Proceedings of the 2018 IEEE International
Conference on Intelligence and Safety for Robotics
Shenyang, China, August 24-27, 2018

Safe Human-Robot-Interaction in Highly Flexible Warehouses using Augmented Reality and Heterogenous Fleet Management System

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***Abstract*— Nowadays, production systems and warehouses still lack human-robot collaboration. Often due to safety issues robots are kept behind safety fences and the overall system is shutdown once a human enters. This paper is based on a new concept to overcome these issues. It consists of a safety concept which ensures a more efficient human-robot collaboration. The human worker can be localized via a safety vest which he/she wears and the nearby robots are also aware of this information. We propose a more efficient and safe overall system by using an Augmented Reality device which offers a simple interface between humans and robots and a Heterogeneous Fleet Management System which plans and provides collision-free paths for humans and robots and ensures that the resulting environment is safe for both robots and humans.**

I. INTRODUCTION

Safety is a vital factor for operation in automated warehouses. Especially when humans and robots share the same workspace and collaborate, all safety aspects have to be analyzed in detail [1]. One way to deal with it is to use costly safety scanners for each (mobile) robot to guarantee no collision encounters between humans and robots. This increases the overall costs of the system. Another far easier way to guarantee safety is to separate the robots and humans completely from one another by using sophisticated safety methods e.g. solid or light fences as well as laser barriers around the working area of the robots. Each time the safety barrier is crossed by a human, parts of the system or the complete system will be shut down. Therefore, the downtime of the system increases which leads to higher process cycle costs. To overcome this inefficiency the separation between robots and humans needs to be prevented [2]. For creating a collaborative working environment, humans and robots have to be able to share the same workspace and move around freely. Therefore, path planning algorithms as well as frameworks which consider the movement of the robots as well as the behavior of the human have to be developed [3].

There exist a variety of solutions ([4], [5], [6] and [7]) in which the robots are equipped with sensors e.g. laser scanners to perceive their environment. They can localize nearby humans and try to predict the behavior and movement of the human. Those solutions are limited. Only the robot knows about the position of the human and not vice versa. Therefore, unforeseen appearances of robots can lead to a reduced acceptance of the human towards robots. Sysbot et al. [8] has proposed a planner which tries to overcome this problem by on the one hand taking into account the comfort and expectations of humans that may be near a robot when planning the paths of the robot. On the other hand the planner ensures that there is always a safe distance between robot and human and tries to keep the robot in the field of view of the human to increase the acceptance.

Our approach ensures that robots as well as humans are aware of one another in an automated warehouse. Baesed on the safety concept introduced by the Safelog consortium, we propose the use of Augmented Reality (AR) device which assists the human during his tasks and informs him about nearby robots and a heterogeneous fleet manager which plans a collision-free path for robots as well as humans. In this way humans and cyber-physical systems (CPS) [2] are able to work together as partners.

II. BACKGROUND

A. Existing Safety Concepts

Robots have been used extensively in manufacturing and warehousing industries alongside human workers for the last few decades. In the work done by Khalid et al. [2], he proposed requirements for safety in collaborative environments for humans and robots. According to his work human-robot-interaction can be classified into four main categories. This classification is based on the distance between the two entities, workspace sharing level and the complexity of collaborative tasks, which both are doing mutually. In the first level, guidance is provided manually or at reduced robot speed. This is only suitable for small robots. The second level uses sensors and robots operate in the human-free space. If there is human intervention, the robots will stop. For level three, ranging technologies are used to monitor safe distance between human and robot. For the last level, vision is used to keep the robot informed about the presence of humans. Force sensors are used to guide the speed of the vehicle. An overview of this framework is described in Table 1, depicting the aims pursued by the safety systems, hardware and software systems that are deployed, devices that are used, and the actions involved in each type of safety system.

*This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 688117 (SafeLog).

