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► **To cite this version:**

Yves Sallez, Thierry Berger, Thérèse Bonte. The concept of “safety bubble” for reconfigurable assembly systems. *Manufacturing Letters*, 2020, 24, pp.77-81. 10.1016/j.mfglet.2020.03.015 . hal-03367233

HAL Id: hal-03367233

<https://uphf.hal.science/hal-03367233v1>

Submitted on 3 Jul 2024

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The concept of “safety bubble” for reconfigurable assembly systems

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a b s t r a c t

Keywords:

Reconfigurable manufacturing system
Safety
Collaborative robotics

In the last decade, Reconfigurable Manufacturing Systems (RMS) have been proposed to deal with mass-customization problems and volatile markets. Applied to the field of assembly, this concept gives rise to Reconfigurable Assembly Systems (RAS). The latter are composed of different basic units (e.g., conveyor units, robotized units) linked together. Issues regarding the physical design, scheduling, and control of RAS have been studied intensively but very few studies have addressed safety problems. However, this issue is of primary concern for RAS containing robotized units with frequent interventions of human operators. Indeed, traditional safety approaches fail to take into account the versatility of RAS. In this context, the paper proposes a new way of dealing with safety in RAS with the concept of “safety bubble”. The latter aims to ensure operator safety by sharing safety data between units. An implementation methodology of this safety bubble is presented and on-going developments “off-line” on a multi-agent platform and “on-line” on a real demonstrator are described.

1. Introduction and motivations

To cope with product variety due to mass customization and substantial fluctuations in production volumes, manufacturing systems must continually adapt their production. In [1,2], Koren introduces the concept of Reconfigurable Manufacturing Systems (RMS) to cope with sudden changes in market or regulatory requirements. RMS can adjust their production capacity and functionality within a part family by rapidly changing their structure, as well as hardware and software components.

Reconfigurable Assembly Systems (RAS) [3–6] are a variant of this RMS concept in the field of assembly. As depicted in the example in Fig. 1, a RAS is composed of one or several cells corresponding to a set of basic units (e.g., conveyor units, robotized units) linked together. During the production phase, a fleet of mobile robots can be used to transport products (i.e. work-in-progress) between the different cells.

Numerous studies [6–11] deal with issues relating to the design or control of RMS but very few explore the inherent safety issues [12–14]. However, when dangerous equipment, such as a classical industrial robot, is involved in RAS, dealing with safety issues is crucial to avoid operator injury [15]. Traditional safety approaches (i.e. risk analysis, risk assessment, and risk reduction) must be

implemented for each new configuration of the RAS [16–18]. This requires tedious, time-consuming work by experts and then only a few configurations can be studied and certified as “safe”. In [12,13], safety is clearly a bottleneck in attaining “Plug-and-Produce” systems. Fig. 1 highlights the role of the safety manager who must analyze each new configuration taking into account the standards, directives, and technical knowledge regarding the RAS. Traditional safety approaches fail to take into account the versatility of RAS [14]. To address this issue, [12] identifies challenges for implementing a risk assessment and safety analysis software solution.

This paper details an approach to deal with RAS safety, as well as the associated deployment methodology and on-going developments.

2. Proposition

2.1. The “safety bubble” concept

Before detailing the concept of “safety bubble”, some assumptions are made:

- As illustrated in Fig. 1, each RAS cell is built by coupling three types of units:
 - o “Robotized” units (RU) on which operators intervene occasionally (e.g., maintenance operations, replenishment of components). To maintain good productivity, the aim is

