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Retrofitting indoor bridge cranes for autonomy: Development of an autonomous pallet cage transport system

Nachrüstung von Brückenkranen für den autonomen Betrieb: Entwicklung eines autonomen Gitterbox-Transportsystems

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While bridge cranes are widely available systems for handling heavy materials, they are mainly used manually and for isolated transports which results in a low degree of utilization. This work proposes a retrofittable, removable system, that enables the existing bridge crane to transport pallet cages autonomously, also in crowded industrial environments without the need of restricted areas at shopfloor level. The system consists of a newly developed removable load handling device, a camera and radar sensor based perception system and a control structure, that implements a new developed safety concept and a process control system for autonomy. A requirements study is discussed, upon which a system design is suggested. The suggested system design is validated by a prototype built on a standard bridge crane.

[Keywords: Autonomous transport system, machinery safety, computer vision, bridge crane, pallet cage, material handling]

Während Brückenkrane ein weit verbreitetes Materialflusssystem zum Bewegen schwerer Lasten sind, werden sie überwiegend manuell und für isolierte Transporte eingesetzt, was zu einem geringen Auslastungsgrad führt. In dieser Arbeit wird ein nachrüstbares und abnehmbares System, das bestehende Brückenkrane zum autonomen Transport von Gitterboxen befähigt, eingeführt und dabei auch in überfüllten Industrieumgebungen ohne Sperrzonen auf der Fertigungsebene arbeiten kann. Das System besteht aus einem neu entwickeltem Lastaufnahmemittel, einem kamera- und sensorbasiertem Wahrnehmungssystem und einer Steuerungsstruktur, die ein neu entwickeltes Sicherheitskonzept sowie ein Prozesssteuerungssystem umsetzt. Es wird eine Anforderungsstudie diskutiert, auf deren Grundlage ein Systementwurf vorgeschlagen wird. Dieser wird durch einen Prototypen validiert, der auf einem Standard-Brückenkran aufgebaut ist.

[Schlüsselwörter: Autonomes Transportsystem, Maschinensicherheit, Computer Vision, Brückenkran, Gitterbox, Materialflusssysteme, Fördertechnik]

1 INTRODUCTION

Overhead cranes are widely existing systems for handling heavy loads in production and storage areas for indoor material transport. They are typically operated manually and only for isolated transport tasks [1], resulting in a low degree of utilization. Accordingly, this product segment holds untapped potential for handling indoor transport tasks.

Pallet cages are a widespread large load carrier in production plants, as they can be filled with loose individual parts in a time and cost-efficient manner. Therefore, pallet cages are ideally suited for transport tasks within the production and for the supply of the assembly or final assembly operations. Today, transporting pallet cages is typically carried out by industrial trucks on defined transport routes. Also, the typical block storage of pallet cages requires sufficiently large aisles for maneuvering the vehicles [2].

Overhead cranes could be utilized for the aisle-free transport of pallet cages. If this is also done autonomously and without fixed sources and sinks, the identified potential of existing overhead cranes could be leveraged. In the concept presented in this work, the classic overhead crane is retrofitted to allow freely moving, i.e., without external safety measures, autonomous pallet cages transport in indoor applications. The suggested mechanical design provides the necessary load handling device and mechanical stabilization for safe autonomous operation but is simultaneously removable such that the crane can be operated manually with original functionality if necessary.

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The subsequent paper is structured as follows. The state of the art is presented in section 2. The operational concept for the autonomous pallet cage transport system is presented in section 3. The system should be able to operate safely in industrial environments with personnel and other machinery, and the design should be suitable to allow retrofitting pre-existing standard overhead bridge cranes for autonomy, with the option to easily decouple the system to allow for manual operation when needed. The requirements to achieve this are elaborated in section 4. A design concept to meet the formulated requirements is introduced in section 5. The design concept was validated by means of a prototype, presented in section 6, followed by a brief discussion of the results and conclusions.

2 State of the art

Cranes can be used for pallet cage transport by using pallet cage cross beams. In this case, the load locks of the crossbeam must be closed by an operator after it has been placed on the crane, whereupon the attached crossbeam can be hung on the hook of a crane. Stacking is complicated with this method because of the need to manually open the locks after the pallet cage has been set down.

In terms of fully automated indoor cranes, various kinds of transport solutions are commercially available. For example, bridge cranes equipped with a specialized load handling device (LHD) can be used for automated storage and retrieval of paper rolls or other standardized load units [3, 4]. The common safety concept for such automated indoor cranes is to allow automated operation only within areas without people. Safety measures such as fencing with access control, light curtains or motion detectors are used to detect entry or presence of people, which leads to the equipment being stopped. Automated operation is resumed when people have left the area, most commonly only after manual release.