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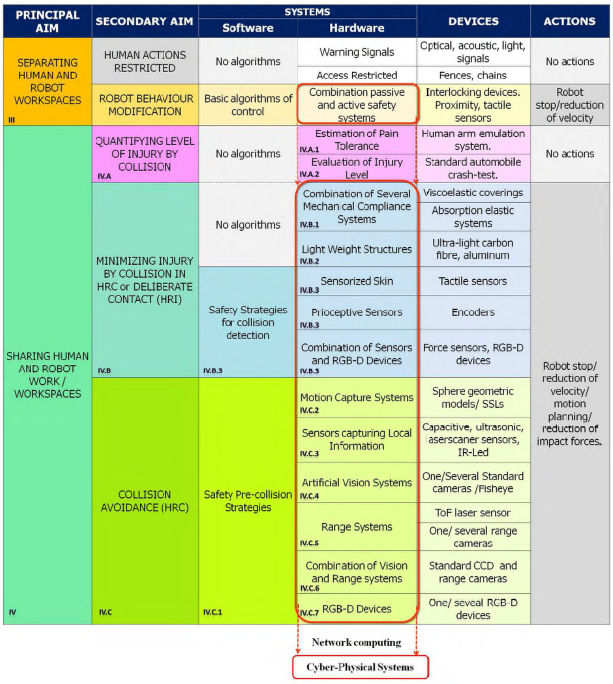

Fig. 1. Safety Framework after Khalid et al. [2]

B. Coordination of Robots

The coordination of robots in logistic environments has special requirements and constraints related to the used routing algorithms and data representations. In almost all cases, current routing algorithms do not focus these requirements or are not able to integrate these due to inappropriate data representations. Special requirements for routing algorithms e.g. are routing of multiple robots to the same destination, handling of blocking robots that may lead to a deadlock situation, creation of order sequencing, managing heterogeneous robot fleets. The handling of scalability and performance when the number of robots is increased is also a crucial issue. Especially in the latter case, a decentralized approach can help to fulfill these requirements.

As mentioned before, requirements to the routing appear on the one side, on the other side the data representation of the logistic environment is a key factor. Special traffic regulations, like restricted driving directions (e.g. one way roads), or critical traffic situations, like narrow lanes, have to be mapped into the graph or data representation of the routing algorithm. It is also necessary to depict vehicle positions and the positions of objects such as relocatable storage areas as a logistical environment is in a state of constant changes, whereby all of these possible changes and requirements must be continuously updated in the data representation of the routing algorithm. Traditional graphs or maps that are used within most routing algorithms do not fulfill these requirements. In this case these graphs or maps have to be extended with additional attributes. E.g. existing ones can be converted to multi-dimensional layer representations of the environment, an early basic approach can be found in [9]. Hence all improvements have to be considered by the applied routing algorithms described in the following paragraphs.

A first approach that can cope with the management of a heterogeneous fleet of robots was developed by Purwin [20]. There, a classical prioritized planning algorithm was adopted into a decentralized one. The basic idea is that every path of a robot is surrounded by a geometrical bounding box, whereby all movements of the robot are performed inside this box. Bounding boxes are shared among all robots and checked for collisions with the local bounding box of the current path. Direct communication between the involved robots is used for resolving collisions. One more advantage of this approach is that different routing techniques for individual robots can be used.

Another decentralized path-planning approach, known as "Cooperative Dynamic Algorithm", is described in the PhD Thesis of Regele [9]. It is based on a broadcast exchange of messages between the participants, which is used for a dynamic and coordinated path planning of each vehicle. The major advantage is that this algorithm is completely decentralized hence it is highly scalable. It uses two different maps as an environmental model: firstly a distance map that describes the static environment, and secondly a local environment map that represents dynamic obstacles like robots and the local path. The local environment map is a discrete representation of a short area around the robot, which means that this particular area is divided into cells with an occupancy at a specific time slot. Local environment maps are shared among all robots. In case of two overlapping local environment maps, the robots start checking whether a collision exists or not. Occurring collisions are solved by direct communication between the robots.

