Give me a hand -

The Potential of Mobile Assistive Robots in Automotive Logistics and Assembly Applications

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***Abstract*—This paper gives an outlook on the potential use of mobile assistive robots in automotive logistics and assembly applications. Motivated by the rising mass customization and the high demand of flexibility in car assembly, the potential of robotic co-workers is analyzed including the proposition of a technical specification. Among the set of possible scenarios, given in car assembly, the mounting of trailer coupling is presented as a use case to highlight a typical application scenario of assistive robotics. Besides the specific use case, a set of general criteria for the industrial use of mobile robots is presented in this paper. To reach the goal of industrial assistive robots, new approaches in the field of safety technologies, robot reconfiguration, knowledge integration and intuitive human-robot cooperation are overviewed, and set in context to related work. Following an overview of state of the art systems and related projects, the paper concludes with future work that integrates the goal of the EU-funded LOCOBOT project for low-cost robotic co-workers.**

Index Terms*—Intelligent manufacturing, human-robot interaction, knowledge integration, reconfigurable mobile robots

I. Introduction

In car manufacturing, like in most manufacturing domains, a steady trend toward mass customization and decreasing time to market was encountered during the last decade. While efficient automated and semi-automated processes are widely implemented in modern assembly lines, actual automation solutions cannot provide the required level of flexibility. In combination with aging workforces and the steady effort to create ergonomic workplaces, the flexible design of interactive workplaces in assembly and logistics is the motivation to analyze the potential use of mobile assistants in car manufacturing.

The investigated type of assistive system is characterized by its capability to work interactive with the human as a robotic co-worker in a broad variety of applications. The potential of mobile assistive robots for automotive applications is analyzed in this paper. Therefore, the cooperative mounting of a trailer coupling in the assembly line is presented as a use case, which allows to illustrate an example application.

Additional to this specific setup, a set of criteria for the industrial use of assistive robots points out the general requirements for their application in car assembly and logistics. These requirements are complemented by a list of specifications to select the corresponding application for a mobile assistant. To reach the goal of an industry-compliant assistive robot, this paper presents new approaches toward augmented safety and efficiency in the required human-robot cooperation. Additional to the integration of a reconfiguration mechanism, the active integration of knowledge enhances flexibility and industrial applicability. In cooperation with AUDI AG and in the project LOCOBOT (7th framework programme FP7), these approaches are further investigated for their practical application in the car plant of Audi in future work. While section II introduces the use case, the general criteria of an industrial use are overviewed in section III. Before a discussion of related projects in section V, new approaches for assistant robots are described in section IV. The paper concludes with the presentation of future work in section VI.

II. An industrial use case

To outline how a mobile manipulator can be useful as an assistant, a use case from automotive car assembly is chosen, where robot and human are mounting a trailer coupling to the car body while a second human worker in the same working zone mounts braking tubes. The trailer coupling has an approximate weight of between 12 kg and 20 kg. For mounting it to the car, it has to be lifted overhead to a height of almost 2 m. This posture is highly critical from an ergonomic point of view and thus underlines the positive effect of handing the carrying and lifting task over to a robot, only leaving the easier but more delicate tasks, like fixing the screw, to the human. In a human-robot task cooperation, the robot picks up the trailer coupling in the storage place, lifts it to the desired position and waits for the human worker to accomplish the mounting process by fixing the coupling to the car body.

This use case illustrates the example of humans and robot in a shared workspace and incorporates many aspects of current research on human-robot interaction like human-aware robot motion and intention recognition in a joint task execution. Abandoning the commonly used strict separation of human and robot introduces the challenging problem of assuring physical integrity of the worker at any time. Moreover, short cycle times create the need for building a system capable of reacting and adapting to a dynamic environment in a robust way. Besides these future developments, introducing a robot system to a productive environment demands compliance to standard industrial requirements like reliability and availability. Section

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III aims at developing a comprehensive set of criteria for the use of mobile assistants in production facilities and the choice of appropriate application scenarios.

III. Criteria and potential for industrial robots in automotive manufacturing

The use case presented in the last section specifies a challenging but beneficial application for robot assistants in assembly. Before the requirements for these applications in a car plant are further detailed, general criteria for the use of assistive robots are given in Table I. Besides the required robustness in unstructured environment, a flexible gripping technology has to be applied so that different part geometries can be handled. For conformity of a single robot system with the entire range of tasks, a payload of 20 kg and a workspace of 1.8 m have to be supplied. These requirements result from the standardized industrial environments, regarding for example heights of shelves or conveyors, box dimensions, or the average weight of handled parts. The payload is important as this technology desires the relief of the aging workforce as described in the introduction. One of the most challenging requirements in the industrial use of assistive systems is a safe man-machine-interaction with parallel handling of a payload up to 20 kg. The 24-hour energy supply and the availability of 99 % round off the set of general industrial criteria as described in Table I.

