Intuitive robot programming for automation of low standardized logistic processes

M. Rohde, S. Kunaschk, M. Lütjen, F. Ahrlich and A.-K. Pallasch

Abstract**—**The increasing globalization of trade flows causes a continuous growth of packaged goods and results in an increasing demand for handling of general cargo. Due to low standardized logistic processes, the use of automation technologies for improving the handling efficiency is very challenging. Depending on requests of suppliers and customers, the logistics service providers have to develop individual solutions for logistics processes. If automation technology, e.g. industrial robots, is used to optimize the processes, it has to adapt to changed conditions. This leads to complex systems and time-consuming tasks of robot programming. In order to face this challenge, this paper presents an approach for intuitive control of robots by using a cyber physical system (CPS). First, it describes challenges for automation of logistic processes and discusses the main idea of cyber physical systems. Subsequently, the concept of cyber physical robotic systems for logistics (CPRSL) is depicted and an example application is given, which bases on robot programming by demonstration (PbD). Within the logistic task of "depalletizing boxes" the system is tested and evaluated.

Keywords**—** cyber physical systems, human machine interface, industrial robots, robotic in logistics

I. Introduction

BASED on increasing global interweavement of economics, politics, culture, communication etc. and on worldwide distributed sourcing and manufacturing, efficient logistics processes are needed. Logistics processes contain sub-processes like packaging, handling, storage as well as transportation. In order to optimize the whole logistics chain, all sub-processes have to be improved. Regarding distribution centers, the increasing of the degree of automation is one option to improve the efficiency [1]. The automation of logistics processes is an upcoming research field, which focuses on the improvement of material handling by the use of robotics and mobile technologies [2], [3]. Due to low standardized processes, the approach of using PbD is very promoting. Low standardized processes need a lot of cognition for analyzing the actual situation and planning the operations. This cognition has to be taught by humans.

Therefore the field of PbD deals with the interpretation of human actions in different contexts [4]. Such interpretation can be done for example by the use of machine learning techniques or intuitive teaching devices. The main idea of this paper is to use such an intuitive teaching device by integrating it into the concept of cyber-physical systems (CPS), which allows to interact with other embedded systems via a cyber network or in this case via a virtual reality environment.

II. Challenges for Automation of Logistics Processes

Logistics have to deal with a lot of external and internal disturbances. External disturbances are for example bad weather, traffic or production delays. Even internal disturbances can occur, like e.g. wrong labeling, wrong lot sizes or machine breakdowns. All disturbances affect the logistics performance in a negative way, as the optimal scheduled allocation of resources and materials is hindered. Besides, the system load varies strongly because markets and products change very fast and global. Such a dynamic environment encourages the low level of process standardization, which is common in logistics. Regarding production processes, the degree of automation is very high. Since the 1970th robots are successfully integrated to support production processes. Due to the lower degree of standardization, these methods and technologies cannot be transferred to logistics processes without customization but their general applicability is proven. Thus, the automation of logistics processes is a very big challenge.

The automation of logistics processes affects all kinds of system inherent flows: information, control and material. In general, the objective is to reach an integrated automation of all flows in order to improve the overall process efficiency. This requires synchronized flows. In order to get more time for allocating and setting up needed resources, the information and the control flow must precede the material flow in an ideal cycle.

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"Logistics automation is the application of computer software and/or automated machinery to improve the efficiency of logistics operations." [5]

With focus on material flows, the core operations of logistics are packaging, handling, storage and transportation (PHS&T)[5]. It is useful to design automated logistics systems based on these physical operations, because the installation of information technology is more flexible than the machinery hardware for PHS&T. According to the very different processes and tasks, each logistics system has to be tailor-made. In order to develop automated logistics systems a couple of different hardware and software components have to be combined [2], [5], [7]:

- mobile & fixed machinery
- identification & tracking technologies
- monitoring & control software

Mobile and fixed machinery is needed for the execution of the PHS&T-processes. Automated cranes, conveyors, power & free systems, sortation systems and industrial robots provide amongst others the backbone of the machinery. In general, the use of robotics in logistics is a very auspicious field [3]. The RoboScan'07 study shows that 41 percent of the questioned logisticians are already using robotic systems in their application areas and over 60 percent wants to introduce or enhance the automation of logistic processes with robotic systems [8]. Additionally, automated guided vehicles allow the automation of transports. In order to control the logistics processes also identification and tracking technologies are needed. Based on bar codes or RFID-tags, the products and materials may be identified automatically whilst moving through the machineries. As a result, the system situation can be captured and used as input for the monitoring & control software.

