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Evaluation of Performance and Cargo-Shock of an Autonomous Handling System for Container Unloading

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ABSTRACT

In the business-to-business sector large quantities of the internationally traded goods are transported by hundreds in identical parcels inside shipping containers. These parcels are often unloaded manually, which is labor-intensive and physically demanding. In previous papers, we presented a novel semi-autonomous container unloading system and an estimation of the performance. In this paper we evaluate the proposed system. Tests are performed in a laboratory testbed with a container and different sized parcels. We use this testbed to record the times for individual tasks of the system as well as the acceleration of the parcels. For comparison, we test the acceleration in the manual and bulk unloading scenario. Following a line-by-line approach, the proposed system's performance ranges from 261 to 3,014 parcels per hour, between manual and bulk performance. The throughput depends on the parcel's size and is higher for small parcels. With a maximum shock on the parcels of less than the proposed system induces significantly less force than other approaches (manual and bulk).

KEYWORDS: Autonomous Systems · Container Unloading · Cyber-Physical Systems · System validation · Performance Evaluation · Shock (mechanics)

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1. INTRODUCTION

Most of the goods in international trade are transported in containers, mainly by ship, and then packed and emptied in the hinterland [1]. To increase transport efficiency on both ships and trucks, containerized goods are loaded with individual parcels instead of pallets, making it more difficult to empty the containers [2, 3]. Continuous increase in transport volume creates the need for improved efficiency in unloading such containers [4].

Several automated solutions for unloading containers are available, but they are not economical as fully autonomous solutions often fail due to variable loading patterns [5]. Existing solutions pick items one at a time, limiting potential throughput, or treat parcels in bulk, damaging fragile goods. To overcome the problems of existing solutions, we developed a system with a new unloading strategy. The system we present in this paper grips entire parcel rows gently and unloads the container line-by- line to prevent damage but maintain high unloading performance on the other hand. If autonomy fails due to unforeseen complex situations, our system's semi-autonomous approach can prevent downtime through short-term human interaction.

This solution focuses on parcel contract logistics, where it is usual that one container is completely packed with just one or two different goods resulting in a uniform parcel pattern. The system is designed to unload those structured packed containers following an 80/20 approach, which means that 80 % of the containers can be unloaded with the system autonomously. In 20 %, a worker has to interfere (by making a decision, controlling the robot manually, or unloading single parcels by hand). In this paper, we evaluate the performance of the system and the shock acting on the parcels during unloading compared to other unloading strategies. First, we present existing unloading techniques and then describe our newly developed unloading system. In this context, we look at the underlying unloading process and break it down into elemental tasks for which we identify parameters influencing the unloading performance. We present a method that we then use in the subsequent performance evaluation of our newly developed system for autonomous container unloading. We describe the experimental setup used to generate the required data and explain how the timing measurements and impact tests were performed. Afterward, the test results are presented and subsequently discussed. Finally, we draw a conclusion and give an outlook on future work that still needs to be done.

2. RELATED WORK

2.1. State of the art

Current reviews of autonomous unloading systems for stacked parcels in containers are presented in [5, 6]. A systematic characterization of the seven identified unloading systems can be seen in Figure 1. The Parcel Picker is a semi-autonomous system for bulk unloading. An operator stands on the machine, manually pulling the parcels on a stationary telescopic belt conveyor [7]. The Carton Mover is a semi- autonomous system for half-row unloading [8]. The operator controls the system, pulling parcels directly on a conveyor belt. The COPAL C2 is a semi-autonomous system for single and multi-parcel unloading with open linear kinematics mounted on a mobile platform [9]. An operator, supported by an automatic height and gripping-point correction, controls the system and places the items on an integrated conveyor belt. The DAIFUKU Robotic Truck Unloader is a fully autonomous system for single parcel unloading consisting of a jointed-arm robot mounted on a mobile platform [10]. The entire system can move into a container, scan the scenario, and place parcels individually on a conveyor. The Honeywell Robotic Unloader is a fully autonomous system for half-row unloading, which combines a grip of multiple parcels with a moving floor [11]. The system consists of a straddle-arm with a full-width vacuum gripper mounted as the end effector. The Siemens RUBUS is a fully autonomous system for bulk unloading, pulling a carrier layer out of the container. It holds stacked parcels with a heavy curtain, causing them to collapse [12]. The Boston Dynamics Stretch is a fully autonomous system for single parcel unloading with a seven degree-of-freedom arm [13]. The system uses a vacuum gripper for individual parcel handling, placing each gripped item onto an attached conveyor.