Besides complex assembly tasks, as presented in the use case in section II, sequencing and pre-sorting tasks of heavy (>5 kg) components are in the main focus of logistic applications. After promising tests in the car factory of Audi, the following list of characteristics was developed as criteria for an appropriate selection of applications:

- Need for a frequent area restructuring.
- Handling of components with a mass higher than 5 kg.
- Assembly processes with a long distance approach.
- High variety of parts that are delivered sorted.
- Requirement to work interactive with/or near a human.

As many applications in automtoive assembly fulfill at least a sub-set of the named selection criteria, the potential of industrial assistive robots in automotive applications can be rated high if the set of industrial requirements, given in Table I, can be fulfilled. Actions to approach these criteria are presented in the following section including safety, reconfiguration activities, process knowledge integration and intuitive human-robot cooperation.

IV. Future research for mobile assistants

The vast set of requirements for the use of mobile assistants in series-production reveals a number of scientific as well as engineering problems to be solved before the technology can be used in an industrial environment, particularly in direct interaction with persons. Depending on robot power and the payload to be handled, safety is a core issue. For augmenting flexibility and efficiency of mobile manipulators, open questions in the field of reconfiguration, knowledge representation and human-robot cooperation have to be addressed. Approaches toward these problems will be covered in the following sections.

TABLE I
General criteria for an industrial use of assistive robotics in automotive industry

	Industrial requirements for assistive robotics
Navigation	Robustness in unstructured environment
Gripping technology	Applicability for different part geometries
Hardware components	Economic components with compliance of industrial standards
Workload	20 kg
Workspace	1.8 m
Availability	99 %
Energy supply	24 hours
Safety	CE labelled application for man-machine interaction

A. *Safety issues in shared workspaces*

Safety is the primary concern when introducing assistive mobile robots in car assembly, as a strict workspace separation is not suitable anymore. A risk analysis according to ISO 12100 [1] and ISO 14121 [2] shows that mechanical hazards as free impact and crushing are the major concerns. The injuries of unexpected human-robot impacts can be limited by lightweight/compliant mechanical design of the manipulator and post-collision reaction strategies [3]. However, up to now lightweight robots are restricted in payload and workspace and cannot fulfill requirements given in Section III as the criteria demand the handling of payloads up to 20 kg.

Thus, safe operation of the robot must be achieved by preventing undesirable contact between robot and human by the use of external sensors. Different types of sensors can be used to detect objects in the environment, including proximity sensors, laser scanners, single and stereo cameras or recent technologies like Photonic Mixer Devices (PMD) [4]. Several publications deal with workspace surveillance of static robot cells with PMD-sensors [5] [6] [7]. PMD-cameras provide, beyond grayscale data, information about the distance between sensor and observed object. The volume occupied by the robot can be retrieved from the known configuration and dimension of the robot at any given time and subtracted from the scene. Distances between remaining unknown objects and robot are evaluated and pre-collision strategies as lowering velocity or local path replanning methods are applied.

Our approach is to apply the results of static camera based surveillance to rigid mobile manipulators. Multiple PMDs, used as depth measuring sensors, observe the close environment of the mobile robot for collision avoidance. The compact cameras can be operated at high frame rate and do not include any mechanical moving parts, being thus very suitable for mobile systems. In contrast to static workspace surveillance, flexibility of the mobile system requests sensors to be mounted on the mobile manipulator. The thereby limited field-of-view of the pinhole-model-like sensor increases the occlusion problem which makes sensor placement a crucial issue. The a priori knowledge of the process model and the workspace layout enables CAD-based offline simulation for a given application scenario and defines movements of the robot during task execution. Object occlusion can be retrieved by simulation, taking restrictions as sensor field-of-view and senor placement into consideration. The global minimisation of object occlusion leads to the optimal sensor placement for a specific application.