In scientific literature, Handrich [5] and Schubert [6] have already drawn up concepts for automated indoor material handling systems based on cranes and the necessary safety requirements in a personnel-accessible environment. In these works, the automation of the actual transport of load carriers, which takes place in a person-accessible environment, was addressed. The handover stations for loading and unloading of the payload are always fixed, with fencing and safety measures to ensure people are not present. As mentioned by Handrich [5], the safety of transporting the payload between the handover stations (protection against falling payload) can be ensured either through a form fitting LHD or through an additional intermediate floor or lattice below the crane traveling area and above the actual operational area with people. Schubert [6] presents designs for form fitting LHD for both open and closed load carriers.

An automatic pallet cage transport system is presented in [7]. The system allows pallet cages to be stored and retrieved using a fixed handover point for pick-ups and drop-offs. The pallet cages are lifted from above by a specially developed LHD and can thus be transported in a space-efficient manner. The design includes a specialized crane trolley and a load handling device, which can be added or retrofitted onto an existing bridge crane system but does not allow for easy decoupling to restore normal manual functionality. The area used for automated operation is monitored by a set of light curtains, which stop the crane upon entry. The exclusion area is extended with the help of additional light curtains to include the handover point when the crane needs to drive there. In the context of [7], it has also already been demonstrated that automated high-density block storage of pallet cages can be realized with the help of overhead cranes.

Outside of retrofitting, to increase modularity and flexibility for both system production and operations of new overhead crane systems, the detachable autonomous pallet cage transport solution presented here can be combined with novel modular concepts for the overhead crane girders, such as the overhead crane girder in the form of a segmented truss system presented in [8] and [9]. In [10], the concept of a pre-stressed and segmented overhead crane system is introduced.

In contrast to the current state of the art, this paper will develop a pallet cage transport solution that does not require fixed pick-up and drop-off points, while operating autonomously in industrial environments safely from the moment the order is placed, without relying on fixed operating zones relying on external safety measures to exclude people. The system can be retrofitted onto an existing bridge crane with a standard hoist, and will include a coupling mechanism which, alongside reducing assembly effort, allows for easily decoupling the LHD and stabilization mechanism to restore the original functionality as manually operated crane.

3 Operational Concept

The pallet cage transport system concept presented here can be used as a bridge crane-based automated storage and retrieval system (AS/RS) with block storage similarly as described in [7], but with the important relaxation that the handover point is no longer fixed, pallet cages can instead be delivered to any point in the crane's movement space as long as there is a suitable space for lowering the pallet cage. In addition to transporting the payload to/from storage stack ("pickup to stack" and "stack to dropoff") and within stack ("stack to stack" for storage management), intermediate transports ("pickup to dropoff") between two arbitrary points are possible. While the management of a crane-operated block storage system has already been discussed in [7], the focus in the following will be on the "pickup to dropoff" order type. The principal operating cycle for the

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other order types is similar to the one described below, with the exception that one or both positions are fixed storage slots.

Here, it is assumed that a transport order, consisting of a rough position of the pallet cage to be picked up as well as a generally reachable target position, is given. Once an order is confirmed, the route to the pickup position must first be planned and then travelled to. The crane travels at a safe traveling height. At the pickup position, the system must recognize the existing pallet cages and select the one to be picked up. Suitable procedures must be used to determine the exact position and orientation of the pallet cage to be picked up. The LHD of the crane must be aligned with the pallet cage for pickup. For the pickup itself, the LHD is lowered onto the pallet cage. The pallet cage can be lifted up once it has been properly grabbed with the locking mechanisms by the LHD. Once lifted to the traveling height, the route to the target position is planned and the plan executed. Pallet cages may only be dropped off in the delivery area in suitable, free spaces to prevent damage to equipment or injury to persons. Such a suitable drop-off location, closest possible to the desired delivery position, must be selected by the system itself. Fine positioning and alignment must now be carried out above the selected delivery location before the LHD can finally be lowered to the ground to deliver the pallet cage. After lifting the empty LHD again, the transport order is completed, and the system is ready to accept the next order.

The movement of the crane does not take place in empty halls. In the movement space of the crane, there can be people, other equipment such as industrial trucks, or other objects, for which the transport process may pose a hazard. Fixed equipment such as other material handling machinery or large processing equipment might also be present in movement space, as well as other fixed structures, such as walls, ventilation pipes or shelving. Safety hazards from the crane colliding with fixed structures and equipment must be prevented. Restricted zones (zones where the crane is not allowed to operate at all) are used to limit the possible movement space of the crane to regions where collisions with fixed structures are avoided (cf. Figure 1). The upper area of the movement space below the hall ceiling, above a certain height, is usually mostly restricted through collision hazards with fixed objects. The lower area of the crane movement space, below a certain height, is the area with people and other moving equipment. Crane movement in this area poses a substantial risk and should in general be avoided. During horizontal travelling the crane is restricted to the upper area of the movement space (i.e., the lower area is treated as a restricted zone). To fulfill its intended function, as pallet cages must be both picked and dropped off on the hall floor, the lower area cannot be completely excluded from the allowed operating area. Therefore, to facilitate picking up and dropping off payloads, a corridor must be temporarily created in the otherwise restricted lower area in which the crane can operate safely. This operating corridor must be monitored by means of suitable safety technology and closed immediately (i.e., crane movement within the area be prevented) while people or other moving equipment are present within it.