"Monitoring and control software" is for example a MES-System, which is used at an operational level in a production environment. MES is the abbreviation for manufacturing execution system. A MES-system gets production plans as input data from an enterprise resource planning (ERP) system. By considering sensor data from machine monitoring, it provides real-time decision capabilities for smaller production sub-systems. Only smaller production sub-systems can be controlled in such a way because the data volume is too big for complete control with ERP. Therefore, a hierarchical approach is commonly applied by using ERP-systems for mid- and long-term planning and MES-software for short term planning [9].

GUDEHUS defines some directives for the automation of logistics [10]:

- Higher rate of mechanization and automation of logistics requires a good utilization in order to face the higher fixed costs
- Conventional transport and warehouse equipment are more flexible but have higher variable costs
- Costs of highly mechanized and automated systems can be less than half of conventional systems compared with same system load
- If only small capacities are required or the system load varies strongly it is more efficient to use conventional systems
- In order to get an higher system load it is useful to centralize logistics functions and consolidate transports and stocks

Additionally, some more directives can be defined:

- Centralization of logistics functions can be increased by standardization of logistics processes
- Development of more universal machineries improves the possibility for consolidation and allows handling of low standardized processes
- Implementation of new planning and control strategies is necessary for balancing the system load
- Standardization of logistics process parameters enable less complex automation solutions

In conclusion, logistics have a high demand for intelligent automation, which is able to face the challenges of high dynamic logistics environments. The RoboScan'07 study shows that only 25 percent of the questioned logisticians demand for a full automation of their processes. Cyber physical systems provide an opportunity for further development of such intelligent automation, which can also interact with human workers.

III. Cyber Physical Systems

The term of cyber physical systems (CPS) is characterized by the integration of computing and physical processes [11]. Differentiating to "embedded systems" the aspect of networking is emphasized. There are a lot of successful applications for embedded systems, like e.g. automotive communication devices and control systems, which show the general demand for close interaction between computing and physical process. The next step in evolution is the enhancement of embedded systems with networking capabilities [12].

Cyber physical systems can communicate among each other in the cyberspace, which leads to networks and the capability of interaction. Fig. 1 depicts the architecture of CPS.

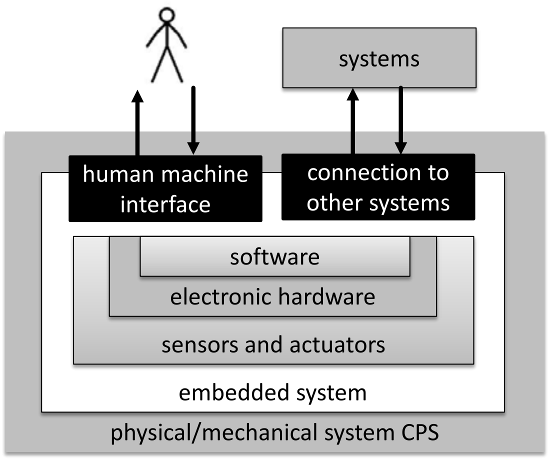

Fig. 1 architecture of CPS [13]

The connection to other systems allows the consideration of different local information for information processing and evaluation. The objective is to enable the CPS to execute tasks (controlling, regulating, monitoring, communication and signal processing) in an efficient and autonomous way [14].

A. *Design Challenges of CPS*

A general challenge in the design of CPS is the integration of analog-physical and digital-cyber world [13]. In consequence, the different model types of these two disciplines have to be integrated. The analog-physical world is described by continuous mathematical models, while the digital world is based on discrete logic. In order to face these challenge six prioritized research directions are identified by DAMM [15]:

- seamless interaction
- autonomous systems
- distributed real-time situational awareness and problem solving
- safe and secure systems
- principles of architecture
- virtual engineering

In order to get a seamless interaction between different IT-systems, it is necessary to overcome language barriers by establishing secure authentication self-explanatory to interaction interfaces. Besides, the CPS should be able to behave as autonomous systems in order to reach a good performance even in unknown environments. The objective of distributed real-time situational awareness and problem solving is to create a joint picture in real time conditions in order to realize coordinated actions of the semi-autonomous sub-systems. It is necessary to develop safe and secure systems in order to establish and maintain confidence. One key to success is the design of standardized domain-independent principles of architectures in order to reach higher goals in complex systems, like e.g. sustainability. The last direction of research is the improvement of development processes by methods and tools, like e.g. virtual engineering, which help to design complex and cross-domain systems. SZTIPANOVITS refers to a new generation of CASE (computer-aided software engineering) tools, which give the opportunity for convergence in control, system and software engineering built on the principles of model- based design [16].