For time efficient distance computation, Cartesian space is divided into cells and organized in an octree structure. Cells represent object classification, measured distance and the respective uncertainty of multiple sensors according to the sensor model of Flacco [5]. The required braking distance will be derived from a braking model considering robot's current inertia distribution as well as the grasped part. The goal is to respect minimum required safety distances to obstacles as derived from ISO standards [8]. Additionally, the current situation can give indication about its imminent risk. Distances to surrounding humans, occluded areas, operating speed and future trajectory of the robot classify potentially hazardous situations. Based on observations, strategies for an adapted behavior in situations of augmented hazard are developed.

B. Reconfigurability in industrial mobile robots

The reconfigurability in mobile assistive robots is of main importance for their flexible use in a dynamic production environment as the manufacturing tasks that are executed by these machines change frequently. While they have to be highly adaptable, the maintenance of productivity is required during process execution. Reconfigurability for agent-based manufacturing is investigated in literature such as the ADACOR [9] approach or the Restore Invariant Approach [10]. With respect to the application of robot assistants in productive environments, the approaches presented in literature do neither offer the adequate reaction to frequent process changes nor do they provide the hardware abstraction that is required for varying robot configurations.

By taking the use case of Section II as a basis, a potential reconfiguration mechanism for assistive systems is presented in the MobComm approach [11]. By the application of this mechanism, robot functionalities can be assembled by an intelligent composition of already existing skills as a dynamic reaction to functional process changes.

In case the functionality *Wait for human* is not available in the system after the initialization of the process *Mount trailer coupling*, this skill can be composed self-organised by the assistant system. For this composition, an application layer is proposed in MobComm that allows to insert a new robot functionality by semantic description. For the *Wait for human*-skill the following description is required:

If *HUMAN DETECTED* do *FOLLOW* else *STOP*.

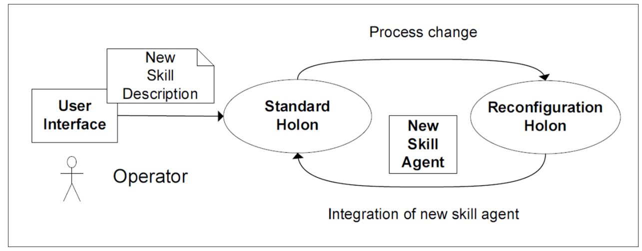

Fig. 1. Overview of the MobComm reconfiguration mechanism. Adapted from [12].

By the insertion of this semantic description into the system, already known skills of the robot are extracted such as *FOLLOW* or *DETECT*. Due to the high requirements regarding productivity in industrial environments, the reconfiguration of *Wait for human*-functionality is composed in a separate Multi-Agent-System within the holonic structure of MobComm as presented in Fig. 1.

The encapsulated reconfiguration mechanism utilizes the actual robot configuration and is able to compose a new robot functionality by the application of an agent-based negotiation. This mechanism includes the integration of conditions such as the specific reaction to a found human. Compared to approaches in literature such as SIARAS [13] or Plug and Produce [14] where simulation environments are provided for the validation of the new functionalities, MobComm is able to validate its reconfiguration results in real-world before they are usable in a new configuration.

The advantage of a reconfiguration layer that follows the MobComm approach, is a flexible reaction to process changes by the composition of missing functionalities without any loss of productivity in the actual manufacturing process. This type of reconfigurability can be applied to assistive systems additional to other ways of a flexible process execution like the knowledge integration given in section IV-C. Furthermore, MobComm is usable configuration independent for different hardware systems.

C. Knowledge Integration

The requirements introduced in Section III demand a highly dexterous behavior of the robot. Providing the robot control with sufficient information about its surroundings during runtime is therefore mandatory. The primary source of information is sensors as they provide live data in a high frequency. However, to obtain information out of data, an accurate interpretation model is necessary as otherwise computational costs and the required processing time prohibit the desired behavior. In order to set up such models, knowledge about the structure of the surroundings is necessary, which can be seen as a second source of information. In the majority of logistics or assembly environments a priori knowledge about the structure is available. It can be derived e.g. from engineering tools or application experts. How to integrate this knowledge most beneficial into robot control is still a field of research.