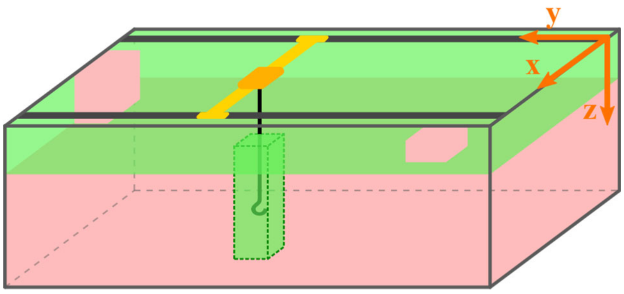

Figure 1. Restricted zones (red area) and non-restricted zones (green area) for horizontal crane movement as well as temporary vertical corridor for payload pick up and drop off (green cuboid)

4 System Requirements

This section discusses the necessary system requirements to implement the operational concept within the safe boundaries as described in the previous section. The discussion here focusses on three aspects, mechanical requirements, and requirements for the perception and control system of the crane. Each are described in their respective subsections below.

4.1 Mechanical Requirements

The standard hoists with load hooks attached to ropes or chains used in overhead cranes are not suitable for reliable and highly accurate LHD positioning, since they do not allow complete restriction of all translational and rotational degrees of freedom. Load sway can be significantly reduced by automated assistance functions but cannot be completely prevented. Additionally, angular alignment of the LHD is not possible.

Therefore, the key requirement for the mechanical design is to allow only the desired degrees of freedom. This corresponds to reducing the permissible translational degrees of freedom to a lifting or lowering movement and the rotational degrees of freedom to rotation in the plane (i.e., rotation about the lifting axis), so that it is possible to pick up an arbitrarily rotated pallet cage. The design should eliminate load sway caused by horizontal movements. In addition, the mechanical system should be designed to be as torsionally stiff as possible to reduce the vibrations of the system.

Besides the ability to pick up the pallet cage in any position or rotation, stable handling of an inhomogeneous load distribution should also be guaranteed, which is why horizontal alignment must be ensured during the entire transport. Thus, the system must be able to absorb moments around the travelling axes of the bridge crane.

Since the process control system cannot reliably exclude the possibility of a load passing over people (people can be avoided during navigation, but they might still walk below the crane), the risk associated with this must be mitigated by mechanical design. The intermediate floor-solution [5] is not suited for the operational concept, as it cannot support arbitrary handover points. The mechanical design of the LHD must therefore support a form fitting locking of the pallet cage.

The LHD and the stabilization mechanisms should be designed to allow for restoring the original manual functionality of the bridge crane within a few minutes. The coupling and decoupling of the mechanisms can be performed assisted by a (semi-)automated process.

4.2 Perception System Requirements

To achieve the required level of autonomy, the crane's environment must be monitored. Driving over people should be avoided, so the trajectory planning system must receive the necessary information during travel. This information must include at minimum the current positions of all people in the vicinity. If the intended movement direction of the people is also calculated, it can be used in combination with the current positions for dynamic reassignment of the safety zones. It must be noted, however, that the detection by means of a camera system is a non-safety-related comfort function and can thus only serve to increase process safety after adequate risk reduction has been achieved through other means.

Furthermore, the perception system must recognize all positions of the pallet cages in the camera field of view at the pickup position. The candidate pallet cage for pick up is to be identified according to predefined decision criteria. For further process assurance, the pallet cage must be examined for possible mechanical impairments and overfilling, which would make proper pick-up impossible. The perception system can then indicate that it detected a suitable pallet cage at the determined relative position and orientation. The required accuracy of the position and orientation is set by the mechanical tolerances and the control accuracy and of the system components that execute the fine positioning.

In addition, a suitable drop-off location must be found once the delivery area is reached. If it is not possible to deposit the pallet cage at the specified target coordinates, an alternate position within a suitable range must be determined. In this case, the deposit area must be free and sufficiently large to allow adequate space and a safety margin for the crane and payload.

4.3 Control System Requirements

Conventional overhead cranes are operated by a machine operator via control pendants or via a radio remote controller. These controllers usually use pushbuttons to provide travel commands for moving the crane along the machine axes in both directions at two different speeds (creep speed, rapid speed). If frequency converters for drive control are not utilized, the dual speed control is implemented with a contactor circuit. To ensure adequate positioning accuracy, it is recommendable to update the crane with frequency converter-based drive control system. For backwards compatibility, the drive system should be able to emulate the pushbutton-based dual speed control when operated in manual mode. Drives and associated control circuits for the LHD need to be added to the crane. Some added actuator circuitry will be safety-related to implement the necessary safety functions for the crane. To implement the controls for the autonomous operation, the crane additionally needs to be equipped with further control components, such as a (safety-)PLC (Programmable Logic Controller) and/or IPC (Industrial PC).