In addition, SHA defines four challenges of cyber-physical system research with focus on telecommunication [17]:

- real-time system abstractions
- robustness of CPS
- system QoS composition challenge
- knowledge engineering in CPS

The real-time system abstraction deals with the need for novel distributed real-time computing and group communication methods for dynamic topology control in wireless CPS systems. By developing safe and secure systems, the robustness should be improved in order to handle unknown environments and events. The system QoS composition challenge addresses the requirement for regarding not only the compensability at each QoS dimension but also the question of how protocols interact. In order to interpret the many types of data in many different physical domains and application contexts, it is necessary to use machine learning and real-time stream data mining techniques. Thereby, it is a challenge to integrate distributed, dynamic, heterogeneous information sources, which can include data streams from the physical and cyber-world.

B. *Networked Robots*

The concept of networked robots is linked to the concept of CPS but refers to the field of robotics. Thereby, the term of robots is defined as follows:

“A robot is an automatically controlled, reprogrammable, multipurpose mechanical system, with several degrees of freedom, which may be either fixed in place or mobile.” [18]

The main idea of networked robots is the cooperation of several robots in order to perform tasks, which cannot be executed by a single robot or multiple uncoordinated robots [19]. Therefore, it is very necessary to establish network communication between the robots and additionally stationary sensors, embedded computers or human users [4]. The IEEE technical committee on networked robots defines that a networked robot is a robotic device, which is connected to a communication network such as the Internet or LAN networks. Thus, the connection to the network can be wired or wireless.

Three classes of networked robots can be identified [20]. The first class comprises *teleoperated robots*, which have human supervisors sending commands and receive feedback via the network. The second class covers *ubiquitous robotics*, where networked robots are integrated into ubiquitous computing environments that include networked sensors, actuators and human users. The third class contains *sensor networks*, which allow robots to measure spatially and temporally distributed phenomena more efficiently, in particular when the robots are mobile.

IV. Concept of CPRS for Logistics

The concept of cyber-physical robotic systems for logistics (CPRSL) defines an application-oriented research field, which includes aspects of CPS and networked robots. With respect to logistics and the PHS&T-processes, the focus of CPRSL is handling of goods. This includes all kind of logistics scenarios, like activities of grasping, picking and placing goods. The concept of CPRSL includes the following principles for the development of robotic systems:

- consistently use of virtual environment for teleoperation and collision detection
- integration of human users as co-workers, supervisors or teachers
- using learning techniques and innovative input devices
- knowledge engineering for sustainable use of learned tasks
- using flexible and modular equipment

The objective of CPRSL is to achieve high adaptive and versatile robotic systems in order to deal with low standardized logistics processes. The representation of each robot in the virtual environment allows coordination and control of the real word robots (Fig. 2).

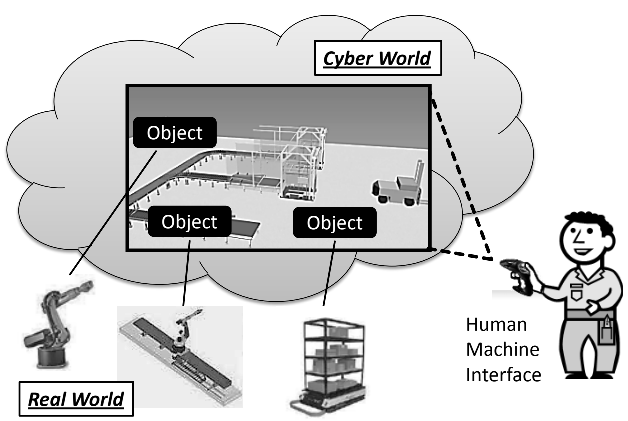

Fig. 2 using virtual environment of cyber world for coordination and control of real world

Additionally, the precondition for teleoperation and collision detection is given. By using innovative input devices the human supervisor can be next to the robot or far away in a teleoperation center, which is equipped with virtual reality devices. By referring to ideas of mixed reality, the virtual reality can be also enhanced with real world data or images in order to improve the efficiency of teleoperations [21].

