# The concept of "safety bubble" to build ethical reconfigurable assembly systems

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**Abstract:** The concept of Reconfigurable Assembly System has been proposed in the last decade to deal with mass-customization problems and volatile market environment. If physical design or control issues of these systems have been studied intensively, very few works concern the inherent ethical risks and associated safety problems. However these issues are of first interest for reconfigurable robotized systems with frequent interventions of human operators. Indeed, the re-configurability features of these manufacturing systems induce new issues in safety. The manufacturing enterprises must pay attention to the possible consequence of the Reconfigurable Assembly System design on the safety of the humans and on their possible responsibility in case of an accident. The present paper proposes the concept of safety bubble aiming to insure human's safety by cooperation among safe robotized units. After a presentation of the ethical considerations, a design methodology of such safety bubble is detailed. The on-going works in simulation and on a real demonstrator, including collaborative robots and mobile robots, are then described.

*Keywords:* Industry 4.0, ethics, safety, reconfigurable manufacturing system, robotics.

## 1. INTRODUCTION

For philosophy, ethics concerns understanding of the moral basis of right action (Bennett-Woods 2018). So, faced with a difficult choice for actions, ethical reflection is a source of guidance. Ethical actions and ethical decisions (decision that is a prerequisite for action) concern many professions as for example medicine, business… and engineering. Engineering ethics is professional ethics which corresponds to morally permissible standards of conduct that, ideally, every member of a profession wants every other member to follow (Harris et al. 1996).

Ethics is cultural (Paasche-Orlow 2004). So it may evolve due to change in trends, obligations and wishes of the group and its individuals. With the evolution of knowledge, technologies and societies, the group of living beings is enlarged to group composed of living and artificial beings (i.e., artificial systems) asking new questions as "Can a machine be ethical?" (Moor 2006; Hooker 2018), "Can a robot have rights?" (Gunkel 2018). Generally, these artificial systems are a mix of physical and cyber parts to constitute what is named "cyber physical system" (CPS). For example in the industry 4.0 context the work situation involves human operators interacting with artificial workers, as for example, automatized machines, collaborative robots (i.e., cobots), reconfigurable systems... This paradigm change implied evolution in the relation and interaction, between man and CPS (Riek and Howard 2014; Trentesaux and Rault 2017). Here we are in the domain of the interaction. Without interaction, or action, ethics no longer has any reason to be.

For example, in the early days of industrial robotics it was not accepted that a contact exists between a human and a working robot. So, generally, the classical industrial robot is surrounded by fences. With nowadays systems, as in the case of the industry 4.0, it is accepted that a cobot comes in contact with the human. For example (cf. Figure 1) the Omron robot manufacturer gives access to a functionality to tune the robot speed considering the part of the human body in contact (Omron 2019).

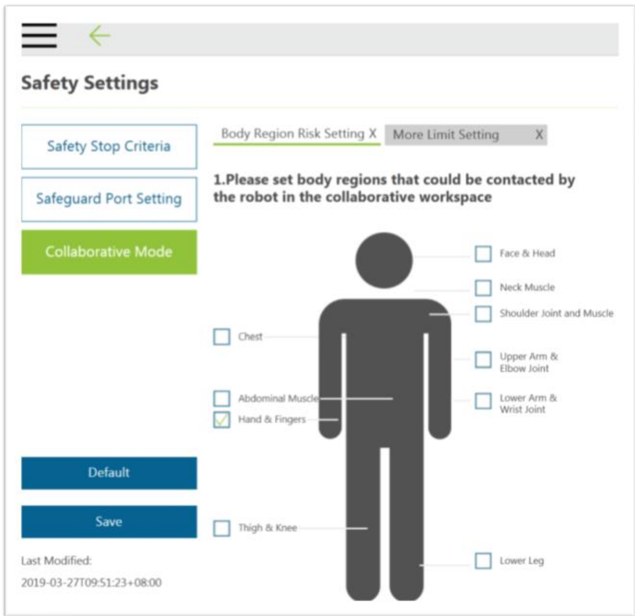


Fig. 1. Display example for adjusting the contact between robot and human (Omron 2019).