In addition to the possibility of influencing output variables, autonomous control also requires input variables in the form of position and velocity information for all machine axes. Since the position of the crane is decisive for the safety zone monitoring described above, this information must be acquired and processed in a safety-oriented manner. When the crane or the transported load enters one of the defined restricted zones, all machine movements must be brought to an immediate standstill and held in this state until the situation is manually resolved. Movement may only be restarted after the fault has been manually reset and the system is released into autonomous operation. In addition to the self-monitoring of the system, it must be possible for persons in the movement area to initiate an emergency stop at any time, which requires the installation of emergency stop stations throughout the movement area.

In addition to the restricted areas for the horizontal movement, the safety control system must include a safety-related supervision system of the operating area directly below the crane, as well as supervision of the payload status (locking mechanism supervision and load measurement). Vertical movements are only enabled while the payload has either been completely grabbed (all locking mechanisms closed) or fully released (all locking mechanisms open), and the operating area below the crane is free. While below a certain threshold height, that is defined by the already mentioned restricted zone within the lower space of the working environment, horizontal movement of the crane shall be disabled or allowed only at reduced speed to prevent hazardous situations caused by the sideways movement of the LHD on the ground level. If the presence of people in the operating area is detected, all crane movement must be stopped, and the safe state maintained until no person is within the operating area. Similarly, if the payload is only partially grabbed (locking mechanism not fully closed) during lifting, further upward crane movement shall be stopped to prevent loss of control of the payload. If the payload lock status changes during transport, crane movement shall be similarly stopped, again requiring manual intervention to reset.

5 System Design

A system design concept was derived based on the previously described operational concept and requirements. The system design is elaborated below, with again a focus on the three aspects of mechanical design, the perception system, and the safe machine control system.

5.1 Removable load handling device with mechanical stabilization

The mechanical concept for gripping and safely transporting a pallet cage consists of two components: the load handling device and mechanical stabilization, shown in Figure 4a. In [7] it has already been shown that gripping from above is the most promising approach. The LHD design from this work was used as a basis for the design here. In this case, mechanical grabbing of the pallet cage takes place from the inside, with rotary locks closing at the four corner points after the LHD has been lowered on the pallet cage, creating a form-fitting connection. Redundant securing of the load (necessary to ensure safety, e.g., in case of damaged pallet cages) is ensured by adding two lateral supports which additionally support the bottom of the pallet cage, preventing loss of control in case of mechanical damage to the pallet cage. The open or closed state of each lock must be separately detected, e.g., with an inductive sensor.

The LHD and the handled pallet cage are stabilized by a scissor mechanism, which not only provides sufficient torsional stiffness but also minimizes load sway during motion. In addition, the degrees of freedom are limited to the extent that only the hoisting or lowering movement and in-plane rotation are possible. To ensure rotation around the hoist-axis, the load handling device is connected to the scissor mechanism via a rotary drive. Due to the torsional stiffness of the scissor, the orientation of the LHD can thus be adjusted as required.

The scissor mechanism, together with the LHD, are suspended from the load hook of the hoist and additionally locked to the trolley at the top by a motorized locking mechanism. The entire load is therefore always suspended from the hoist's load hook. The scissor mechanism does not contribute towards load carrying, but only limits the degrees of freedom according to the requirements and serves to stabilize the overall system. In addition, the assembly or disassembly of the mechanical system is automated by means of the motorized attachment mechanism.

5.2 Machine vision-based perception system

For the developed concept, the required person detection is realized using two cameras on the sides at the top of the developed attachment (see Figure 4b). The entire environment of the crane is hereby continuously monitored, and the positions of all persons are identified and transmitted to the control system by means of AI-based evaluation of the video stream. At the same time, the approximate direction of movement of the persons is determined using a tracking algorithm. The current position and the calculated direction of movement are then used to dynamically adjust the crane's travel trajectory.

Another camera, which is mounted centrally at the bottom of the load handling device (see Figure 4b), is used to detect the pallet cages at the pick-up location. This will provide as undistorted and unobstructed view as possible of the pallet cages. Furthermore, an AI-based object detection system determines the positions of the pallet cages. The network architecture available in [11] and based on the YOLO Architecture first presented in [12] was identified as suitable for the task. It provides fast processing time while maintaining high accuracy. For the training of the object detection system, a dataset with sufficiently high variability must be generated to make the detections robust to changing and unknown scenarios. For this purpose, images with various positions, orientations and fillings were acquired with varying numbers of pallet cages. Additionally different image augmentation techniques were applied to further improve variability in the dataset. After training the system then provides information about the pallet cages in the field of view based on bounding boxes. Due to the simple geometry of pallet cages, the detected bounding box can directly determine the pallet cage's orientation.