A. Robot Programming

The use of a robot system can be very helpful for production and handling tasks. Robots are able to work fast with a high accuracy. The kinematics of a robot describes the degrees of freedom of the robot tool as well as the work range. In general, robots are able to handle heavy weights and fulfill complex and dangerous tasks. Unfortunately, an industrial robot system is not a “Plug-and-Play” component. For an automation application every task and every movement of the robot axis have to be programmed. The complexity of the program depends on the task and the system components as well as on peripheral devices. The market offers a lot of different robots of different manufacturers. In general, the user has to provide special skills, machine related, in order to program the robot. Nearly every producer of robot systems has its own program language. Therefore, the programmer has to participate at different training and education courses, the more complex the task used to be. Robot programs are only transferable to equal systems [22].

1) Offline Programming

Industrial robots are capital-intensive resources. In order to use them in a profit-making manner, it is important ensure a high usage rate. Contrary to this, programming of a robot system cannot be performed whilst usage of the system. Hence, various offline programming methods have been developed which enable the user to generate a routine or complete program without needing a real robot. [23] Amongst others, these methods are:

- Text based programming
- offline programming based on visualization
- hybrid-programming

Typical offline programming methods are based on plain robot code in the specific robot programming language. Till jet, there is no universal robot programming language for industrial robots from different manufacturers. If using this text based method, the programmer has to be a trained expert in order to know the special commands. This procedure guarantees a high flexibility especially to administrate the in- and output signals and the communication with collaborative systems. Some manufacturers of robots provide a development environment for the offline programming. Within this software it is possible to test and compile the code [24].

Another offline programming method is based on visualization. By using CAD-data the characteristics of the robot, the handling objects as well as the peripheral devices, are described and simulated in a virtual world. Movements of the robot can be evaluated directly by the user. The input of the robot movement commands can be done textual or by using devices like the computer mouse, a space mouse or special haptic input devices [25].

Due to small geometric divergence between the virtual and the real world there are unfortunately few offline created robot programs that can be transferred and used directly by the robot. In these cases there is the need for little modifications of the robot program direct at the robot system. The online reprogramming of offline generated robot programs is called hybrid-programming [26].

2) Online Programming

Due to the fact, that the movements of a robot are depending of the arrangement of the system components, the handling objects and their accessibility as well as the peripheral devices, online programming methods for robots are quite serviceable. For online robot programming the application of a real robot is mandatory. Regarding complex movements, this is a big advantage because collisions can be recognized quite early in the real robot-cell.

There are two different online-programming methods:

- Teach-In principle
- Play-Back principle

For the Teach-In principle, the robot is moved in dedicated positions by the programmer. The positions are saved and brought to a desired order within the robot program. A continuous recording of the robot movements forced by the user is done at the Play-Back principle. For both procedures the user first defines a movement of the robot but in a subsequent step the administration of I/O-signals has to be done

3) Robot Programming by Demonstration

As mentioned above, the knowledge engineering of CPS is one of the most challenging research questions today. Without knowledge, no intelligent automation can be done. Due to high dynamics in logistics as e.g. fast changing processes, the robots must be adaptable to different local environments and tasks. The faster they learn new processes or can be taught to them, the more profitable they work. Therefore, innovative methods and techniques for rapid robot configuration and programming are required.

The field of programming by demonstration (PbD) is not new and started about 30 years ago [27]. Nevertheless, it pursues the training of robots with very flexible user-based interfaces instead of pre-programming robots offline. Thus, the concept is still contemporary. In the fields of logistics, the programming by demonstration seems to be one of the key elements for a rapid robot configuration and programming, because each robot has to be taught to his very special task belonging to a superior process.

PbD belongs to the class of imitation learning, which is a powerful technique to classify attempts in good and bad examples. The Fig. 3 shows such an imitation learning, where a reproduction attempt is evaluated by a user or the robot itself.