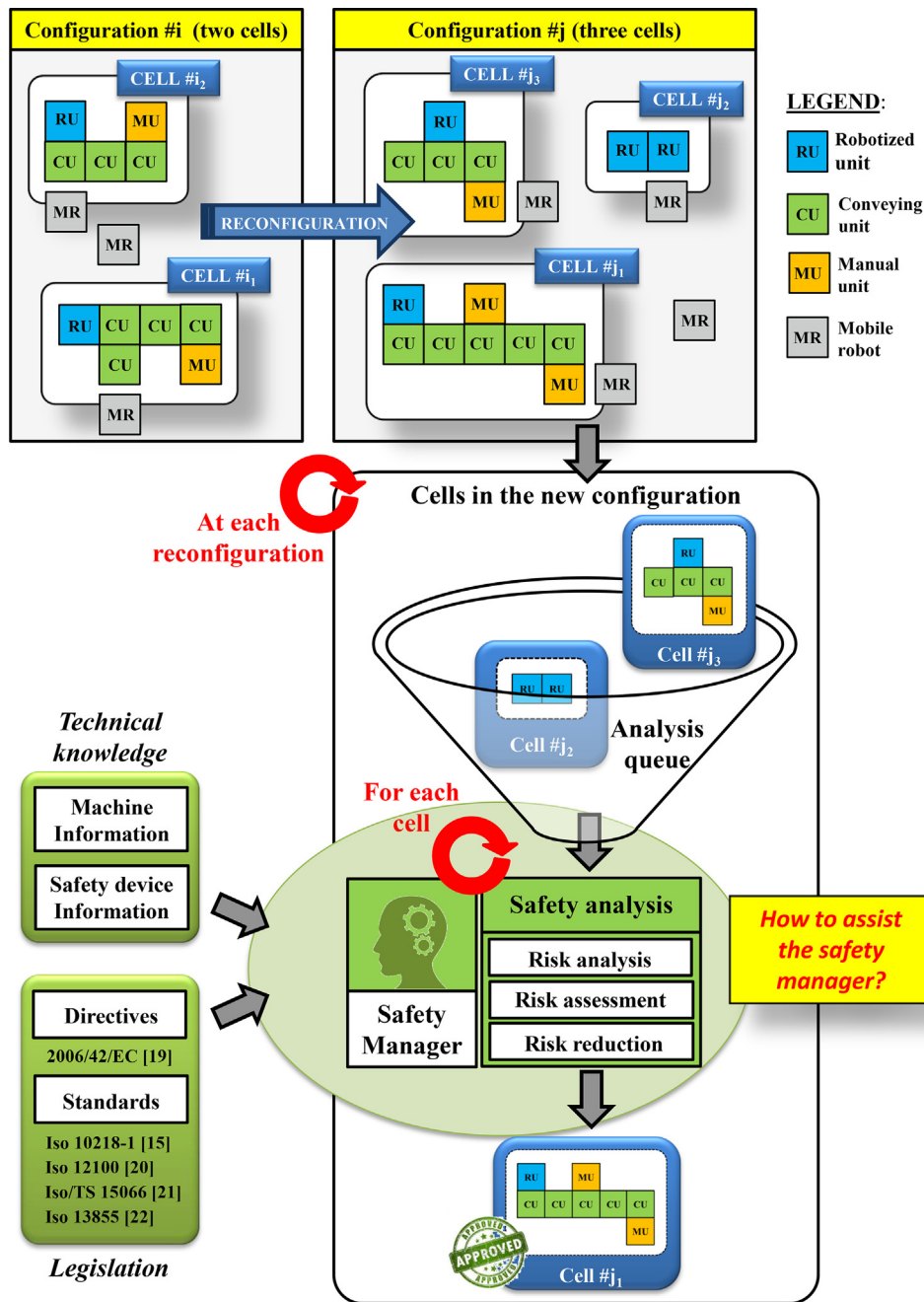


Fig. 1. Illustration of the reconfiguration process and relative safety issues.