Approaches that are able to handle the blocking robots problem are described in [11] and [12]. In this case a distinction must be made between two types of blocking: the first type of blocking is one where a robot runs out of tasks and remains on its position. Solutions to this type of blocking can be found in the Push and Rotate algorithm [12]. This algorithm operates on an undirected graph-based topology, which needs to have at least two unoccupied vertices and one node with at least three edges. This restriction ensures that the application of an exchange between two agents can be performed. The algorithm applies a sequential planning for each agent. The key strategy is based on repression of agents which blocks the path of the planning agent. Hence blocking agents will be moved away temporary.

The second type of blocking occurs if multiple robots try to route to the same destination. In a logistics context, a typical example is the routing to a picking station. Such situations can be handled by prioritized planning approaches like CARP [11]. CARP is a time window based routing approach, which operates on directed graphs. The calculated routes can be defined as $\pi_i = ([r_1, \tau_1], \ldots, [r_n, \tau_n]), \tau_i = [t_i, t_i')$ whereby r_i is a node of the resource graph and r_i is a time window that indicates that resource r_i is available from time t_i to t_i'. Within the routing, paths are planned sequentially. Previously planned paths will be reconsidered during the current path calculation process. Every node of the graph has its own time windows, defining whether the node is accessible or not. For planning conflict-free routes, overlapping time windows between the individual nodes of a route are required, in a way that $\tau \cap \tau' \neq \emptyset$.

C. Human-Robot-Interaction

Human-robot-interaction (HRI) is often described as a sub discipline of human-computer-interaction or human-machine-interaction, dealing with the encounter between human and robots. Regardless of the role of the human and the autonomy of the robot, some type of interaction takes place [13]. Based on existing classification approaches for HRI Onnasch, Maier and Jürgensohn have developed a taxonomy for HRI which divides HRI depending on the role of the human, the form of interaction, the autonomy of the robot and other criteria [14]. The term interaction itself is used in a huge variety of meaning. Meads [15] defines it in his theory of interactionism as a correlated action between two or more individuals. Messages and meaning are transmitted via symbols which have to be interpreted at the receiver's side. Without interaction neither society, nor culture or identity can emerge. Therefore, HRI can be defined as the mutual interpretation process of humans and robots. When it comes to any form of encounter between humans and robots several safety issues have to be considered [16]. To obtain an effective interaction the human has to accept the robot he or she is working with and therefore, further aspects e.g. social and cognitive have to be taken into account [17]. Social rules do not only exist between humans they can be also recognized regarding the interaction with humans and computers and further might be applicable to robots [18]. For example while developing mobile robots the movement behavior has to be adapted to Hall's [19] proxemics. They define the distances human keep towards one another depending on the degree of familiarity. Further on, regarding the design of the interaction interface one has to consider the perception process of the human. For transmitting information the visual perception is mainly used [20]. Therefore, robots should offer visual forms of interaction with the human.

III. CONCEPT

A. Safety Concept

This paper is based on an integrated safety concept created as a part of the Safelog project. Not only does it provide safety for humans but changes the use of mobile robots in co-working spaces. The core of this method is a three-layered safety system which, guides, warns or stops robots as needed. The outermost layer is called Level C and tries to prevent any encounters between robots and the humans. This is done with the help of optimal routing algorithms implemented at the Fleet management System (FMS). The middle layer, or Level B warns humans and robots about a possible encounter that could not be prevented by Level C. On the one hand, human is made aware of the robot presence using the Augmented Reality device view. On the other hand, the robot is guided to move away from the human by the FMS. Ultimately Level A being the safety critical layer shuts down the robot if it breaches the safety distance to the human. The safety distance is calculated based on the speed and acceleration of the robot, the speed of the human and localization error. This level is realized as a virtual circle around the human. There are no movements allowed within this circle. This ensures the intrinsic safety of the overall system.