 

In the context of technologies and industry, particularly the 4.0, the risk became an accepted notion with ethical considerations. For example, for (Asveld and Roeser 2012) it is worth mentioning "the ethics of technological risk". Risk is tolerated if it is controlled and this in order to decrease injuries to human and environment. In this context, safety is the companion to implement an ethical management of the risk.

In the industry 4.0 context, this paper argues that professional ethics is a prerequisite to safety, and this safety an ethical value (and concrete response to ethical questions such as "preventing injury") for a group composed of humans and CPSs (e.g., robots, machines, artificial systems...) interacting.

This paper deals more particularly with the safety issues in RMS and is organized as follow. The next section focuses on our motivations to introduce a break in the safety approaches to deal with RMS re-configurability. The concept of safety bubble and the associated deployment methodology are proposed in a third section. In the fourth section, on-going works relative to this concept are presented. Finally, conclusion and prospects are offered in the last section.

## 2. MOTIVATION

Before presenting the limits of the current safety approaches and the need of a new one, the specificities of the reconfigurable manufacturing systems are introduced.

### *2.1 Reconfigurable manufacturing systems*

Nowadays, industry must face important fluctuations in production volumes due to the fluctuation of markets and product variety. Manufacturing systems must continually and efficiently adapt their production. In this context, the concept of RMS (Reconfigurable Manufacturing Systems) was introduced in (Koren et al., 1999) to increase the speed of responsiveness of manufacturing systems to unpredicted events (e.g., sudden market demand changes, machine failures). The goal is to offer exactly the capacity and functionality needed, when required. RMS can be defined as follows: "*Reconfigurable Manufacturing Systems are designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or regulatory requirements*" (Koren et al., 2010).

The RAS (Reconfigurable Assembly Systems) (Bi et al., 2007; ElMaraghy et al., 2016) are the declination of this concept to the domain of assembly. They are based on modules (e.g., conveyor units, robotized units) that are assembled together to build a specific layout. This last corresponds to a "stationary" configuration of the RAS, remaining valid until a new reconfiguration.

Currently, the RAS development beneficiates of the advances of new technologies like cyber-physical systems or collaborative robots and of new approaches in the field of human-robot cooperation (HRC) (Cherubini et al., 2016; Krüger et al., 2009). Nevertheless, the use of collaborative robot can induce negative repercussions on the productivity. In fact, to reduce the risk in case of collision with the operator, the robot speed is voluntary reduced by regulation. So, to keep good productivity performances, the aim is to use the robots at high speed when the operator is outside the robotized areas and to adapt the speed or stop the robot when the operator enters in the workspace. In this context, the re-configurability of the robotized units induces new safety constraints. However, if some works (Koren et al., 2010; Huettemann et Howevefal, 2016) deal with the RMS design or their control issues, very few explore the inherent safety issues ((Koo et al., 2018; Kock, 2019).

### *2.2 Conventional safety approaches*

As exhibited on the left part of figure 2, the use of conventional approaches implies to perform safety studies for each configuration of the RAS. Classically, these approaches lie on a several steps process: risk analysis, risk evaluation and risk reduction (Koo et al., 2018). For example, the European Machinery Directive (Directive, 2006) and the harmonized standard ISO 12100 (ISO, 2010) provide guidelines and methodologies to identify hazards and realize risk assessment and risk reduction. In addition, different methods are available to support the safety analysis. As an example, (Dhillon, 2003) presents robot safety related facts and figures along with the most useful seven safety analysis methods and the application of the two most widely used methods (i.e., fault tree analysis and Markov analysis).