- to use classical industrial robots at normal speed. However, each robot must be safeguard stopped when an operator enters the workspace.
- o “Conveying” units (CU), which are in charge of conveying products in a cell.
- o “Manual” units (MU) on which operators work continuously. Other units (e.g., storage, inspection units...) that are harmless can be considered as MU.
- A safety area must be ensured around each RU. To allow easy RAS reconfiguration, safety laser scanners (SLS) must be preferred over some classical perimeter safety devices (e.g., barriers, light curtains) that are difficult to move and reconfigure. As described in Fig. 2, placed on a corner of a unit, an SLS can

- be programmed to detect human intrusions into an area (L-shaped) according to a safety distance (calculated according to ISO 13855 [22]). For each SLS, the data defining the geometry of the safety area are put in a field file.
- In this paper, it is assumed that only RU are equipped with SLS placed on two opposite corners and additional SLS can be placed on the other units if necessary. However, in the future of RMS, it is imaginable that all units can be equipped if the cost of the SLS decreases sufficiently.

The aim of the approach is to assist the safety manager in the implantation of the additional safety devices (i.e. SLS and barriers). The approach exploits safety data sharing between SLS to detect

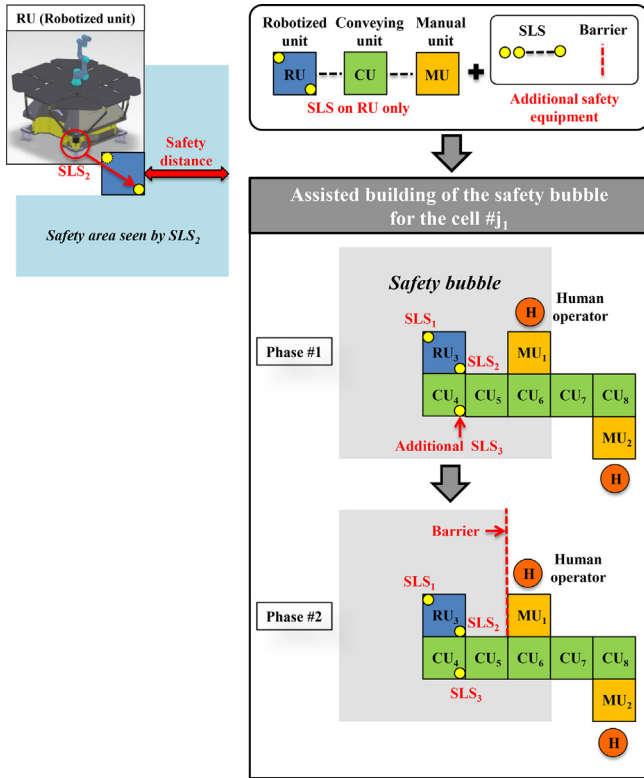


Fig. 2. Assisted building of the “Safety bubble”.

human intrusions into the robotized areas and to build a “safety bubble” around the robots according to a methodology explained in the next section.

2.2. Methodology

The example of cell # j_1 in Fig. 2 is used to illustrate the successive steps of the methodology. As described in Fig. 3, two main phases are proposed.

The “Off-line” phase: four steps are considered in succession.

1/ Preliminary design: the output is a layout of the cell composed of basic units.

2/ Cell layout modeling with a dedicated CAD tool: the output is a CAD model with precise locations of the different units.

3/ Assisted building of the “safety bubble” according to two phases:

- First, an algorithm determines the locations of the additional SLS equipment to ensure the safeguarding of the different RU. In the example in Fig. 2, the conveying units CU_4 and CU_5 obscure SLS_2 on RU_3 . However, an additional SLS_3 can be installed on a corner of CU_4 to offset this deficit. SLS_3 can detect any intrusions into the area in front of CU_4 and CU_5 and sends an alert (safety data) to RU_3 to stop the robot.
- Second, some barriers (which must be installed) are automatically generated between an MU and an RU if a human operator is located closer to the robot than the required safety distance. In the example, a barrier is installed between RU_3 and MU_1 to prevent the operator penetrating directly into the robotized area.
- Third, for each SLS, a field file is automatically generated.

The outputs are a cell layout and a field file for each SLS.