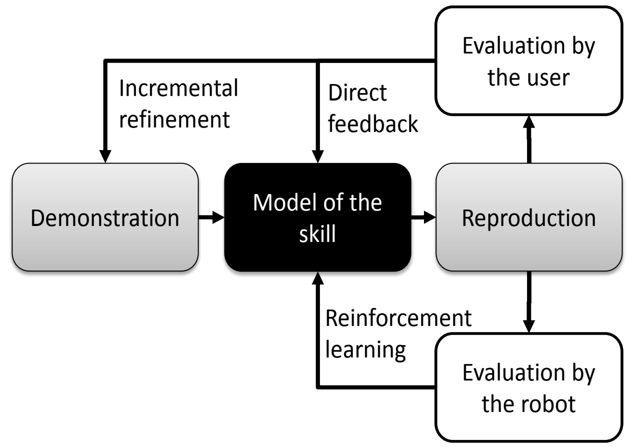

Fig. 3 programming by demonstration with additional learning techniques [27]

Thereby, the user evaluation gives a direct feedback, while evaluation by the robot itself is known as reinforcement learning. In such a scenario, the user defines lacking process parameters and knowledge for the robot. Thus, he is a mediator between the robot-system and its surrounding.

State of the art techniques of PbD for manufacturing tasks [28] are not practicable in logistics, since critical process parameters such as position, orientation and sizes of cargo are highly variable. Thus, direct guiding of a robot to the corresponding handling points leads to time-consuming programming, nevertheless due to low velocities in the human-machine interaction.

B. Application Area Logistics

In general, the automation of processes is based on the extensive specification of general conditions. If a machine has to have a high degree of flexibility its complexity is rather high and complex machines are expensive. This paper focusses on one special case of automation in logistics: handling of goods. Regarding the incoming goods area of a distribution centre general conditions, as e.g. structural conditions of the building may be defined in advance but the system has to be flexible regarding variable conditions like e.g. dimensions and physical characteristics of the goods.

Goods are transported in different packaging; the majority are packed in cubic cardboard boxes. Other popular types of packaging are sacks, e.g. for coffee, and barrels. The Deutsche Post has defined a standard size for cardboard parcels. They can have a minimal length of 200mm (7.87in), a maximal length of 800mm (31.5in) and weight of up to 31.5kg (69.3lbs). All parcels that differ from these guidelines need to be handled separately as bulk goods. Standardised cardboard boxes for overseas containers often have similar measurements.

To get a database of possible measurements and weights of parcels and their frequency of occurrence, BIBA performed a study about the contents of overseas containers at two big contract logisticians. For this purpose three container contents were registered each month over a period of one year. The basis of the study was the following assumption: parcel length ≥ parcel width ≥ parcel height. The following figures show the parcel spectrum. They reveal that approximately 85% of the parcels had fulfilled the standard conditions of Deutsche Post for the parcel edge length. Even though the maximum weight for standardized parcels is 31.5kg (69.3lbs) over 80% of the parcels balanced less than 20 kg (44lbs). The conclusion of this study was that an automation of the incoming goods area for standardized parcels could handle a large part of the incoming goods [29].

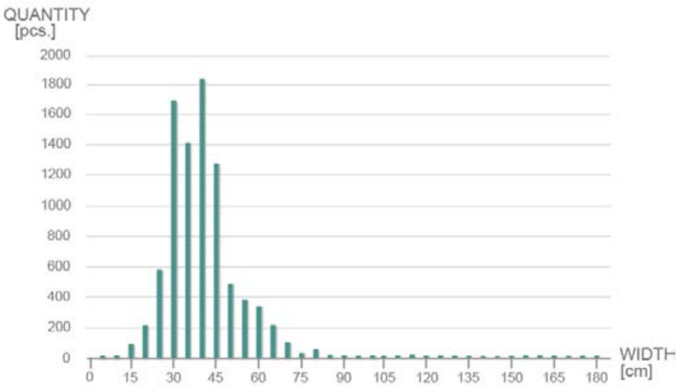

Fig. 4 number of parcels according to width [29]

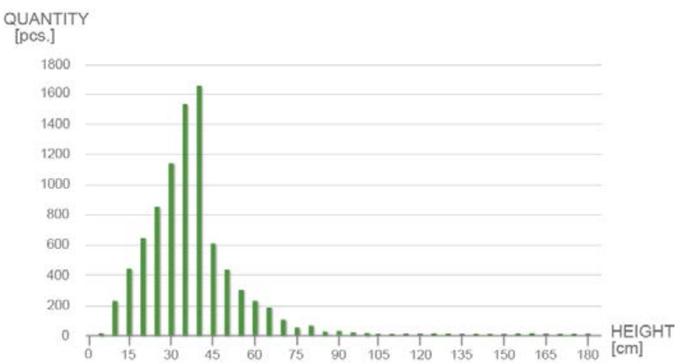

Fig. 5 number of parcels according to height [29]