The analysis of the pallet cage's condition is done in a subsequent step. To guarantee the best possible view, the frame of the pallet cage is to be examined for possible unacceptable deformations and protruding contents only after being already positioned directly above it. In addition to deformations, possible frame rusting is identified and evaluated. The entire analysis of the condition is again implemented as an AI-based system. Here the training data set was, in addition to the previously mentioned steps to ensure variation, due to the lack of real-world data, i.e., due to the limited availability of broken and rusted pallet cages, augmented with synthetic data. This offers the possibility to build the data set from numerous realistic deformation cases without the need to damage and destroy actual pallet cages. The final decision about the clearance for pick-up of the pallet cage is not safety-related, in case of a false assessment the LHD can either not close the locks properly (which is detected by the safety control system) or the safety of transporting a partially deformed pallet cage is ensured through the mechanical redundancy of the LHD.

Further a suitable drop-off location at the destination must be identified. The final drop-off point should be as close as possible to the coordinates specified for the order. The area must be free and sufficiently large. Since for the first approach the entire perception system is to be RGB-camera-based only, no depth-information is available. If a uniform background is always ensured, simple approaches such as edge detection and the use of contrast are viable. Alternatively, an AI-based approach can be applied, which can be trained on common objects in the production and warehouse context. Also, an approach trained on generic object recognition is possible.

5.3 Safe machine control system

To reach the requirements set for system control above in section 4.3, the machine control system needs to include capability for real-time control of the machine movements, performing the necessary safety functions with the required PL according to ISO 13849 [13] to achieve the required risk reduction, integrate the planning functionality and high-level process control with the information received from the perception system to enable autonomous system operation, and interact with an external system (e.g. user HMIs or external material flow controller) for receiving transport orders.

The machine control system can be divided into three main subsystems, as shown in Figure 2. The real-time control of the machine movements, including the interaction with the motor drives and the various sensors over fieldbus, is implemented with a PLC (programmable logic controller). For the safety functions, some of the sensors (e.g., for position measurement) need to be safety components. The safety-related subsystem is implemented with a safety PLC to achieve the required PL. To implement the higher-level process control functionality, the PLC interacts with a separate PC-based system to provide adequate computing capability and a better suited platform. Therefore, in the proposed solution the Robot Operating System (ROS) was used. The PLC-implemented machine controller cyclically updates the process controller with the current system state (position, velocity, payload state, safety control state), and in response cyclically receives a new command to implement (e.g., velocity or position command depending on current task phase).

The main components of the IPC-based process control system are, as shown in Figure 3, in addition to the perception subsystem, discussed above, a process controller - here referenced as the decision maker - that coordinates the entire transport process based on the latest information from the machine controller, perception subsystem, path planner and task manager. The current task of the crane is executed guided by a state machine-logic, which breaks the task down to individual steps with well-defined and runtime monitored pre- and post-conditions. The decision maker is the only instance that sends movement commands to the PLC-based machine controller. During horizontal travel, a path planner is used. Based on current system state (velocity, position), target position provided by the decision maker, as well as environment variables (map, static and dynamic zones) and planning strategy (e.g., fastest, or safest), the path planner returns the optimal route to target position. The horizontal plane reachable by the crane is hereby divided into a grid based on which a modified A* algorithm is executed.

Transport tasks are received via a web-based HMI, that also provides the possibility to monitor current crane status and movements, and are placed in a prioritized queue, held by a task manager instance. The task manager can also accept tasks from other sources than the HMI via the same API.

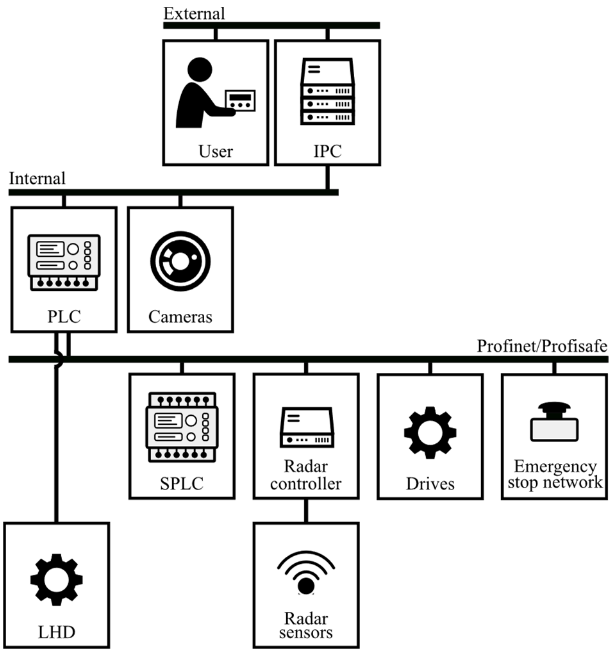

Figure 2. Structure of the machine control system. The PLC is used to implement the real-time machine control, which is supervised by the safety PLC-based safety control system. The IPC is used to implement the high-level process control system.

