On the Proposal of a Unified Safety Framework for Industry 4.0 Multi-Robot Scenario (DISCUSSION PAPER)

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Abstract. Within the context of Industry 4.0, the presence of robotic systems inside the production plant is increasing, thus leading to the need for appropriate safety rules enhancing human-robot interaction. However, without a systematic approach, mapping all the possible scenarios becomes critical. This paper aims at laying the foundations for a unified safety-based semantic approach in cooperative multi-robot industrial environments. The objective of this study is to investigate an approach to organize, store and re-use construction safety knowledge by means of defining a new ontology and the construction of rules for safety application.

1 Introduction

The Industry 4.0 paradigm is driving the innovation of manufacturing and production processes [6] and robotics is a key element enabling such epochal change [11]. The increasing use of robotic systems in industries is enhancing human-robot interaction (*i.e.*, HRI) [13]. Safety is becoming a critical issue since humans and robots interact while sharing working space and tasks. Indeed, standards have already been developed to regulate safety (ISO 20218 [5]). On the basis of such standards, many works investigate the definition of safety algorithms and rules for very specific use-cases, such as for the design of industrial work-cells, physical human-robot interaction for the execution of cooperative applications, etc. However, even if safety rules can be found in the standards, their application is still not straightforward in real industrial environments and no contribution

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to a unified safety framework has been proposed to address the complexity of a production plant (*i.e.*, the set of robots, sensors, human workers, tasks, tools and obstacles).

The lack of knowledge related to the tool in use by the robot while cooperating with a human operator may result in unpredictable accidents (*e.g.*, in the case the robot is manipulating a bulky and heavy part with a mechanical gripper while cooperating with a human operator such information is important to define workspace limitations, velocity etc.). Since in common industrial applications such knowledge is not yet available, robots are used under their achievable performance (in order to always ensure safety), resulting in decreasing production capabilities. The combination of the Semantic Web technologies and ontologies (that define concepts of a certain domain and relations between them) can enable such knowledge.

The aim of this paper is to fill this gap and present an initial work toward a unified knowledge framework for the definition of safety rules in production environments by using semantic technologies. Our contributions can be summarized as follows: (i) definition of a framework for the specific case of safety rules; (ii) development of an ontology to describe concepts of the working space; (iii) case study related to a cooperative installation task.

This paper is organized as follows: the application scenarios are introduced in Section 2 while the state-of-the-art is presented in Section 3. The proposed framework is described in Section 4 while conclusions end the paper in Section 5.

2 Application Scenarios

More and more industries are embracing innovation on the process of assembly of their products by means of advanced human-robot collaborative solutions, *i.e.*, i) a Lightweight Mobile Arm (LMA) to perform autonomous transportation of the parts and installation tasks, ii) an empowering robot to perform installation tasks, iii) a sensing solution for cluttered environments to identify human workers inside the working scene.

Considering such multi-robot environment, the definition of a unified safety framework is mandatory. We define three scenarios related to the multi-robot collaborative environment.

Scenario 1 - Exoskeleton Empowering Human Worker: exoskeletons are used to relieve humans from heavy tasks, physically connected to the worker.

Scenario 2 - Empowering Robot for Cooperative Installation Task: the empowering robot is used to install bulky/heavy components (hatracks). Such manipulator, equipped with a force sensor, a mechanical gripper and a vision system (to track humans) is physically interacting with the human operator.

Scenario 3 - LMA for Autonomous Installation Task: the LMA is used to autonomously install medium-size components (e.g., side-wall panels). Such manipulator, equipped with a force sensor, a mechanical gripper and with a vision system (to track humans) should not interact with humans for this task.

3 Related Work

A plethora of EU-funded project have investigated and are currently investigating safety issues at different levels (physical interaction, workspace design, etc.). In the Saphari project[1], collision avoidance and prevention algorithms have been developed to activate collaboration by using human gestures and voice commands [3]. This safety control framework was tested on the lightweight robot LWR-IV, from KUKA [3]. The H2020 COVR project [2] investigates the development of an intuitive toolkit and a range of testing protocols for the validation of safety for cobots.

Standards (e.g. ISO 20218:2011 [5]) have been defined to regulate human-robot collaborative modalities in industrial plants. EU-funded projects[3][4][5], together with dedicated research activities [2, 7], have enhanced such developments. Although many works can be found in the state of the art covering safety related topics, only few contributions are devoted to define a unified safety framework [8, 10]. To overcome such limitation in the industrial context, some works are exploiting safety representations applying semantic technologies, *i.e.*, representing safety as an ontology that includes the main concepts of the safety standard and the relationships between the concepts. Applying these concepts, some works have used this representation format in order to exploit semantic technology capabilities for safety assurance and certification. The application of semantic technologies to improve the safety in working environments, *e.g.*, by developing ontologies that represent safety concepts and the relation between them, have been studied in [4]. Specifically for Industry 4.0, the authors in [1] present a method to design new instances of collaborative cells, by taking into account the ISO 15066 and extending the CORA (Core Ontologies for Robotics and Automation) ontology. However, this work is limited to specific cooperative work-cells and it does not take into account the complete and complex production plant environment. The work [12] proposes to integrate task-level planning with semantically represented workplace safety rules, but only a specific application is considered. The authors of [15] address how an Artificial Intelligence technique like Answer Set Programming (ASP) can be applied to support the planning of mobile robot, while explicitly modeling rigid knowledge time-dependent internal knowledge, time-dependent external knowledge, and action knowledge. However, from the analysis of the state-of-the-art, at the best of our knowledge, no contribution has been proposed to define a unified safety framework considering the whole production process involving human-robot cooperation.