Despite many unloading systems for containers or trucks, none of these solutions has yet found widespread application [5]. This is due to too low unloading performance due to variable packing patterns and system downtimes caused by complex scenarios requiring manual intervention [6, 14].

The available solutions can be classified according to various features [6, 14]. One feature that directly affects process time is the type of unloading. Techniques include single item unloading (500 to 1,000 parcels per hour) [15–17], gripping of multiple parcels stored in a

System Characteristics	Characteristic values				
Unloading kinematics	Moving floor (29 %)	Single linear axis kinematics	Two lines axis kinematics (43 %)	Multi-DoF robotic arm (29 %)	
Level of automation	Manual (0)	Semi-autonomous (43 %)	Fully autonomous (57 %)		
Unloading type	Bulk unloading (29 %)	Full-width unloading	Half-row unloading (29 %)	Single parcel unloading (43 %)	
Mobility	Stationary	Linear axis (43 %)	Two linear axes (29 %)	Multidirectional (14 %)	Multidirectional and rotational (14 %)
Operation mode	Single-gate (43 %)	Multi-gate (57 %)			
Goods	Parcels (100 %)	Bags (14 %)	Unpacked goods		
Picking classification	Grasping (14 %)	Vacuum (57 %)	Belt (29 %)		
Conveyor	Stationary (43 %)	Telescopic (57 %)			

0 % — 100 % Proportion of system with corresponding characteristic

Figure 1: Systematic characterization of unloading systems (in accordance with [6]). The color indicates the number of systems with the mentioned characteristics.

Figure 2: Example of performance of manual unloading [14]

row (1,500 parcels per hour) [18], and bulk unloading of the entire contents of the container onto conveyors (1,500 to 25,000 parcels per hour) [11, 12]. Compared to manual unloading with 420 to 840 parcels per hour [14]. Figure 2 presents the performance of manual unloading during a survey period. It shows the current performance over time, the mean performance, and a break-adjusted mean performance. Additionally, the performance of the best 10 % of all measured days is given. Both the average as well as the top 10 % performance show high variation, resulting in highly variable unloading performance.

In bulk unloading, the system does not pick up individual items but unloads the entire load of the container via conveyors in the floor, where the parcels can be damaged by falling. As Figure 1 shows, there is no other system following the approach of full-width unloading. Of the systems performing half-row unloading, none works autonomously but is dependent on an operator controlling every move.

Systems of predetermined times are often used for better comparability of systems and processes [19]. For manual operations, these systems are based on the times of human movements. Due to the different ways tasks are processed, this approach can only be applied to machines to a limited extent [20]. In [21], a method for calculating the unloading time of a robotic unloader is presented. This approach is similar to other approaches in logistics, in which the times of all sub-processes are measured, and the sum is used to estimate the total time of the process [22, 23]. System tests or simulations are recommended to verify the processing time [22].

2.2. System for line-by-line unloading

The unloading system, which was introduced in [14] and described in detail in [24], consists of an omnidirectional mobile chassis to allow high maneuvering capability in the container and between two unloading gates, a vertically moveable platform with tilt-adjustment, and three individually movable gripping-modules with vacuum suction cups to grip and pull parcels. The platform and center of the robot are equipped with conveyors to move the unloaded items to external material-handling technology at the back of the system. Figure 3 highlights the controllable parts of the system.

With this setup, the system can unload complete rows of parcels with the same bottom line in one gripping process. Multiple parcels can be unloaded simultaneously, increasing the overall throughput of the system compared to a single grip.