Fig. 2. SafeLog Safety Concept

This safety architecture is implemented with the help of a Safety Vest which is worn by all humans in the co-working space. The Safety Vest as well as the robots are equipped with radio based ranging technology that calculates the distance between the human and the robots. The safety vest is also capable of self-localization with the help of optical sensors mounted on it. The proposed method is depicted in Fig. 2. Upcoming papers from the Safelog consortium will have more details about the safety concept. In this paper we emphasize on how the use of AR and Fleet Management System in warehouses can introduce a safe environment for humans and robots.

B. Heterogeneous Fleet Management System

The main target of the heterogeneous fleet management system is to involve the human into the planning and coordination of paths. This is important to ensure a safe coexistence of humans and machines which operate together in the same environment. To ensure this, the path planner will always try to avoid crossing paths or blockings between humans and robots. To achieve this, a planned human path will always have a higher priority than a robot path. This is important because the behavior of humans is non-deterministic. Therefore, path instructions by the system must be handled as a recommendation for humans and not as commands as it is the case for robots. Hence, planned paths for humans can directly affect planned paths for robots in a way that a robot path must be replanned. For ensuring a smooth coexistence of humans and robots, the safety levels of human beings in the logistics environment are always considered during calculation of new paths.

To establish a flexible and scalable path planning architecture, a new routing architecture will be presented, where an agent based approach will be introduced. The chosen

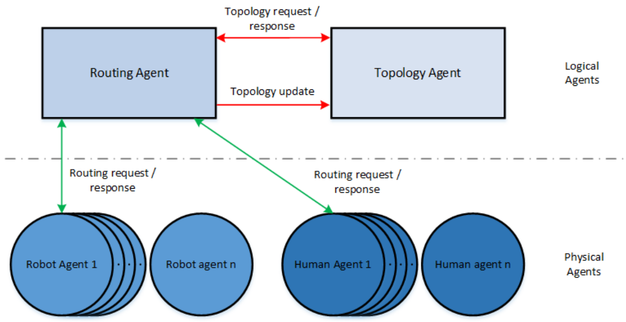

Fig. 3. Communication between logical and physical agents

design provides possibility of a simple decentralization as well as reduction of the complexity of the routing algorithm by division into different agents. The presented approach consists of two different types of agents: logical agents that represent a software component which reacts to its environmental influences. Based on the perceived influences, the agent acts autonomously within its own behaviors and tries to reach its predefined goals. Routing agents and topology agents are examples for this agent type.

A physical agent is a human agent or extends a logical agent by a technical component or a connection to an external control unit, e.g. might be represented by a robotic agent or AGV. Fig. 3 shows how the different types of agents interact. Their interaction is described in the following paragraphs.

The major task of the routing agent is to compute routes that are requested by the physical agents. For that reason, a routing service is offered to physical agents. Beside the route calculation, another key feature is the route management, whereby previous planned routes have to be adopted in the topology and made retrievable for new route calculations. The basis of the route calculation is a topology, managed by the topology agent.

A physical agent is directly related to a robot or human entity. Therefore, a physical agent consists of information about its type (robot or human entity) a set of attributes, e.g. footprint, carry capabilities, current position, etc. The physical agent also contains special behaviors like translating calculated routes from a routing agent into driving or walking commands, receiving travel destinations from other agents and providing current status for other agents. In case of a human being representation, if a deviation from the planned path is detected, replanning for the human will directly be performed.

The topology agent depicts the current representation of the logistics environment in a topology. This topology is offered to other agents, for example to the routing agent. In the case where a new route is calculated, the topology will be updated. Hence, the topology is already up to date in a way that all movements of robots and humans and positions of physical agents and objects are stored. The representation of the topology is in a form like an extended graph or multi-dimensional map as mentioned in section II B.

C. *Human-Robot-Interaction using AR*

The growing complexity of machines, robots and technical systems in production and logistics systems demands the design and implementation of new intuitive and natural ways of interaction between machines and human workers. These new forms of human robot interaction integrate CPS and humans in socio-technical systems [1], where robots adapt to human workers in addition to enable safely working together with each other. This solution is mainly driven by providing context-based information in multi-modal ways for the worker [21].