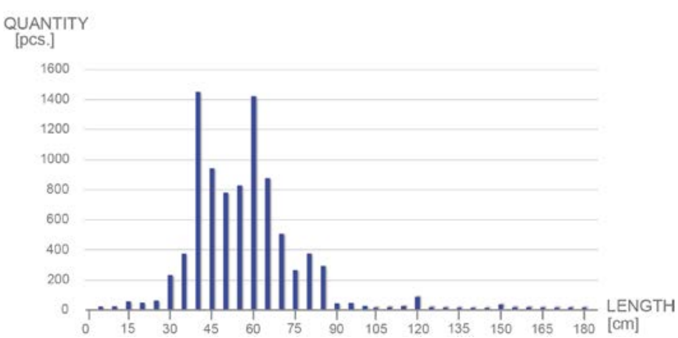

Fig. 6 number of parcels according to length [29]

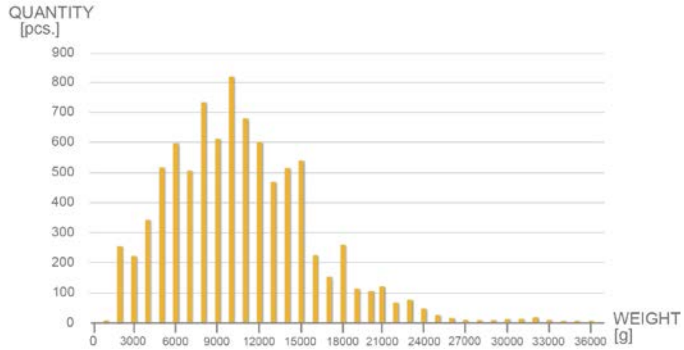

Fig. 7 number of parcels according to weight [29]

C. *Example Application of CPRSL*

The following scenario uses new techniques of PbD developed for workers instead of technical service personal in order to depalletize different homogeneous parcels from a pallet. In general, also palletizing scenarios can be imagined. By using this scenario as an example of a CPRSL, there is the definition of five subsystems:

- handling-objects
- robot simulation tool
- tracking system (controller and input device)
- interface between software and tracking system
- interface between software and industrial robot

In the chosen scenario, parcels of different weight and sizes but in a range as described in chapter IV.B as well as closed plastic boxes, typically used for logistics processes, represent the handling-objects, which have to be depalletized by a standard industrial robot.

The robot simulation tool (EASY-ROB™) is used in order to give a visual feedback and to interpolate the movement of the robot between user defined points. Within this tool, a complete motion planning for industrial robots can be done. The visual feedback allows the user to detect collisions while moving the tool center point (TCP) of the robot along a generated trajectory. A robot program, generated in the system specific code, can be exported. In order to define the task specific handling points by the user, a manual controlled 6 DOF-tracking input device is tracked by IR-cameras (tracking system). Specific interfaces between the tracking system, the software and the industrial robot ensure the communication of the parts. Fig. 8 shows the scenario represented in the simulated virtual world.

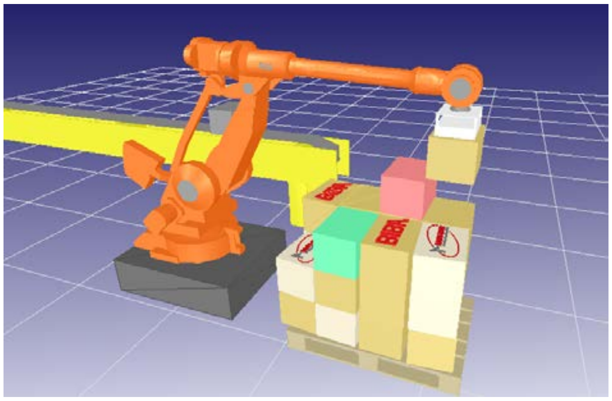

Fig. 8 simulation of the demonstrator

The demonstrator operates as follows: The user places a filled pallet within the workspace of the robot. In the software he has to define if the parcels on the pallet are available in straight stacks or nested. The position of the pallet is given to the system by three edges of the pallet. For this purpose, the user has to detect the edges with the 6 DOF-tracking device. The tracking system detects the position within the system coordinates. The size of the parcels is given to the system in the same way: the user detects three edges of one parcel.

