amount of data to process and store for real-time processing by AI models, discipline models, and data analytics tools;
- Variety: it is normally related to the different information sources that will generate the data flows (e.g. satellite components, EGSE, SCOES), but can also be related to the type of the information that can be unstructured (e.g. communication network data, contextual data, time reference), structured (e.g. fields of the PUS packets) or semi-structured (e.g. data generated by the Mission Control System itself, simulators, external tools, or even the operator entries itself);

- Velocity: is related to the speed of the telemetry data point flow, but also to the performance of the processing software modules needed by the system to process the data flow. Speed of generation and rate of analysis will be two key performance indicators to take into account for the SW infrastructure definition;
- Veracity: it is a property to define trusted/untrusted data flows and information. This is fundamental for example in case of failure or wrong configuration of an EGSE that potentially can arise false positive alarms about the status of a satellite component under test generating any kind of exhalation to the customer, suppliers and the Agency. Untrusted data can be also spurious data ingested from internal applications such as operator input flows and tools. An example of untrusted data flow is a misaligned data sequence with the expected time reference that can potentially corrupt the quality of a model analysis.

As for the Big Data, we have to address computational and storage availability. A strict agreement on how the data shall be represented is the key for the success for the future analysis. Assumed all aspects have been strictly defined, it is possible to deploy as complex as needed AI and Data Analytics tools that can process the information stored in the central, distributed, data repository in two wais: real-time, batch. In the real-time is it needed to ingest and process at the highest speed all the data coming from the field assets and give immediate feedbacks about the status of each component under test. Typically, real-time analysis is approximated to have best performance with medium precision. In batch, instead, the whole repository of data is processed, and the accuracy of the analysis shall be maximum scarifying the time and the responsiveness of the feedbacks.

For the batch analysis, it can be interested to use also data produced before the activation of a certain experiment, but during the “packing period”. Putting in relation small alarms about the conditioning air or the power consumption of the transport containers, hydrogen pumps over the time, can lead to identify and predict issues not related to the failure of the component, but to a certain combination of events that have led to the violation of the LTS condition for the specific component. Monitoring in real-time these parameters and having an AI companion able to learn from discipline expert feedbacks to detect potential alarms in our opinion is a must-to-have for a useful LTS application.

In the industry is emerging a very promising technology that is related to the Augmented Reality. Major players such as Google, Microsoft and other OEMs are putting into the market their own proposals and in 2019 is expected these technologies will become even more effective for the industrial context. At the time of writing, Microsoft has just announced the version 2.0 of their HoloLens smart glasses. This allows operators in the clean room to avoid entering in contact with the components or going around to get access to the transport containers monitors, but it can be possible to project directly in the view (e.g. from a window that is dominating the warehouse) which asset needs attention and an urgent activation of the expert teams. Moreover, the most interesting use-cases are related to the support at maintenance and fault recover conditions with an expert connected by remote, that potentially is drawing and projecting on a mixed reality, some graphical information: pointers, lines, circle to underling a certain component where to focus the attention. From our experience, such a device is a basic component that an operator shall have in order to have projected the “TODO list” of actions to perform for a certain activity, to record a video log book of the task performed that can be used as a “training on the job” for another colleague that is facing a problem already resolved in the past. The integration of such a technology, with data flown by the sensors and assets, with cloud infrastructures where the information is stored and archived, is the most innovative knowledge management system that Intelligentia can put in field for supporting a long-term satellite application.

The last point in our survey is related to the applicability of Blockchain technology to the LTS storage monitoring. Blockchain is used in its most known use case as a method to validate and grant the correctness of the information. Blockchains can be used to assess that the information stored in the knowledge repository is valid and has not been manipulated. This kind of application can be used to “sign” and “mark as immutable” the baselines introduced in the central system after an intermediate check or at a certain point of the future after routine check or milestone achievement (e.g. decommissioning of a satellite for the lunch phase).

GUIDELINES FOR SATELLITE LTS IMPLEMENTATION

Most of the applications and frameworks developed by Intelligentia in the past years can be adopted for the satellite LTS ecosystem. Looking at the emerging technologies and at the points mentioned in the previous sections, we can derive the following guidelines to implement the satellite LTS as an Industry 4.0 use case:

- Field applications (in terms of software and/or hardware) for integrating heterogeneous EGSEs, SCOEs, test benches, hardware components, field PCs, transport container monitoring tools, sensors, able to harmonise the structure of the information in respect of defined standards for long term storage;
- Cloud infrastructure for Big Data storage and computational processing and AI based analytics (e.g. IaaS – Infrastructure as a Service, and PaaS – Platform as a Service) that grant an open standard for data migration via export of the ecosystem or front-end APIs;
- Custom software components for data processing during the overall lifecycle of the LTS integrating Artificial Intelligence and the relevant future cutting-edge technologies for preventive maintenance, decision making support, and monitoring of relevant and critical components;
- Tailored, customizable, usable, portable, and multi-channel dashboards (e.g. web dashboard, apps, customized offline applications) for delivering information to each stakeholder involved in the LTS program for its own purpose;
- Custom portals for knowledge management and data digitalization such as:
    - information systems for maintenance planning and execution,
    - personnel skills management for tracking competence availability in each project stage (e.g. mitigate issues on turn-over of old personnel or employee leave),
    - training and incident history management,
    - video log repository for each activity performed tagged automatically (AI needed) or manually by the user that created it;
- Custom applications and tools for supporting the operators in performing his job and in retrieving the right information at the right time, in the right context.

Starting with a bottom-up approach, the field applications are for sure the first place where to start working. When creating data sources and integrating all of them with the cloud, it must be considered the following aspects:

- Specific hardware (HW) and middleware (MW) components able to intercept specific EGSE, SCOEs, sensors data flows, convert the information in a standard and common format. This layer can be implemented via embedded HW components (e.g. microcontrollers, FPGA) that act as "protocol adapters";
- Generic HW components acting as Gateways (e.g. IoT Gateways). Their focus is to accept a certain number of sources and take care of transmitting such information to the central cloud repository for storage and processing in a secure way, taking care of encrypting the information and/or even the communication channels. The Gateway has to handle connectivity issues by storing a certain amount of data locally in a FIFO buffer for granting the lowest data loss rate of precious data (e.g. telemetries flow during an experiment).

For the cloud infrastructures there are plenty of solutions. If Space Agencies or Primes prefer to avoid public clusters, we could consider two different solutions: private and/or hybrid cloud infrastructure. In the private cloud, all the ecosystem is controlled and managed by the hardware tenant. In the case of the hybrid cloud, usually the information is stored at customer premise, while for the computational resources are used the public cloud. In this schema, only the information to be processed in the cloud is moved out of the private context.

In the private cloud, the challenge is to grant a scalable ecosystem able to survive to disaster, to scale vertically and horizontally in answer to the demand, to replicate the information over several nodes, and to grant an independent infrastructural layer from the specific server hardware. For this kind of applications, a possible open-source, backed by the most important software system integrators (e.g. IBM/RedHat, Cisco, Intel, Rackspace, VMWare, Google) is represented by OpenStack, a project that is leading the development of an open source IaaS. OpenStack provides the capabilities to set-up a datacentre with vertical and horizontal scaling, of computational power.

OpenStack can be coupled with RedHat Ceph, another open-source, enterprise driven project aimed at creating a scalable software storage ecosystem for big data. Ceph is able to vertically and horizontally scale resources without requiring expensive and special hardware for storage. It is able to run on commodity hardware (e.g. standard PCs). In case of failure of a node, the information intrinsically replicated in the cluster is automatically migrated to other nodes to preserve the availability and reliability. Such an approach does not require a huge investment and can scale by incrementally introducing new hardware when strictly required. As a prove, Intelligentia has developed during 2016/2017 its own OpenStack ecosystem updated to version "Queens" integrated with a Ceph cluster adding resources with small incremental investments up to 140TB of space, more than 1TB of RAM and hundreds of CPUs.

This set-up offers the possibility to host dedicated applications to the final customers for IoT contexts where sensors and industrial machinery telemetries are collected via IoT Gateways and sent to the cloud using encrypted channels.

On the top of OpenStack we have developed a framework platform named SAM (Smart Asset Monitoring), integrating open source components (e.g. Apache Kafka, Apache Spark and Hadoop, and MemSQL) for data processing and storage accordingly to a Lambda reference architecture. We have than created a middleware application able to abstract low level details about data ingestion, pre-processing, and persistent storage.

SAM is designed as a cloud application based on a Java clustered back-end, a web GUI based on HMTL5 and CSS3 able to provide responsive and easy to maintain interfaces for data presentation to the final user. SAM is used as building block for customized software "control room", enriching the low-level data with contextual data regarding asset datasheets attachments, and external data sources and tools. SAM exposes an easy-to-use REST APIs layer, allowing the integration with third party software, mobile Apps, eternal services for alarms notification (e.g. text SMS, emails, in-app push notifications), or just data downloads for post processing or archives. SAM is the building block for IoT applications developed by Intelligentia. When coupled with the Gateway IoT developed and offered by Intelligentia, the data flows are enriched also with geo-tagging so that is possible to monitor where the information has been produced, and then use this kind of information for creating KPIs related to groups of assets. SAM natively supports the integrations with 2D planimetries so that each alarm can be linked to the related asset in a visual way. Moreover, alarms can be grouped into maps overviews such as reported in figures below.