While the autonomous transport process is mainly controlled and supervised via the PC-Based part of the control system including the perception system, the safety controller, with the safety-related sensors and actuators of the crane, implements the required safety functions to ensure the safety of the operation. The required performance levels according to ISO 13849 [13] for the safety functions were defined based on a risk assessment according to ISO 12100 [14]. All the main safety functions of the crane were assessed to require PL e due to the continuous hazard exposure of the personnel in the crane operating area, potentially high severity outcomes due to heavy payload and the machine itself, as well as the hazard not being in all cases easily avoidable for the personnel (e.g., when the crane

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with payload approaches a person from above and behind). The main safety functions are:

- *Mode selection and machine start*: To start autonomous operation, the autonomous mode must be selected and started manually. Any faults or triggered safety functions must be manually reset before restarting the machine is allowed.
- *Crane operating area supervision and collision avoidance*: 3D-supervision of the operating area directly under the crane. While people are present in the operating area, all crane movements are stopped.
- *Restricted areas*: Prevent crane travel in areas, where due to other equipment or permanent structure at crane travelling height, or high personnel and other equipment density, the crane movement could unavoidably lead to accidents. Immediate stop of all crane movements if the crane position is within any of the defined restriction areas. In this case manual intervention is necessary to restore the crane to normal operating area.
- *Payload monitoring*: Supervision of the payload status. While the payload locking mechanisms are all either locked or open, vertical movement is allowed (if simultaneously allowed by collision avoidance). If the payload locking mechanisms are in a mixed state (some open, some locked), further crane travel is prevented, and manual intervention is necessary. If the payload weight is detected during lifting to be over the allowed maximum limit, upward vertical movement is disabled.
- *Distributed emergency stop*: As a complementary protective measure (as required per machinery directive [15] and ISO 12100 [14]), emergency stop stations for the crane are distributed throughout the crane operating area to allow personnel to stop crane operation in case of emergency. Activating the emergency stop at any of the stations will result in immediate stop of all crane movements. Manual reset and re-release into autonomous operation is required before further operation.

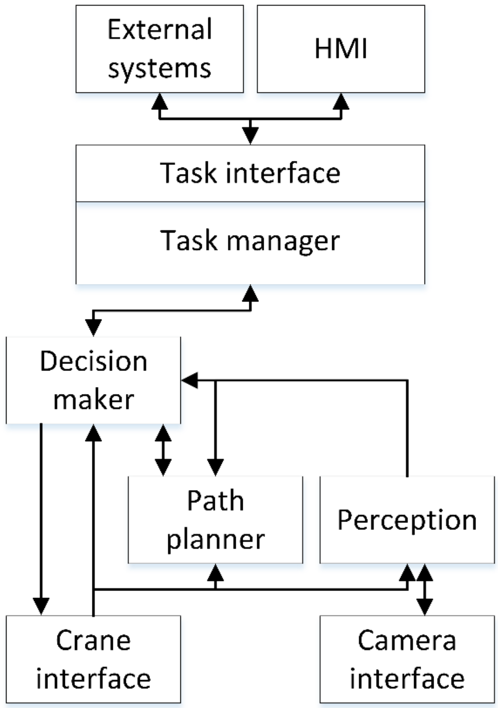

Figure 3. Internal architecture of the process control software. Tasks (transport orders) are received through an HMI from external systems through the task interface. The crane PLC sends the crane state over the crane interface, used by several modules, and receives commands from the decision maker. The perception-subsystem receives the images from the cameras and provides processed information to the path planner and decision maker. The decision maker communicates with the other modules and coordinates the transport process to execute the transport orders received from task management.

The supervision of the operating area under the crane can be implemented with the help of safety-related radar sensors (cf. Figure 4c), which allow for 3-dimensional area monitoring as necessary for this application, where a typical laser scanner-based solution (2-dimensional) would be inadequate. Commercial safety-certified radar systems are available, with certification up to PL d according to ISO 13849 [13], e.g., from [16], can differentiate between people and static objects, as long as the sensor itself is not moving. To achieve PL e, redundant coverage of the whole operating area is required. For this application, the payload, the LHD and associated components must move within the supervised area for normal operation, which is a challenge for defining the supervision zones of the sensors. The supervised operating area was divided into an inner and outer zone. As soon as the payload or LHD reaches the inner zone directly below the crane and below a certain height (safely detected with other sensors), the zone is muted, and only the outer zone remains active if the LHD is within the inner zone. The outer zone guarantees that movement of the crane is stopped if people or moving equipment come too close while the crane operates below traveling height.