Cognitive processes of the humans are replaced by easy comprehensive perceptive processes [22]. One solution to achieve this is to provide interfaces that use AR as proposed in this concept. Although different senses can be augmented, the visual sense with the highest information flow of all senses is the most important one [20]. Nevertheless, sounds e.g. for warning can be used if the background sound in the working environment is very low. While using AR the virtual context-based information is transported to the human by overlaying the information in the perceived real world environment. Smart glasses are used to enable this method and visually show information in a perspectively correct projection over real world objects of interest. Thus, purposeful interaction is possible and cognitive overload can be avoided when working in processes like picking, navigating and maintenance.

As an example, the picking process can be improved by the use of AR on smart glasses. This is a prime example, since the worker has to act hands-free for performance purposes. Parts of the conventional process, like the presentation of warehouse management system (WMS) provided order picking lists, are extended in a simple way. The object to pick is shown as virtual representation, the directions to shelves and racks are highlighted as routing instructions and sufficiently supported by the glasses built-in inertial measurement unit (IMU) that is able to track the head movement of the person. Including information of localization systems, it is possible to route the user through the warehouse to the destination and virtually point at items to pick. On the way, paths of crossing robots, even if they are not in the view field, are drawn on the screen and users are aware of path interfering robots. This can help to avoid collisions and also to stabilize process flow. Since the FMS is calculating routes and positions of all participants - robots and humans - new routes in case of irregularities are computed and deployed the respective actors.

For the reduction of stress and implementation of a sufficient human robot collaboration, the proposed concept focuses on the human awareness of robots. Especially in warehouses with robots hidden underneath or behind racks, the stress level of human workers may rise due to fast moving objects, which the worker is not able to see or does not know neither their goal position nor their trajectories. By the use of AR, information about these robots can be displayed directly on the wearable of the worker. While he moves through the warehouse close to robots, their trajectories will be shown in the view field. The trade-off between information overload and insecurity of the worker due to unnoticed closely moving robots is achieved by displaying only information of nearby hidden robots and alarming the human about robots in respect to Safety Level C.

Finally, a service technician can be integrated better into the environment using the benefits of AR. Similar to the picker, the service technician will be guided through the warehouse to a defective robot or any other faulty machine. The same information regarding the awareness of robots in Safety Level C is shown on his wearable. In addition, he will be guided through maintenance and repairing tasks. Textual information as well as images and 3D models are directly displayed on the real robot as an overlay. In this way, screws to be removed can be indicated by virtual screwdrivers pointing at these. On the one hand, this allows easily changing the maintenance and repairing processes on the fly and stable processes can be guaranteed. On the other hand, workers with less experience can be guided adequately through the processes and new tasks can be learned more effectively. This can finally raise the overall equipment effectiveness.

IV. CONCLUSION

In this paper we have proposed a system which addresses safety issues in a workspace which humans and robots share. Since the robots are aware of the humans position in the warehouse, only the robots close by have to reduce their speed or stop. Therefore, the downtime of the overall systems is greatly reduced which leads to a more effective production process. This combined with the AR device can strengthen the acceptance of the human towards the robots. With the AR device he/she is always aware of the nearby robots and their movements even if the robots are hidden from plain sight, for example robots that move under the racks. This ensures the safety feeling of the human and also the intrinsic safety of the system. Furthermore, the Heterogeneous Fleet Manager ensures fewer encounters between human and robots and an efficient overall system with optimal process cycle costs. This work is the first prototype of the concept and is still under research. The described system is one step towards a social networked industry in which humans and robots will work together and the different skill-sets of each entity can be used in an optimal way.

ACKNOWLEDGMENT

The authors especially thank the consortium of SafeLog for the support and great work for the recent achievements. Further information about the Safelog project and the consortium partners is available on the project website at `http://safelog-project.eu/`.

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