Subsequently, the positions of the parcels have to be defined. The operator selects the center point of the top parcels surface with the input controller (Fig. 9). Thus, the position and orientation of the controller is relevant to the location of the parcels. The user has to detect all parcels at the highest position of the pile. By selecting a top surface of a parcel the system generates a model of the parcel within the software at the defined position automatically. Due to the selected modus – stacked or nested accumulation of parcels – there will be only one parcel at the position of the input controller or a straight pile of parcels from the detected position down to the pallet. Depending on the selected modus the robot simulation tool calculates trajectories for the highest parcels of the pile (nested) or for all parcels (straight).

Fig. 9 positioning of the parcels by a “6 DOF-tracking device”

The user can check the planed motion of the robot within a simulation on a screen. Collisions or singularities of the robot can be identified and counteracted. If the movement of the robot is without any malfunction and approved by the user, the system generates a system specific robot program and transfers it to the robot automatically. The robot executes the planned movement and can be used for the next task. In addition to the motion planning by defining the gripping points of individual handling tasks, the system may also be used by the continuous tracking of the 6 DOF-tracking device in order to generate a program on the base of the hand-movement of the user. Examples for this are painting or welding operations of components in small batch production.

V. Test and Evaluation

In order to evaluate the applicability of this method, a demonstrator has been built. It shows depalletization of cubic boxes stacked in piles off EUR-pallets. To take different situations into account, several test cases with different box types, sizes, weights and packing patterns were built. The box types and their dimensions are shown in Table I. The packing pattern for each box is shown in Fig. 10. Box 1 to Box 3 are common cardboard boxes with usual dimensions. Box 4 is a coverable plastic box with integrated handles that is often used to carry small loose goods. These boxes are common loading devices in the field of logistic and they are often stacked on pallets for further commissioning and distribution. Each type of boxes is filled with the weights 10 kg and 18 kg, respectively according to the weight distribution shown in Fig. 7.

The hardware setup consists of an industrial robot ABB IRB4400L30 with a flange mounted plane sucking gripper for gripping and moving the boxes. Depalletized boxes are laid down on a conveyor belt next to the robot. To get positioning data and to receive user input a 6 DOF tracking system (ART) with a Flystick is used. A standard personal computer is used to run the robot simulation software EasyRob®.

Each test case is processed in exactly the same order by a human worker (M) as well as by the automation system (A). Regarding M, the overall time of the process and the weight the worker had moved was taken. For A the time to set up the system was taken additionally.

Table I box types with dimensions (mm)

	Width	Depth	Height
Box 1	600	400	220
Box 2	390	290	270
Box 3	400	250	150
Box 4	300	400	210

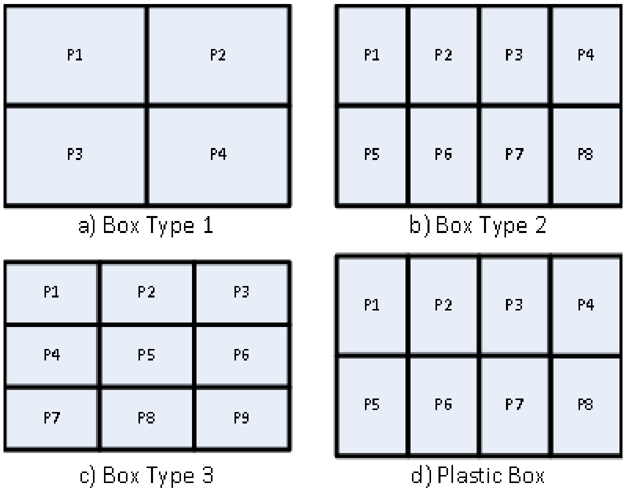

Fig. 10 packing patterns on pallet

The main data to compare the manual and automatic depalletization is the process time. Therefore Fig. 11, 12, 13 and 14 shows the overall and the single depalletization times for each box type with light and heavy weights respectively. It can be seen, that the automated system is working constantly faster for the low weight only for Box 1 to Box 3. The reason for faster manual depalletization time of Box 4 (the plastic boxes) is the good handling of them by humans through their small dimensions and the integrated handles. Cardboard boxes are generally more difficult to grasp for a human and therefore it takes longer to handle them. Looking at the single depalettization time of one box (Fig. 14) it can be seen, that the automatic system works nearly independent of the box dimensions. In contrast, the human worker is much slower at handling boxes with the higher weight. Especially in these cases using the automatic system would speed up the process of depalletization by half the time. The additional time for setting up and programming the system to cope with each new situation does not influence the applicability of this automation system.