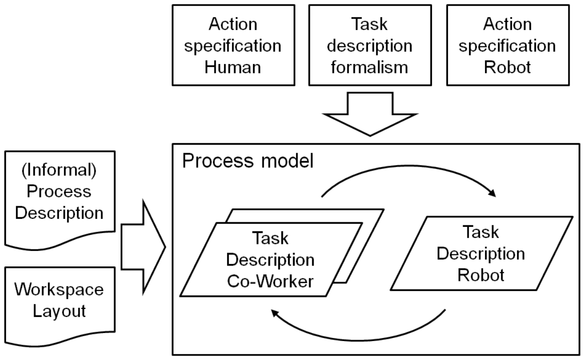

Fig. 2. Process model generation

A recent approach is presented in [15]. The authors describe a knowledge integration framework (KIF) as part of the ROSETTA project [16]. For a given robot configuration, an abstract task description can be transformed into code executable by a robot controller using KIF. It is assumed that the required knowledge is available in the AutomationML [17] exchange format, which is an effort to provide information of different engineering disciplines and tools in a unified modeling language (ML). While this assumption is sensible for highly automated environments, tasks involving human co-workers imply a lack of knowledge. In contrast, our approach is centered on the humans that cooperate with the robot and share its workspace. As the human component is beyond doubt the main source of variations in the context, knowledge about it is most valuable for the resulting robot behavior.

The goal is to provide the robot control with an abstract model of the application process and the cooperation in advance, allowing an efficient application integration and refine the model during runtime (cf. Section IV-D). The generation of the process model is sketched in Fig. 2. The central components are the task descriptions of the robot and the co-workers. Following approaches as presented in [18], actions constitute the atomic elements of a task description. The available actions for humans and robot are defined in action specifications. Each description holds:

- The involved work steps,
- relevant objects,
- spatial information (relevant places) and
- execution times.

By connecting work steps of different task descriptions in the process model a synchronization of the cooperation is enabled. In a first attempt, a hierarchical task network [19] was chosen to represent the task descriptions. An examplary human co-worker task is pictured in Fig. 3. The task is structured in activities and actions. Further task description formalisms and action specifications will be investigated in future work.

D. Human-robot cooperation and adaptation

A major goal in human-robot cooperation is to minimize the requirement for user intervention during collaboration. Achieving acceptance of the robotic co-worker requires that cooperation is intuitive and that the human does not feel hindered by the robot. This involves capabilities like recognizing when a user is in a collaborative state as well as if a user has performed all necessary steps for the interaction process. Moreover, long previous training periods must be avoided and adaptability to changing workplaces must be ensured.

Following the idea presented in Section IV-C, a set of information required to enable task execution must be provided in advance. To reduce the complexity of the process model, a minimalistic level of detail should be sufficient. Modelling a completely predefined work process is hard when a human co-worker is involved, as human task execution induces variations in time and place. In order to respond to the dynamic environment, the robot has to rely on sensor observations. During interaction, the robot will recognize previously modeled situations, learn from observations, enhance the a priori model and gradually improve process suitability. Coming back to the presented use case, information to be retrieved from sensor data includes:

- Relevant places and objects to distinguish plans: the place to pick up the coupling, the place to mount the coupling, the place where the worker picks up a certain tool.
- Human activities and actions: Human actions during activity of fixing the coupling to the car like depicted in Fig. 3.

While recognizing and tracking humans from mobile systems using vision based sensing is a well studied problem, the trajectory information will be used to reason on the human plan, identifying who is the one to interact with and the exact time of interaction. Semantics of the observed trajectories are derived from the process model and can be supported by additional information as listed in Section IV-C.

During close interaction, it seems straightforward to use information about the human pose for the recognition of a state change. An important conlcusion from Section IV-C is that industrial environment mostly permits to give an abstracted description of the task. Namely action sequences and their

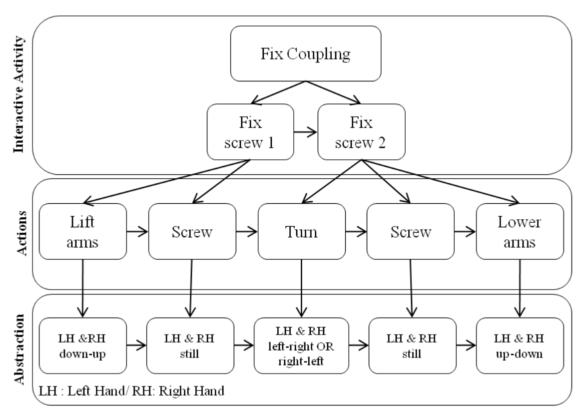

Fig. 3. Abstract task formulation

formulation as movements of certain body parts as in Fig. 3. Studies comparing appearance-based to pose-based features for action recognition indicate that using pose promises to improve detection significantly [20]. Powerful technologies for generating human articulated motion data like Microsoft SDK for Kinect [21] or the Omek Beckon™ SDK [22] for CamCube and D-Imager allow to investigate, whether such a predefined set of actions can be robustly reconstructed from sensor data. Detected actions and activities serve the robot decision making during joint task execution. Related work deals with the extraction of atomic actions from body movements captured by a multi-camera network [23]. [24] presents an algorithm for the automated generation of motion sequences from body-part movements.