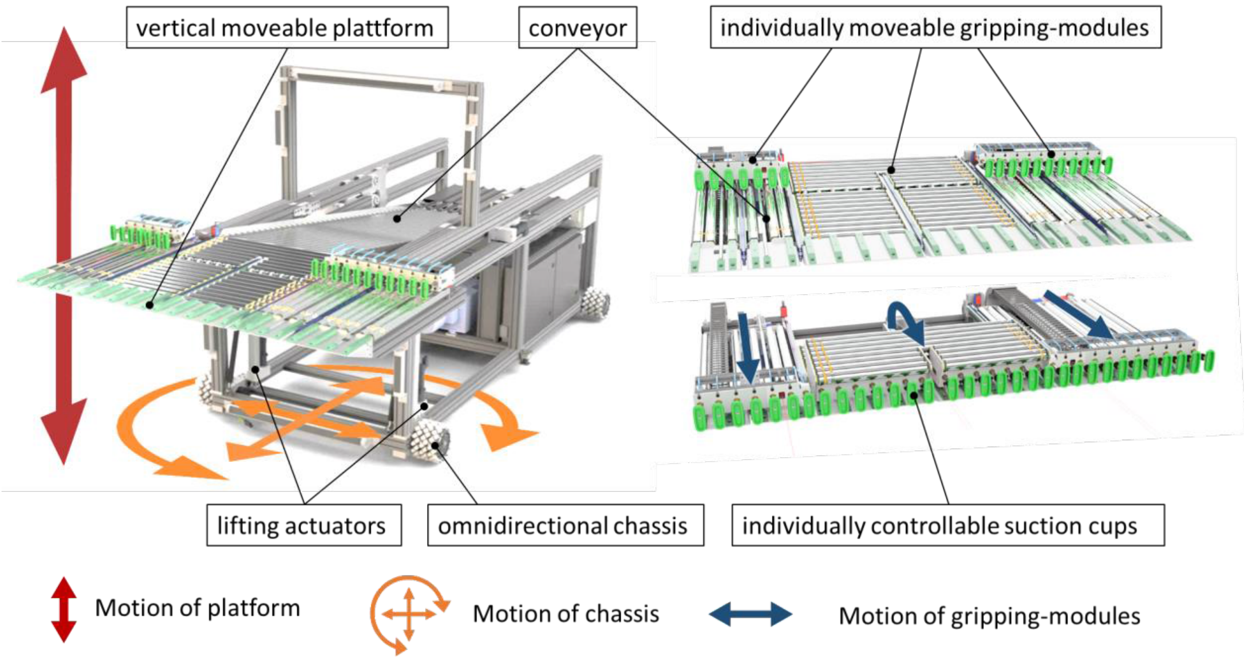

Figure 3. The unloading system with its degrees of freedom modules (in accordance with [14])

Figure 4: Pattern of a carton layer in a standard sea container as used in the tests.

2.3. Unloading process and parameters

Although there is a considerable variation between containers in terms of package sizes, the contents of individual containers are packed relatively evenly with a small variety in parcel size. In the case of large quantities of identical parcels, containers can be filled with homogeneous parcel types. A typical situation found in a container is shown in Figure 4. In a preliminary analysis of containers unloaded at a german logistics company, the majority showed a completely homogeneous stacking pattern.

The unloading of these properly stacked packages can be automated through repeated execution of identical process steps consisting of individual tasks [24]. Figure 5 shows the process steps and the associated tasks performed by the robot. First, four depth cameras scan the area in front of the robot. A parcel detection algorithm identifies individual parcels in each of these four images. After merging these four images, the parcels are selected for the next pick-up based on their accessibility, and the robot's optimal unloading position is calculated. This step is processed within under a second and takes the same time regardless of parcel size. Then the robot approaches the parcels by moving its chassis and platform simultaneously. When a new parcel layer has to be unloaded, the chassis movement takes longer and varies with the parcel size. To pick up the parcels, the robot moves the gripper modules to the front of the platform and starts the vacuum as soon as the front of the parcel is close to the suction cups. The vacuum is individually monitored and controlled. As soon as all parcels have been gripped successfully or the non-gripping suction cups are deactivated (grab), the gripper modules move to the rear (pull). The robot switches off the vacuum and moves the gripper modules to their resting position, with the middle module sinking below the conveyor belts. Finally, the conveyor modules unload all the parcels that are pulled onto the platform to the back of the robot (convey), where an external material-handling technology is installed on the robot. After transfer, the cycle for unloading a parcel has been completed and can be restarted with the identification of the next packages to be unloaded.