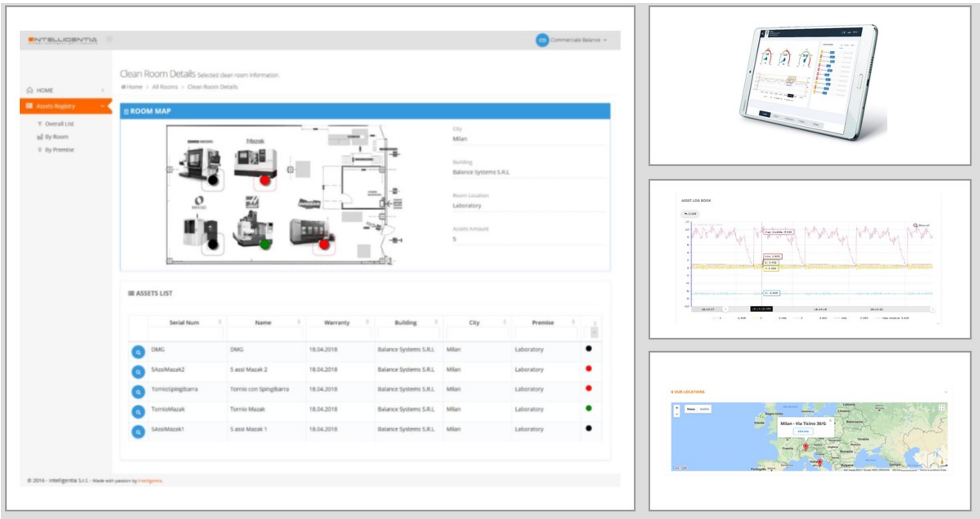

Figure 2 An example of SAM dashboards and mobile app

SAM is offered as PaaS where most of the low-level entities are already modelled, and via APIs it is possible to attach to an asset any kind of external information such as files, documents, videos tutorial, technical data.
Moreover, using the APIs and the HoloLens integration, we can design customized applications for visualizing the status of the observed asset.

In case of satellite LTS, once a specific alarm code is detected by the data flows or batch processing, SAM can perform the following activities:

- Create an event code and notify immediately the monitoring subscribers (e.g. users' email, SMS, third party software, lights/audio signals on the physical asset);
- Mark the event in the data timeseries and notify the real-time storage to apportion the last X (configurable) hours of data for batch processing;
- After the processing of the alarm code(s), SAM is able to identify the team skills required for handling the event, thus avoiding the waste of time in asking around for the right colleague to involve.

When the technician engages the asset for solving the problem, a contextual help is offered via tablet/iPad application on which the detailed "asset card" is shown, with its monitored KPIs, alarm data series, and attached technical documentation, video log, procedures, and notes/suggestions from other users.

As for satellite monitoring and maintenance automation during their long-term storage, we can highlight the following aspects and concepts:

- Besides collecting data from SCOEs or EGSEs (via the most used protocols, such as the EGSE Data Exchange Network (EDEN)), we can gather and monitor environmental data, such as temperature, humidity, and light intensity;
- It is possible to import MIB files and the Electronic Data Sheets (EDS) for each item under control. As for the latter, the tool can automatically set the monitoring parameters and the type of checks to be performed;
- If a certain observed data value violates the asset normal working range, an alert is triggered and sent to the concerned users (e.g., AIT engineers) via configurable notification channels (e.g., SMS, emails, push notifications). The most relevant information can be shown to provide the appropriate support.
- Preventive maintenance procedures and checklists can be defined for specific assets. In particular, a digital checklist can be created for any operator, accessible via a tablet, smart-phone, or a video terminal. Post-check reports can be stored for future quality assessment.
- Machine learning approaches and reasoning models can be introduced to correlate observations, improve the diagnostics capabilities, and support the overall decision process.
- Dedicated dashboard can be configured for reporting and data visualization of the concerned assets.

CONCLUSION

In this paper, we have explored the adoption of Industry 4.0 concepts for monitoring, and knowledge digitalization needed during satellite long term storage. In particular, we have presented the adoption of SAM (Smart Assessing Monitoring), an industrial cloud application developed by Intelligentia in the context of Industry 4.0 smart factories. The main idea is to harmonise and automatize such procedures from the different Satellite assets over long time periods.

The proposed platform can provide a centralised knowledge management system, and can be used to plan, track, and support the execution of all the procedures needed during satellite long term storage. This way, the proposed platform can support satellite prime contractors in planning all the needed tasks, tracking all the encountered issues, and mitigating some risks, e.g. key-person dependency risks over very long time periods.

Finally, the authors highlight the importance of gathering more detailed requirements concerning satellite long term storage from support satellite prime contractors. The related industrial processes, methods, and tools have to be better understood, considering the fact that the production of satellites will significantly increase in the near future.

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