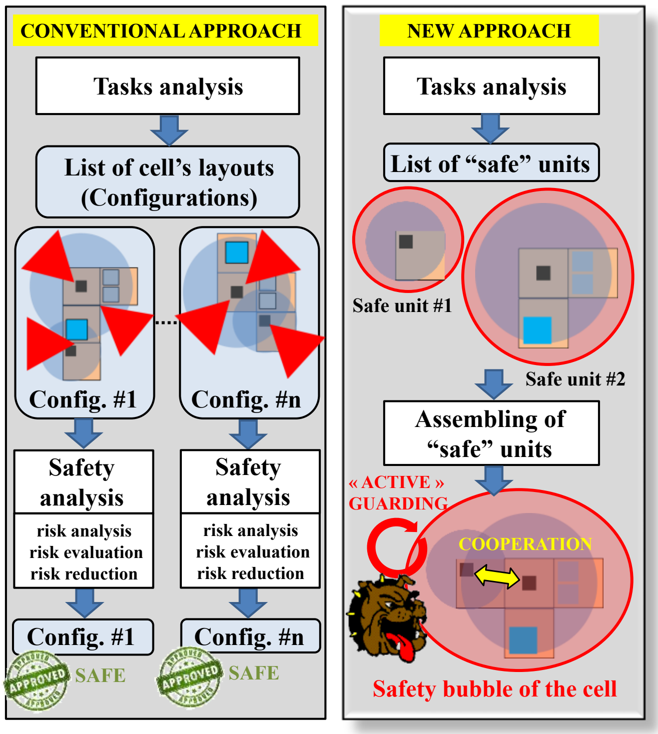


*Fig. 2. The conventional approach and the new approach.*

The previous conventional safety approaches are classically well mastered, but it's clearly tedious to analyze all the possible RAS configurations and certify each of them in a reasonable time. In fact, only a limited number of configurations can be certified as "safe" and deployed in-situ. Even if these approaches can be used to assist the safety experts, they are inefficient to deal with the safety of the RAS.

*2.3 Need of a new approach*

The previous observation has given birth to few recent contributions presented below.

In (Koo et al., 2018), the authors argue that traditional methods of safety study fail to take into account the versatility of "Plug-and-Produce" systems, confirming our previous assumptions (Sallez et al, 2017). The paper identifies challenges for implementing a software solution for assessing the safety of Plug-and-Produce systems. The authors propose some challenges to face high changing dynamics of reconfigurable systems and safety concerns resulting from interactions between reconfigurable components. They argue that the risk assessments and the safety analysis, which are done manually, need to be stepwise automated.

(Koch, 2019) points out equally that safety can be a bottleneck on the way to changeable manufacturing systems. Therefore, for safety verification, validation and configuration novel approaches and methods are demanded.

In another domain, (Zhang et al, 2013) have proposed an approach to prevent falls in the building industry. Based on an automated rule-based checking and coupled with a BIM (Building Information Modelling), the developed system is able to recognize the different hazardous workspaces and to suggest safety measures (i.e., guardrail protection system) already at the design stage before beginning any field work. In the same building field, (Getuli et al., 2017) aims to define a BIM-based design system and focuses on the translation into parametric rules of the Italian construction sites' health and safety normative text. Although, specifically proposed for the building industry, these concepts of software-aided safety checking could be applicable to other areas of engineering.

The next section presents the safety bubble concept which is the proposal of the paper.

## 3. PROPOSAL

*3.1 Safety bubble concept*

The proposed approach aims to deal with the safety problem allowing a more easy re-configurability of a RAS, not restricted to a limited number of "certified" configurations. As illustrated Figure 2 (to the right), the main concept of the proposal is to build a "cooperative safety bubble" by assembling of "safe" units. These last are assumed to be "safe", able to detect the presence of operator entering in their workspace. The cell's layout obtained by coupling of these units exploits two factors, the first is a pooling of safety devices (e.g., safety laser scanners) between safe units, and the second is based on a cooperation between safe units.

Before detailing how to build a "safety bubble" concept, some assumptions are made.

1/ Each configuration of the RAS is based on the assembly of three types of static (i.e., non-mobile during the production phase) units to build several cells:

- "Safe" robotized units (SRU) where operators intervene occasionally (e.g., replenishment of components, maintenance intervention). These SRUs are equipped with appropriate safety devices. For example, two safety laser scanners can be placed in the two corners of each SRU to insure safety.
- "Safe" manual units (SMU) where operators work continuously. These units can be equipped with collaborative robots but the safety is insured by applying the rules and recommendations of the standard ISO/TS 15066 (ISO/TS, 2016).
- Intrinsically "Safe" units (ISU) (e.g., storages, inspection unit, conveying units) are assumed to be safe for the operators and not require additional safety devices.

2/ In each cell of the RAS, the different previous units are assumed to be assembled physically to allow products transfer among them.

3/ The units are equipped with communication devices to share safety information among them.

4/ Each unit can cooperate with mobile robots used to transport products among the different cells of the RAS.