As presented in [21], the total unloading time is the result of the individual unloading steps. Assuming the parcels are loaded homogeneously, the number of rows in a container is the number of layers n_x in length times the number of rows n_z. With an unloading time of t_r the total unloading time t is

$$t = n_x \, n_z \, t_r + t_{system} \quad (1)$$

where t_{system} are additional times needed for system boot and shutdown before and after the unloading process.

To plan the system tests, we identified the influencing parameters for all tasks needed. First, the external influence parameters for each task were determined by interviewing experts in unloading systems and the unloading process. We derived the elementary parameters from the first-order principles and the experts' assessments for each task. This allows us to vary only the parameters relevant to the task, significantly reducing the number of tests required for each task. By combining the individual times with the parameters of the unloading process (e.g., parcel size), we can estimate the total unloading time for different conditions. According to [21], the parcel size is the most affecting parameter in a majority of tasks to be tested.

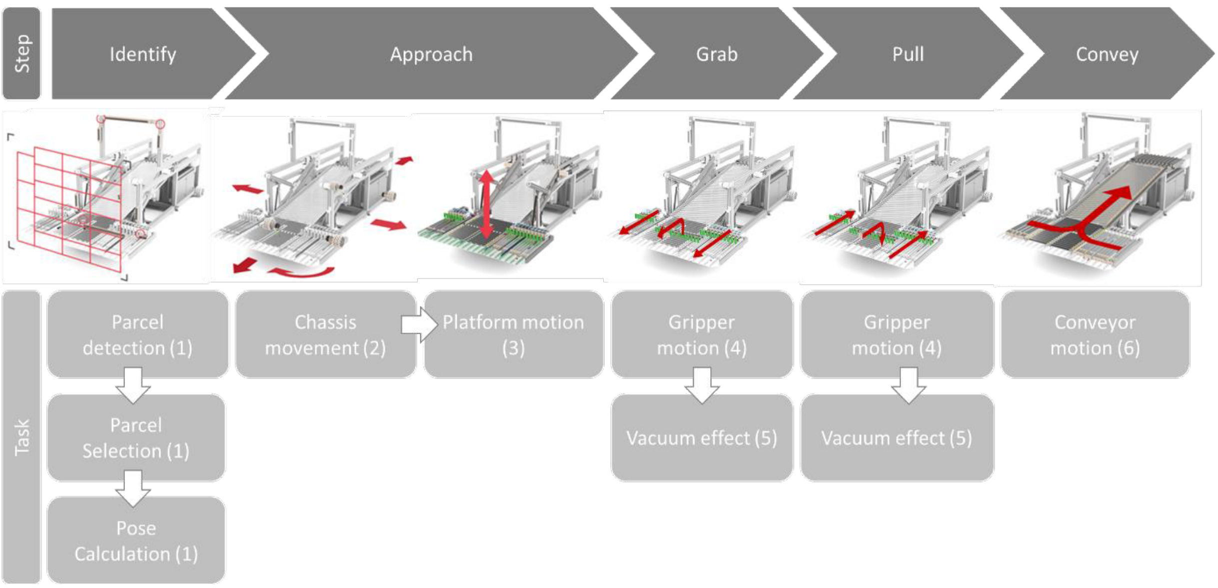

Figure 5. Steps and tasks of the unloading process (in accordance with [25])

Table 1: Parameters affecting unloading performance and robustness of tasks T. Parameters and tasks that do not affect the overall unloading time in the investigated scenario are shown in italics in gray. The last column indicates whether the task is considered in experiments conducted in this work.