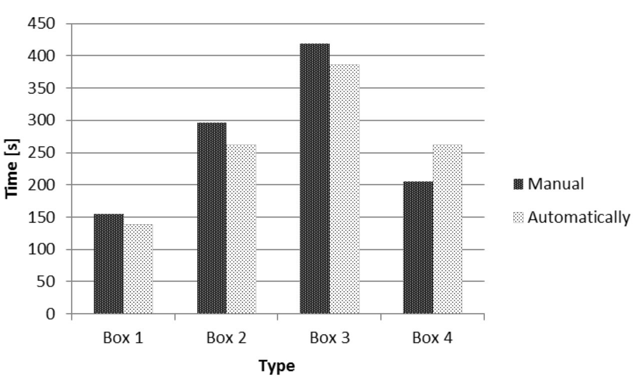

Fig. 11: Depalletization times per pallet of low weight boxes

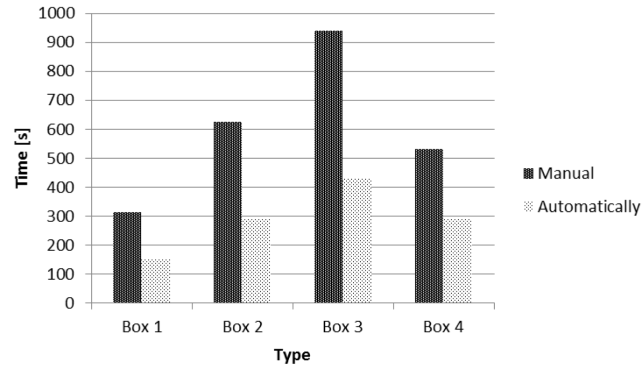

Fig. 12: Depalletization times per pallet of high weight boxes

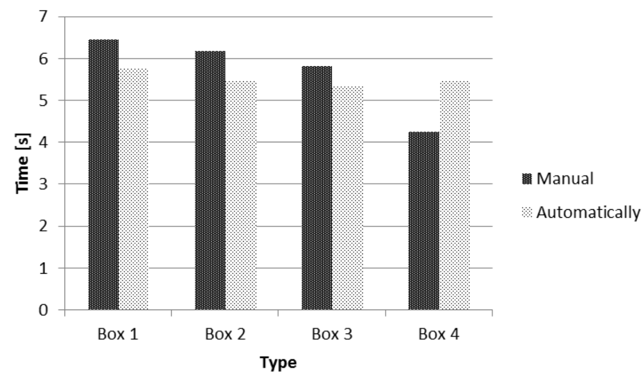

Fig. 13: Depalletization times per low weight box

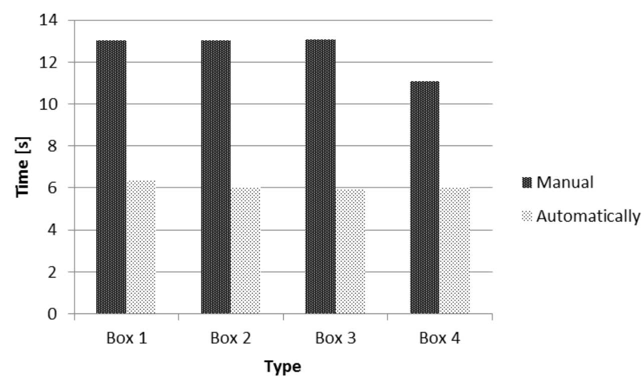

Fig. 14: Depalletization times per high weight box

VI. Conclusion and Prospects

Due to the fact, that a huge amount of logistic processes are low standardized and vary strongly, the automation of these processes is one of the most challenging research fields. Therefore, the concept of cyber-physical robotic systems for logistics (CPRSL) was derived from the original idea of CPS. According to the defined principles of CPRSL, an example application was given by using techniques of PbD together with a standard industrial robot for a depalletizing scenario of homogenous goods. The used setup shows a lot of potential for further development. Recent research focuses on handling heterogeneous goods on different loading devices. Not only pallets will be considered but also overseas container with mixed and chaotic packing patterns. Instancing the unloading system "ParcelRobot" developed by BIBA can unload containers filled with heterogeneous cuboid goods fully automatically but has it's restrict in the size and condition of the parcels. In that case an operator has to rectify the interruption. By adopting described principles an operator could control and program such systems via telerobotics in order to minimize the interruption time and increase the cost effectiveness.

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