*3.2 Methodology*

To deploy the proposed approach, a methodology in three main phases is considered:

- First, an "off-line" design of the "safety bubble" for each cell is realized.

- Second, an "on-line" implementation of the safe RAS (i.e., with its safety bubble) is performed in accordance with the previous design.

- Third, the RAS is exploited with the fleet of mobile robots.

These "off-line" and "on-line" phases are depicted on figure 3 and detailed below:

**"Off-line" design phase**: Three steps are successively considered.

1/ The first step is relative to the modeling of the layout corresponding to a specific configuration of the RAS obtained from a dedicated design system. This last is out of scope of this paper but the interested reader can consult (Lameche et al., 2017). The layout is built with a CAD dedicated tool containing the different units (i.e., SRU, SMU, ISU). All these units are assembled to build the required cells. The output of this step is a raw CAD layout of the RAS containing the different units with their respective safety devices.

2/ The second step is dedicated to the building of the "safety bubble" based on the sharing and the cooperative usage of their safety devices. The building of the safety bubble is partially automated by applying predefined safety rules in two phases:

- First according the location of the different SRUs, the area covered by the safety devices (e.g., safety laser scanners) is determined. The inhibition of some safety devices is performed to avoid interference among them. The no-covered areas are equally highlighted.

- Second, other rules are applied to install fences between SRU and SMU. These fences are used to avoid operator intrusion into no-covered areas by safety laser scanners.

In addition, an adaptation (or tuning) of the different identified safety devices can be performed by the safety manager (who is certified and responsible of the RAS safety). This last can also add and tune additional safety devices if required. The spatial characteristics of the area (where the RAS is installed), the operators' locations and their pathways must be taken into account during this tuning phase. Moreover, the presence of walls or pillars can complicate or simplify the safety considerations. The output of this step is a refined RAS layout with tuned safety.

3/ In the third step, the safety manager validates the safety by checking, for example, that a sufficient safety distance around each SRU is respected. In this task, the safety manager can be helped by a specific safety checking algorithm. This last must be mandatory designed independently of the safety rules applied in the second phase, in order to perform a safety double check. In fact, this algorithm checks that all safety criteria (related to safety standards) are respected. If the safety manager validates the layout, the "on-line" phase can begin.

**<u>"On-line" preparation phase</u>**: Three main steps are considered:

1/ the first step consists in the real <u>implementation of the previously designed RAS layout</u>. The different units are moved to their expected locations and physically assembled together. The safety devices are also inhibited or tuned in accordance with the tuning performed in the second step of the "off-line" phase.

2/ a <u>final validation of the safety</u> is performed by the safety manager on the field. This step is crucial to certificate the implemented layout. Depending on the different countries laws and ethical considerations, it could be mandatory to obtain the validation of a human safety expert before to begin the production. A safety checking is performed to detect any safety flaw allowing an operator to enter in the SRU vicinity without detection. This checking exploits the layout topology, the performance characteristics and locations of the different safety devices. The safety expert could be assisted in this task by a self-discovery algorithm supported by the different equipment (i.e., safe units with their safety devices, other added safety devices) composing the RAS. This self-discovery algorithm is based on equipment interaction in order to identify their respective locations. At the end of this step, this layout is considered operational.

If the result of the safety checking is not satisfying, a return to the previous step is performed to tune the safety devices. If the tuning seems too tedious to realize, the process must be redone from the "off-line" phase.

**<u>"On-line" operational phase</u>**: the third phase corresponds to the operational exploitation of the RAS. The various safety devices associated with the units cooperate with each other to detect any intrusion of the operator into the robotized areas. In addition, the safety bubble must deal with the potential flaws induced by the arrivals and departures of the mobile entities (e.g., mobile robot) as explained in the next section.