T	Task	Performance factors	Length considered in experiments
1	Parcel Detection	*object size (parcel width, parcel height), lightning (brightness, contrast), refractions, reflection (parcel surface)*	
2	Chassis motion	distance (parcel depth), resistance (floor inclination)	$l_{x,1}$
3	Platform Motion	distance (parcel height), *resistance (parcel mass)*	l_z
4	Gripper Motion	resistance (*parcel mass*, platform inclination), lx3	$l_{x,3}$
5	Control Vacuum	resistance (parcel surface: porosity, parcel mass, platform inclination)	
6	Conveyor Motion	distance, resistance (parcel mass), platform height	$l_{y,1}$, $l_{y,2}$, $l_{y,3}$, $l_{x,2}$, $l_{x,3}$

3. METHOD

3.1. Method for performance evaluation of the proposed unloading system

The unloading performance is defined as the number of parcels per hour. For stacked parcels, [21] specify the unloading time of a full container by the number of rows in a container multiplied by the unloading time per row. Assuming only identical parcels stacked in rows, the optimal setup consists of the parcels oriented with their long side to the back [21]. For a standard 1AA 40-feet-container, this results in 39 vertical layers with 21 parcels in width and 11 parcels in height for the small parcel sizes and three parcels in width and height for the large parcel sizes [21]. This contribution compares a task- based calculation with experiments for unloading a vertical layer of parcels. In this case, the unloading time of a container becomes the unloading time for a vertical layer multiplied by the number of parcels in depth.

In previous works, we analyzed the tasks described in the last section and found that the times for parcel detection (task 1) and vacuum control (task 5) are negligible compared to the other tasks (tasks 2, 3, 4, 6) (c.f. [21]). Further, we analyzed which of the task-related performance factors affect task times. The parameters and environmental conditions shown in italics and gray in Table 1 only affect the robustness of task execution (e.g., lighting conditions influence the detection accuracy of the parcel detection algorithm), but not the execution time. Therefore, we neglect these parameters for performance evaluation.

Preliminary studies have shown that only the parameters that affect distance affect discharge time [21]. The reason for this is that all controllers are velocity controllers, and the system is overdesigned concerning the maximum mass of complete rows. Hence we only varied distance parameters and performed the tests on level ground with no floor inclination.

For simplification, we used two different parcel types with varied sizes – small, i.e., 0.3 m x 0.2 m x 0.1 m, and large, i.e., 0.8 m x 0.64 m x 0.6 m. We stacked the parcels according to the parcel contract logistics setup in complete and homogeneous rows from bottom to top. The width and height of the resulting walls directly result from the inside dimensions of a container. Due to the top- to-bottom unloading logic, the approach step of chassis motion is only relevant for a new wall, thus measured for the top row. Table 2 shows the resulting tests-matrix.

Table 2: Test matrix for the evaluation of the developed container unloading system conducted in this paper

Task *T*		**Parcel type**		**Row type**	
		small	**large**	**bottom or center**	**top**
Approach	**2 (chassis)**	x	x		x
	3 (platform)	x	x	x	x
Grip	**4**	x	x	x	x
Convey	**6**	x	x	x	x

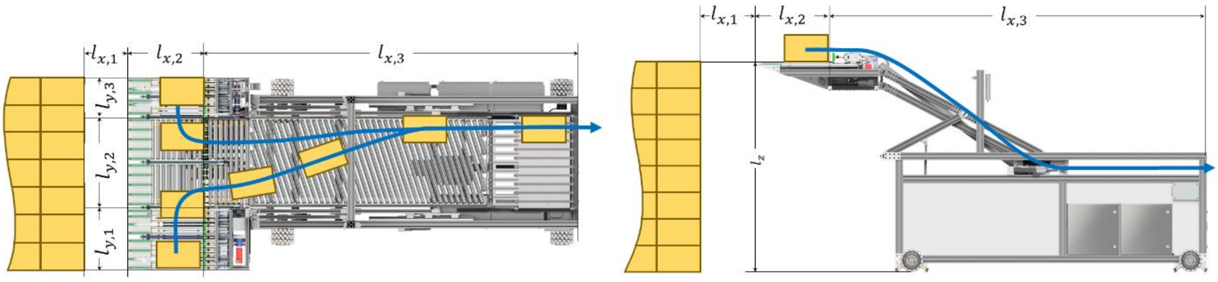

Figure 6: Relevant dimensions during parcel unloading for chassis, platform, gripper, and conveyor motion.