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[1] `http://www.saphari.eu/`

[2] `http://safearoundrobots.com/getcovr`

[3] `http://safearoundrobots.com/getcovr`

[4] `http://www.saphari.eu/`

[5] `http://www.xact-project.eu/`

4 Proposed Approach

The integration of heterogeneous knowledge is required to ensure safety. For instance, the combination of data coming from sensors and from the environment where the robot is operating enables to understand the context where the robot is working, consequently defining appropriate behaviors and safety rules. However, safety depends also on the specific task assigned to the robot and to the tools that the robot is exploiting. This paper proposes a unified robot knowledge approach that considers knowledge coming from sensory data together with context information. Taking inspiration from [8], we introduce an ontology (to conceptualize the environment where the robot is working and formalize the knowledge accessible to the robot in terms of logical rules) with a novel focus on the preservation of safety in the production plant. Robot's knowledge for safety is enhanced by using data coming from sensors with knowledge from reasoning. The framework on top of such approach is shown in Figure 1. Such operation is bidirectional thus enabling to learn from previous situations and taking advantage for further decisions.

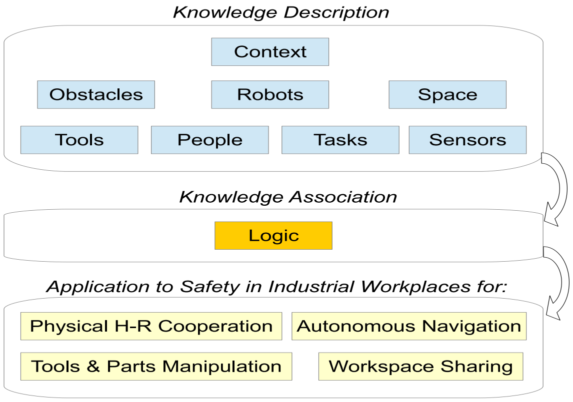

Fig. 1. Unifying framework for safety rules.

4.1 Knowledge Description

A taxonomy provides an ontological structure for human understanding, defining the arrangement of things of interest in a hierarchical structure. Figure 2 shows the taxonomy proposed within a scenario where human and robot should collaborate. This hierarchy takes inspiration from the ifcOWL ontology [9], *i.e.*, the Web Ontology Language (OWL) version of the Industry Foundation Classes (IFC) standard, a widespread open model for the information exchange of Building Information Modeling (BIM) data. Such description allows therefore to define axioms, aiming at identifying the specific cases and the related safety rules for a safe human-robot cooperation inside the production environment. In such taxonomy we unify knowledge from context, obstacles, robots, space, tools, people, sensors and tasks to enhance safety for physical human-robot interaction, workspace sharing, autonomous navigation, tools and parts manipulation. The considered working scenario can be modeled using the following key classes:

- `Object`: a generic tangible (*e.g.*, physical product) or intangible item (*e.g.*, process) that is used to define the global spatial/temporal scenario of the human-robot collaboration (cf. class `IfcObject` in ifcOWL);
- `Person`: defining the human operators that can present in the robot working space (cf. class `IfcActor` in ifcOWL);
- `Task`: defining the actions that the robot/human can perform (*e.g.*, manipulation tasks, assembly tasks, etc.) (cf. class `IfcTask` in ifcOWL);
- `Product`: any object that relates to a geometric or spatial context (cf. class `IfcProduct` in ifcOWL);
- `SpatialElement`: any spatial element that might be used to define a spatial structure or a spatial zones (cf. class `IfcSpatialElement` in ifcOWL);
- `Space`: defining the specific location where the robot is working, *e.g.* assembly lines, storage, corridor, etc. (cf. class `IfcSpace` in ifcOWL);
- `Element`: physically existent object that can be characterized by a placement and 3D representation (cf. class `IfcElement` in ifcOWL).
- `BuildingElement`: any type of static element that may be an obstacle for the robot, *e.g.*, walls, doors, etc. (cf. class `IfcBuildingElement` in ifcOWL);
- `Robot`: defining the robotic systems working inside the production plant, *e.g.* mobile platforms, lightweight manipulators, exoskeletons, etc.;
- `Tool`: defining the specific tool in use to the robot to perform the specific task, *e.g.* mechanical gripper, screwer, etc.;
- `Sensor`: defining different external sensors that the robot can use to perceive the environment, *e.g.* vision systems, force sensors, etc. (cf. class `IfcSensor` in ifcOWL, class `sosa:Sensor` in SSN/SOSA ontology [14]).