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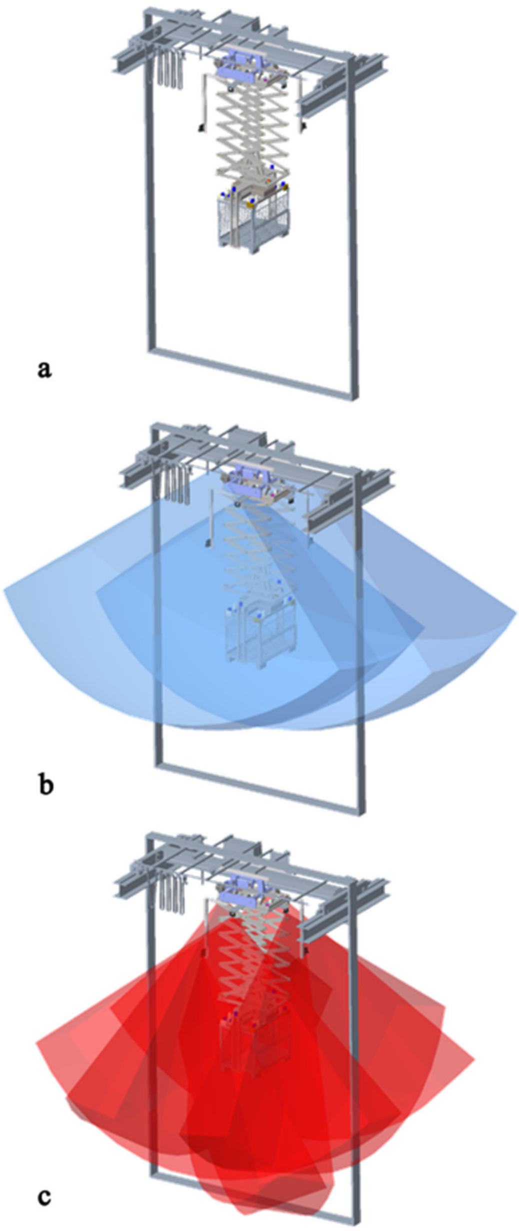

Figure 4. CAD-model of the system, a) LHD with lift mechanism, b) camera coverage and c) radar coverage

6 PROOF OF CONCEPT

A prototype of the proposed system design was built within the scope of the research project "AGiTra" ("Autonomes Gitterbox-Transportsystem") at the Institute for Material Handling and Logistics (IFL) at the Karlsruhe Institute of Technology (KIT). In the following sections, the scope of the research and the limitations are described. Subsequently, the final prototype is presented, and the findings obtained in the project are outlined.

6.1 SCOPE AND LIMITATIONS

The main aim of the prototype was to provide a proof-of-concept of the system design. The integrated prototype allowed for validating the industrial viability of the concept and the interaction between the individual subsystems. As such that prototype is not fully compliant with the relevant regulations [13–15] to be placed on the market. The safety functions, as outlined above, are implemented in the prototype, but e.g., partially relying on non-safety-certified components, and do not reach the required performance levels but are adequate for demonstration purposes.

The main deviations from the design concept as described above are:

- the lack of redundant payload protection (not included in the final prototype due to limited available vertical space on the test area – the main section of the crane runway has only *5* m vertical operating area, with one end having *9* m vertical height for more realistic tests),
- the safety functions were implemented on a standard PLC instead of a safety PLC due to budget limitations and to allow less restricted programming, as the restriction zone functionality requires slightly more complicated logic implementation than possible with some safety PLC programming environments, and
- the utilized machine position sensors are not safety-certified and only single-channel (comparable redundant solutions are commercially widely available but were not utilized due to budget restrictions).

Nonetheless, a prototype implementation of all the main safety functions outlined in the previous section were implemented for the prototype to demonstrate that the operational concept can be implemented in practice and that the process control system can properly operate within the safe envelope provided by the safety system. Apart from the restriction zone functionality (where complicated restriction areas can also be built by combining several rectangular zones) the main novelty in terms of safety functions is the 3-dimensional operating area supervision (cf. Figure 4c). Otherwise, the safety functions as outlined above are comparable to state-of-the-art as employed in industry. The focus thus with the prototype was on validating the 3D operating area supervision and its interaction with the rest of the system during operation.

In terms of the perception subsystem, at the time of writing the prototype system does not yet include the functionality to detect suitable drop-off locations in case the destination coordinates are obstructed. This functionality will be added as future work.

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6.2 Description

The prototype was built on a commercially available standard bridge crane. The prototype setup is shown in Figure 5. The standard crane was supplemented by a mounting device for attaching the scissor mechanism and LHD. The mounting device does not affect the usability in regular crane operation, if the scissor mechanism and LHD are detached. The scissor mechanism is attached by means of mechanical locks, which are primed to be fitted with electric actuators. The LHD attached to the scissor mechanism is equipped with a rotational drive, with a central camera for pallet cage detection, as well as electric rotary locks for the pick-up of the pallet cages. In addition, the radar sensors and cameras described in the concept were installed on the upper pick-up plate of the scissor mechanism. In addition to these components, which can be removed together with the scissor lift, the bridge crane was expanded to include laser position sensors both on the trolley in the z- and y-directions and on the crane bridge in the x-direction (compare Figure 1). All sensors and actuators are integrated into the overall machine control system through fieldbus connection to a machine control PLC. Communication in the prototype is realized using ProfiNet, which in an industrial setting should be replaced by ProfiSafe for the safety-related parts of the control system. Both bus protocols are Ethernet-based, meaning that the same underlying network could also be used to transmit the video feeds of the camera system. Thus, when removing the scissor lift with LHD, only two connections must be disconnected (power and data).