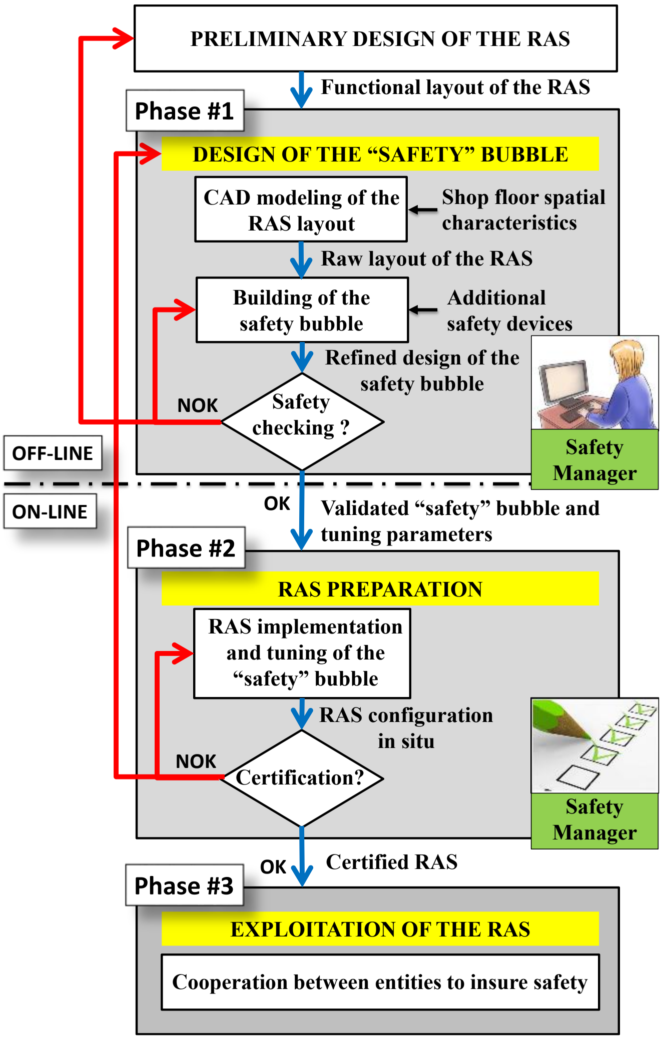


Fig. 3. The phases of the methodology.

The on-going implementation of this proposal is described in the next section.

## 4. ON-GOING WORKS

Our team aims the deployment of the proposal according two ways:

A software tool is currently under development to support the "off-line" design of the "safety" bubble. This software is based on the use of the multi-agent Netlogo platform (Wilensky 1999). This environment was chosen because it easily supports the chosen modelling method and provides an intuitive, well-documented programming language with an elegant graphical interface. In NetLogo, each agent operates on a grid of patches (i.e., a cellular world), and each agent can read and modify some of the patch attributes in its vicinity. This agent-environment interaction is well appropriate to support the simulation of safety areas.

As depicted on Figure 4 and in accordance with the proposed methodology, this software tool is able to automate the building of the safety bubble. Once the different safe units, located on the grid, the tool applies a set of safety rules to:

- Compute the coverage areas of the safety laser scanners installed on the SRUs.
- Inhibit or tune some safety laser scanners to prevent interference among them.
- Compute the locations of additional safety devices (e.g., fences).

The figure 4 shows a layout example composed of two cells. Additional fences have been installed preventing an operator to penetrate directly in the robotized areas.

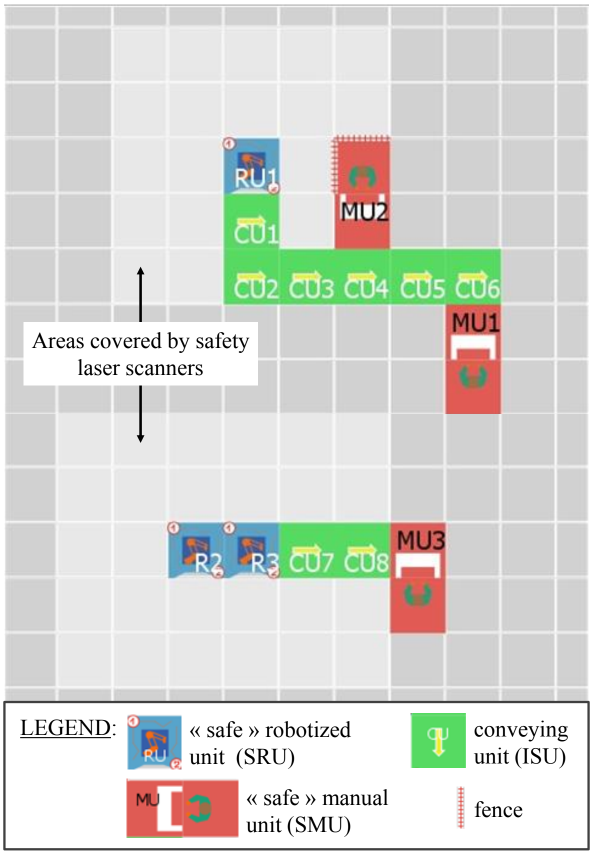


Fig. 4. Screenshot of the RMS layout.