4/ Safety check: a specific algorithm helps the safety manager to verify that all safety criteria standards [19–22] are complied with

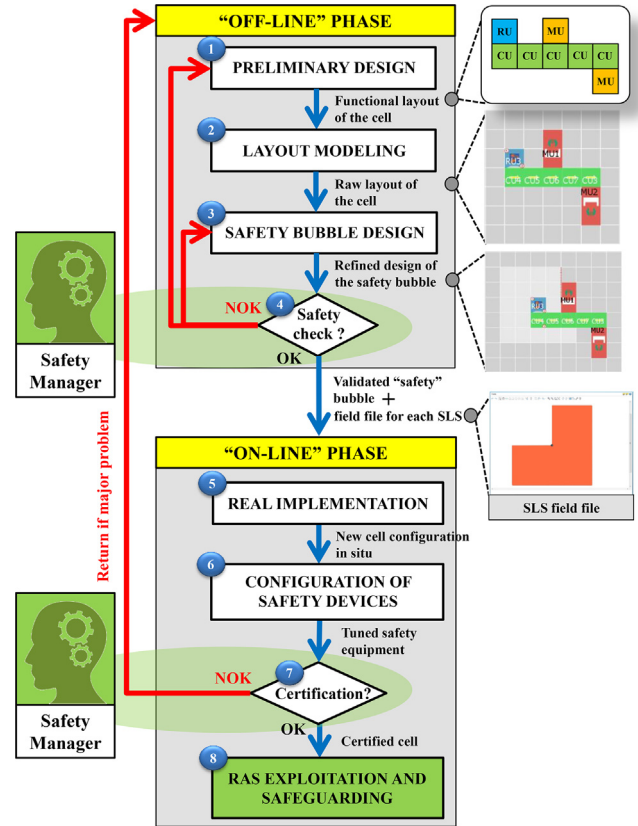


Fig. 3. Illustration of the methodology.

(e.g., regulatory safety distances around each RU). Once the layout is validated, the “on-line” phase can begin.

The “On-line” phase: four steps are considered:

5/ Real implementation of the cell: the units can move autonomously (e.g., CU of the KARIS system [23–24]), or can be moved by human operators. Once placed in their respective locations in the new configuration, the units remain static during the production phase. They are then coupled physically to allow the transfer of products and informationally to allow data sharing by way of a wired safety LAN.

6/ Configuration of safety devices: the SLS are configured according to the field files generated off-line.

7/ Safety certification: classically, the certification of a human safety expert must be obtained before starting production. If the result of this check is not satisfactory, a new configuration of the safety bubble must be generated.