The workspace is modeled by tools, the space where they are located and the context where they are used. In fact, a tool can be recognized not only by its characteristics such as shape, size, material, but also by the spatial context where it is located. Moreover, the knowledge of the robots, the sensors, the obstacles and the human operators inside the working scenario and the allocated tasks to the robots are fundamental to model the working scene. Such ontology definition can therefore be applied to the human-robot cooperation in industrial environments, where physical and non-physical cooperation is required.

4.2 Knowledge Association

Knowledge association creates and describes the relationship between ontology classes and properties by means of axioms. Logical inference can be exploited to automatically generate new knowledge starting from generic axioms and specific instances. Such framework enables robot to perceive the environment and the

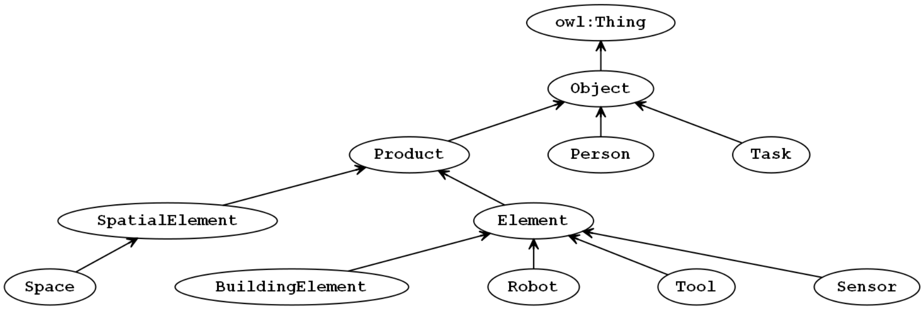

Fig. 2. Taxonomy of the working environment.

context where it is performing in such a way that is easy to avoid obstacles, collisions and to process knowledge coming from other sensors and humans. The axioms are defined using Description Logic (DL) and can be applied also to verify that data are compliant with the ontology schema. Logic representations are defined to identify the specific working scene in which the robot is operating and to consequently define the related safety rules from the standards. Since in the scope of OWL reasoning is monotonic because of the Open World Assumption, the exploitation of other non-monotonic logic languages (*e.g.*, ASP) will be taken in consideration to support the application scenarios.

4.3 Application to Safety

As an example, we describe the three scenarios as in Section 2 and describe the logic representations for defining safety rules for *Scenario 2* in Section 2.

Scenario 1 - Exoskeleton Empowering Human Worker: On the basis of the exoskeleton internal sensors information (*e.g.*, encoders, torque sensors, etc.) it is possible to identify safety-critical situations (such as critical human postures). Moreover, on the basis of the knowledge of the executed task and involved tools, it is possible to on-line check for safety rules to be applied during the task execution.

Scenario 2 - Empowering Robot for Cooperative Installation Task: the complete working scene can be defined having the information related to the tool of the robot, the knowledge about the human operator motion and the safety features implemented by the robot. The related safety rules can be then identified and applied. The examples described by Algorithms 1 and 2 can be exploited, considering the physical HRI installation scenario. Algorithm 1 is considering the use of a safe tool, while Algorithm 2 is considering the use of a non-safe tool. The two proposed scenarios have to apply different safety rules since in the second case the non-safe tool introduces higher safety risks.

Algorithm 1 Scenario 2 - Physical Human-Robot Cooperation with Safe Tool

```
if  Robot in Installation Area &&
    Physical Human-Robot Cooperation Task for Installation &&
    Force Sensor for Human-Robot Cooperation &&
    Safe Tool &&
    Human Operator Tracked by Camera Sensor &&
    Low-Level Safety Emergency Stop then
Apply Safety Rule for Physical HRI Considering Safe Tool and Low-Level Safe Stop Features
```

Algorithm 2 Scenario 2 - Physical Human-Robot Cooperation with Safe Tool

```
if  Robot in Installation Area &&
    Physical Human-Robot Cooperation Task for Installation &&
    Force Sensor for Human-Robot Cooperation &&
    Non-Safe Tool &&
    Human Operator Tracked by Camera Sensor &&
    Low-Level Safety Emergency Stop then
Apply Safety Rule for Physical HRI Considering Non-Safe Tool and Low-Level Safety Stop Features
```

Scenario 3 - Autonomous Installation Task Performed by Lightweight Manipulator Since the target application is supposed to be autonomous, no physical interaction between the robot and human operators should be established during the task execution. However, the human operator may enter the working area of the manipulator. Therefore, one of the key topic defining the safety rules to be applied in such a case is related to the possibility to track the human motion. The complete working scene can be defined having the information related to the tool in use by the robot, the knowledge about the human operator position and the safety features implemented by the robot. In such a way, the related safety rules can be identified and applied.

5 Conclusions

In this paper a unified safety framework for the Industry 4.0 environment is proposed, including (i) the definition of the framework, (ii) the development of an ontology to describe concepts of the working space, and (iii) the definition of safety rules based on the use cases are proposed. A safety application is detailed to described the adopted approach, for assembly of heavy products in industry. The proposed ontology will be further developed, by integrating existing ontology modules and making extension in the human-robot collaboration context.

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