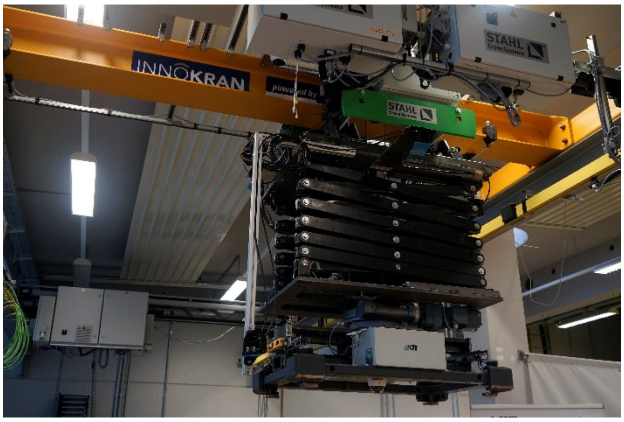

Figure 5. Built prototype

Due to the structural conditions of the available test hall, only limited testing under real conditions is possible: while the front part of the crane runway has a ceiling height of approx. 9 m, only approx. 5 m is available in the rear part (the larger main section of the runway). Likewise, the available crane runway allows only a small span of the crane bridge of four meters. Due to these limitations, the crane and trolley speeds of the prototype were reduced to 20 m/min and 10 m/min for the bridge and trolley respectively (compared to targeted respective speeds of 30 m/min and *20* m/min). With a larger operating area in an industrial environment, the targeted speeds can be safely implemented.

6.3 Findings

Overall, the design concept was successfully implemented in the prototype system. The subsystems were successfully integrated to form the complete system and the operational concept could be implemented, with the limitations described above, with the prototype. The communication between the subsystems (e.g., between the cameras and the perception subsystem, between the modules of the process controller within ROS, between the machine control PLC and the PC-based process control system) was similarly successfully implemented, the targeted cycle times (100ms control loop cycle time on the process control level) were reached. Pallet cages were successfully transported using the prototype system. During testing of the prototype, it was found that vibrations occur in the direction of the crane runway when the scissor mechanism is extended. In the direction of the crane bridge, however, the scissor lift is sufficiently stiff so that hardly any vibrations occur. The torsional stiffness is also sufficiently high to prevent torsion of the scissor lift.

The tests on the prototype showed that the utilized position sensors for the trolley and crane bridge did not provide adequate accuracy for the system to accurately execute the fine positioning with millimeter-range accuracy, when positioning on top of the pallet cage based on the information provided by the developed perception system. For an industrialized version of the system, a more accurate positioning solution is required.

As already shortly mentioned above, a limitation of the chosen radar sensors was detected early on. As the person detection algorithm of the sensors relies on detecting micromovements that people exhibit even when standing still, the sensors cannot be utilized for dynamic restriction zones during horizontal traveling (during horizontal motion the sensors cannot distinguish between people and other objects within the detection field, as the objects are moving relative to the sensor). For adequate risk reduction, the mechanical redundancy for load locking in the LHD combined with horizontal motion restricted through a safety function to traveling height (the radar system is muted while LHD is at traveling height) well above people is therefore necessary to achieve adequate risk reduction. To achieve redundant coverage of the operating area below the crane, required for reaching PL e for an industrial version, a total of 6 sensors are necessary (see Figure 4c). For supervising vertical traveling and payload interaction, the collision protection system concept based on the radars could be validated with the prototype, meaning that the required risk reduction for such an autonomous bridge crane transport system can be reached with an industrialized version of the system. At the time of prototype building, the certified radar sensors on the market could only reach 5m distance for supervision fields, which is inadequate for commercial crane installations, typically in the range of 8-10 m in height. At the time of writing, certified radar sensors with supervision fields up to 9 m are commercially available, meaning that industrialized versions of the system can be fitted on most typical bridge crane installations.

7 Conclusion

Enabling autonomous pallet cage transport in industrial environments by retrofitting existing overhead cranes poses a challenge, especially regarding the safety technology necessary to achieve adequate risk reduction. In this work a set of requirements for autonomous bridge crane operation in industrial environments, without relying on external safety measures, was provided. Based on the requirements, a system design was derived, validated by a prototype built on a commercially available standard bridge crane. The safety of the overall pallet cage transport system can be ensured by a combination of mechanical design measures (form fitting redundant LHD with mechanical stabilization) and a set of safety functions, most importantly restriction zones, 3D operating area supervision and associated collision avoidance. The design includes a coupling mechanism, which can be used to detach the LHD and stabilization mechanism to allow manual crane operation when desired. The safety radar sensors available during prototype building did not yet provide adequate supervision field distance for commercial crane installations (certified range limited to 5m, which is inadequate for typical industrial crane installations with heights 8-10m), while at the time of writing sensors with ranges up to 9m are commercially available, meaning that the concept is now industrially viable for typical industrial crane installations. Furthermore, for the perception subsystem, person and pallet cage detection, and pallet cage transport assisted by the system was successfully implemented. The detection of suitable drop-off locations and the further development of the pallet cage condition analysis are the subject of ongoing further research. The elaborated requirements and suggested system design can be used for implementing commercial autonomous bridge crane-based transport systems of pallet cages or other similar standardized load carriers.

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