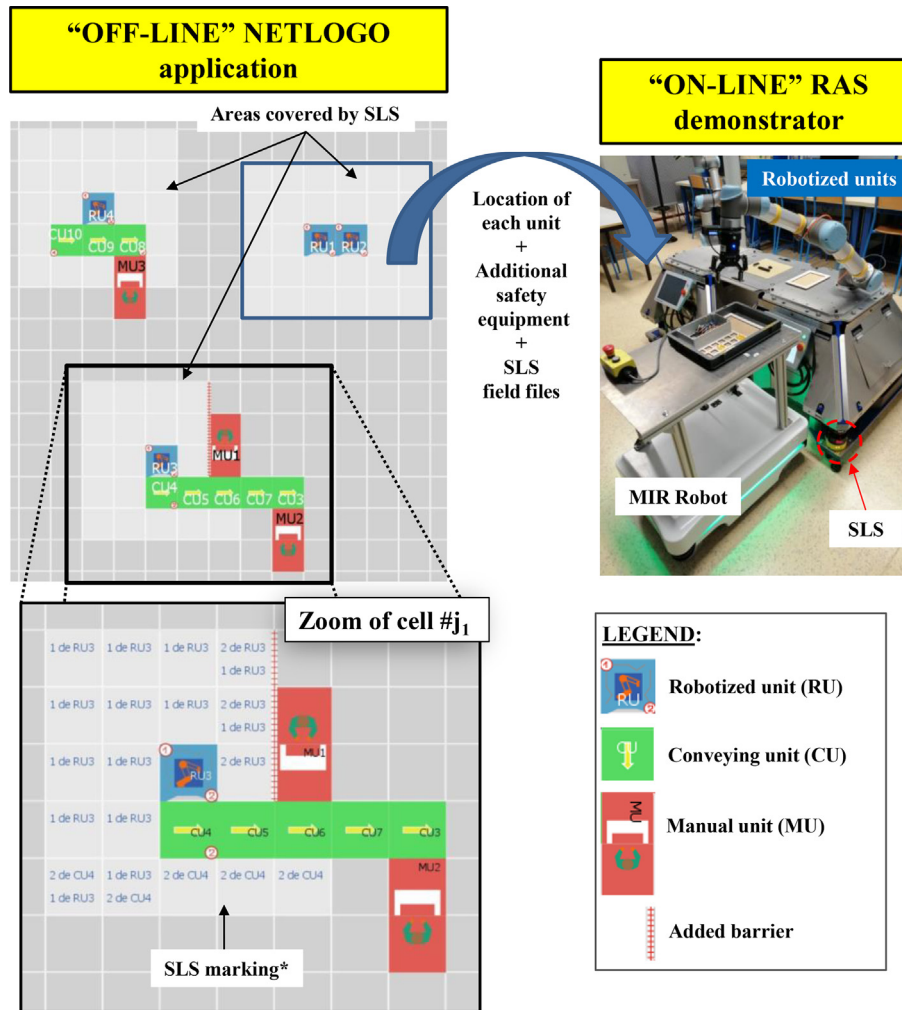
8/ Operational exploitation of the RAS: the various safety devices are operational and share safety data to detect any intrusion into the robotized areas.

In the next section, the on-going developments are presented.

3. On-going developments

The “off-line” phase is currently supported by a software application based on the multi-agent Netlogo platform [25]. Netlogo proposes adequate tools to support cooperation between agents and to tag their environment. The latter characteristic is particularly appropriate for modeling safety areas.

In accordance with the second and third steps of the “off-line” phase, the safety bubble can be built automatically. As described



* Each square of an area covered is “tagged” by the identifier of the associated SLS. Due to the possible redundant coverage of the SLS, there may potentially be several identifiers per square.

Fig. 4. Illustration of current developments.

in the screenshot in Fig. 4 (left part), once the agents representative of the different units are positioned on a grid, the application can:

- first, determine the adequate locations of the additional SLS to secure the RU,
- second, add some barriers between RU and MU, if required,
- third, generate the field files of the SLS.

During the fourth step, dedicated to the safety check, the map of all the squares in the robotized area (in gray in Fig. 2) is analyzed. If all the squares are tagged with SLS identifiers or placed behind a barrier, the safety check is successful.

In our laboratory, a RAS demonstrator is currently under development and must be seen as a proof-of-concept for RAS safety. As depicted in Fig. 4 (right part), a cell was built with Universal UR5 and UR3 robots mounted on mobile platforms. The latter are equipped with two Sick microScan3 SLS installed on opposite corners. When the two mobile platforms are connected together, the four SLS are tuned according to the field files generated during the “off-line” phase. Safety data sharing is based on Ethernet-CIP-Safety. MiR100 mobile robots are used to convey products between cells.

The demonstrator is dedicated to small-size product assembly applications (e.g., electronics or micromechanical systems) but

the principle is relevant to other fields of application (e.g., automotive, aerospace industry [26–28]).

4. Conclusion

To address the inadequacy of traditional approaches dealing with safety issues in RAS, this paper has proposed the concept of “safety bubble”. The latter relies on sharing safety data between units to detect any human intrusion into the robotized areas. A deployment methodology has also been proposed.

The developments, conducted on a multi-agent platform, have demonstrated the validity of the proposal for the “off-line” phase. Work on an “on-line” RAS demonstrator is ongoing to check the practical feasibility.

In the short term, the aim is to definitively validate the “off-line” phase of the methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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