The development of a RAS demonstrator in the field of electronics industry is actually on-going. While the robots perform component assemblies and screwing tasks, the operators carry out more delicate tasks like cabling or very precise insertion. As depicted figure 5, the RAS is built by the assembling of SRUs (moved by the operators) and physically attached via specific fixtures. The SRUs are equipped with Universal UR5 and UR3 robots. The safety of each SRU is insured by two SICK laser scanners installed in the opposite corners. A fleet of three MIR mobiles robots is used to convey products and pallets of components among the cells.

This demonstrator is used to realize in-situ experiments on the cooperative safety between units. The focus is currently held to solve the mobile robot docking problem. As illustrated Figure 5, when a MIR robot must dock an SRU, a flaw can arise in the safety bubble. To allow the mobile robot progression, a progressive opening of a corridor in the safety bubble towards the docking location is performed. To open this corridor, some laser fields must be partially inhibited or restricted. A problematic situation can then arise if an operator follows at the back of the mobile robot (i.e., the safe distance between the robot and the operator is no longer respected). However the embedded safety laser scanners at the back of the mobile robot can be used to detect the operator. The mobile robot can then alert the SRU to stop the robot. This type of cooperation between mobile robot and SRU illustrates the "active" guarding that must occur to insure the integrity of the safety bubble.

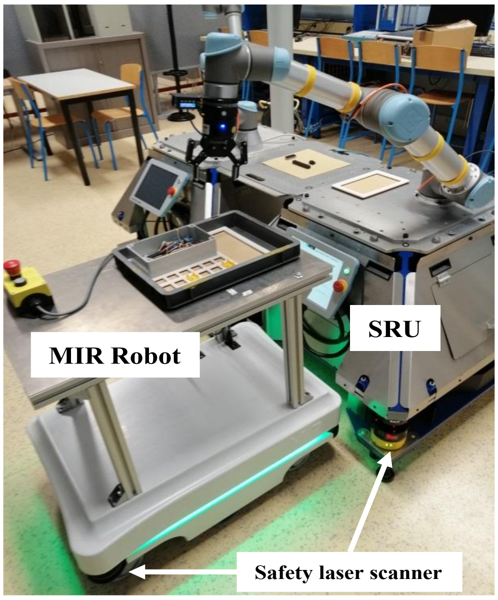


Fig. 5. View of the RAS demonstrator.

In our point of view, the safety management in RAS can lead to new functions among the operational staff. As outlined in (Koo et al, 2018), know-how and experiences of safety managers for an adequate comprehension of relevant standards are crucial to deal with ethical and safety issues of the RAS. In addition, the safety manager must have a good knowledge of the equipment implemented in the RAS (e.g., machine characteristics, inherent safety features…).

## 5. CONCLUSIONS

This paper has positioned "safety" as a professional ethical value. Safety is considered as a companion to implement an ethical management of the risk. New reconfigurable manufacturing systems induce to revisit risk consideration and to deal with new safety challenges. Indeed the usual approaches, appropriated for static (i.e., not reconfigurable) industrial systems, are unable to give an adequate answer. So, the innovative concept of safety bubble has been proposed as a new way to deal with RAS safety issues. This safety bubble is based on cooperation among safe robotized units to detect any intrusion of the operators in the robotized areas. A methodology of deployment with "off-line" and "on-line" phases has equally been proposed.

This work opens the way to more general questions concerning the ethics in modern manufacturing systems. In these last the work situation involves human operators interacting with artificial workers. So, many technical and methodological prospects must be considered, as for example:

- How to detect safely (i.e., always without error) human operators in a dynamic environment? This issue must lead to the development of new sensors or algorithms able to analyze complex situations with human operators and mobile artificial entities.

- How to assess the ethical level of a system? This issue can imply the development of a scale to build an ethics index.

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