In addition, a hypothesis about the spatio-temporal occupation of the common workspace can be generated based on Expectation Maximization as presented in [25] or temporal Occupancy Grid methods. Action recognition builds up knowledge about the way in which a worker performs a given task on a body-part level. These refinements of the process model can help proactive decisions and reactive behaviors [26][27]. The approach contributes to safety as well as to efficiency and can eventually be synchronized with the efforts in robot behaviour adapted to human presence [28].

V. Related Projects

The enhancement of mobile manipulators has been a steady area of research over the last decade. In many approaches, new systems were developed and their capabilities have continuously been improved. Fig. 4 presents some of the most established designs. An early system is the rob@work [29], meanwhile available in evolution rob@work 2 [30]. The systems were designed for delivery and assistance in handling and assembly tasks. The rob@work 2 features a light-weight manipulator that can carry a payload of up to 10 kg [30] and sensorics for collision avoidance. The Neobotix MM-KR16 Platform, using a KUKA KR 16 manipulator is one of the few systems designed for higher payload applications (up to 16 kg) [31]. Enhanced with sensing capabilities, the robot has been successfully tested for high payload presorting applications within the factory environment of Audi. Safe platform navigation is assured via laser range finders. However, due to the use of a standard industrial manipulator, no sensitivity is provided and robot design is not compliant with requirements for use in shared workspaces. The probably most evolved manipulator technology can be found in the KUKA omniRob [32]. It provides a sensitive LWR 4+ arm on an omnidirectional platform. With its integrated sensing capabilities, the omniRob is well-suited for cooperative tasks [32]. A drawback is the low payload capacity of 7 kg that is not sufficient for the most relevant applications as defined in Section III.

Besides the overall system concept for a mobile manipulator, there are several projects dealing with the application of cooperative mobile manipulators in industrial environments. Project ASSISTOR investigated the development of robust mechatronic systems for a direct man-machine interaction in industrial assistance and worked out basics for the approval and standardisation of robots in man-machine interaction [34]. Two ongoing projects fostering the real-world application of mobile manipulators are the EU-funded projects LOCOBOT and TAPAS. The main concern of LOCOBOT is the development of a modular mobile manipulator, capable of handling the specified weight of 20 kg. LOCOBOT creates a set of plug-and-produce kinematic modules with compliant, but precise actuators and intelligent sensing for man-machine cooperation. The system will be evaluated in automotive application scenarios at Audi [36]. The TAPAS project follows the flexible automation of logistic tasks by not only transporting, but also collecting and delivering parts to the needed place. The robots are intended to automate assistive tasks such as preparatory and post-processing works. First test runs were conducted with the Little Helper mobile manipulator [37].

VI. Conclusion

Motivated by the aging workforce and a rising demand of flexibility in logistics and assembly applications, this paper analyzes the potential use of mobile manipulators as assistive co-workers in car manufacturing. A set of criteria for an industrial use and for suitable applications are presented. The highest benefit in the application of assistive systems can be generated, if the technical specifications are complied additional to the selection of a suitable application scenario (cf. Section III). For automotive manufacturing, a high potential can be stated for a vast range of tasks.

Successful integration tests at the Audi factory environment support a further use of mobile manipulators in production facilities. The comparison of the presented requirements with the state of the art technology as presented in Section V gives indication about the directions for further research. To

Fig. 4. Examples of mobile manipulators for industrial use (top l.-r.: rob@work2 [30], omniRob [33], bottom l.-r.: ASSISTOR [34], MM-KR16 [31] and Little Helper [35])

compensate for safety problems in assistive systems with high payload, a multi-sensor collision avoidance strategy is given in Section IV-A. Advancements in reconfigurable software further increase the performance and the flexibility of robotic assistants. Furthermore, concepts for the integration of existing production knowledge and intuitive human-robot cooperation that are based on pose-estimation, are elaborated. Their purpose is the improvement of efficiency and context-awareness of robotic co-workers. In further research work, the concepts will be evaluated with respect to industrial applicability and robustness.

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