3.2. Experimental setup

We conducted all tests in a laboratory test-bed with the container unloading system in front of a 10-feet-container (see Figure 7 left). According to the experiment parameters, we used two different parcel sizes. In each test, all parcels were of identical size as described above and were stacked in homogeneous rows. We performed each test according to the test-matrix in Table 2 ten times, as described in Section 3.1. The tests were performed in front of the container because there was not enough space inside for ten layers. A wooden construct the size of a container inside reconstructed the important areas for localization and navigation algorithms. Figure 3 shows the important distances of the experiment. The distance traveled by the chassis $l_{x,1}$ varies depending on the parcel size and is between 0.3 m and 0.8 m. The distance of the gripping motion $l_{x,2}$ is 0.86 m. The parcels' conveying distance depends on the parcels' position in the y-direction of the robot. The individual parts of the platform $l_{y,1}$, $l_{y,2}$, and $l_{y,3}$ are 0.74 m, 1.7 m, and 0.5 m, respectively, and the length of the conveyor $l_{x,3}$ is 4.3 m. The maximum height of the platform l_z is 2.45 m.

We measured the time of each essential task and the total time for the approach phase (a concurrent combination of the platform and chassis motion). The time was measured from the beginning to the end of the motion of the respective subsystem. The stop time of one step is identical to the start time of the subsequent step, so the total unloading time is the sum of the individual times. Motion detection and time measurement happen in the system. The control computer is connected to the PLC via OPC and monitors the execution of the individual tasks. The execution time of a task corresponds to the time from the transmission of the control goal to the PLC until the message that the goal has been reached. The time for the conveyor motion is determined as the time for clearing the entire platform since a subsequent gripper motion can then be performed again.

In addition to performance evaluation, we have further performed tests to analyze the gentleness of our line-by-line unloading approach compared to bulk and manual piece-by-piece unloading. For these tests, parcels have been equipped with a smartphone using a *TDK icm4x6xx* (error $\leq \pm 2\%$) accelerometer and the software *phyphox* [26] to record the acceleration during unloading (see Figure 7 right). Additional weight has been added to reach a total mass of approximately 5 kg according to [27] (mean parcel mass between 4.5 kg and 7.4 kg). The tests for line-by-line evaluation have been stacked the same way as in the performance tests (see Figure 7 left) in front of our unloading system. For manual piece-by-piece unloading, we have repeated the process by hand. To simulate a bulk unloading scenario, we have stacked a homogeneous parcel wall in a packing pattern typical for container shipping (see Figure 7 middle, our test parcels are marked with an x). The stack has been overturned several times to collect comparative data.

Figure 7: Experimental setup – developed container unloading system in front of container (left), bulk tests (middle) using parcels equipped with an accelerometer and additional weight (right)

To determine the mechanical shock during the three unloading scenarios, the acceleration $\mathbf{a}(t)$, adjusted for gravitation, has been recorded over time t. The shock a_{max} in g is the maximum of the 2-norm of the acceleration divided by 9.81 $\frac{m}{s^2}$.

$$a_{max} = \max \frac{\|\mathbf{a}(t)\|_2}{9.81} \quad (2)$$

4. RESULTS

4.1. Unloading evaluation

The total unloading time results from the sequential steps approach, grip, and convey individual times. Figure 8 shows the total unloading time for a complete row depending on the height of the bottom of the row for the scenario with small parcels (11 rows) and large parcels (3 rows). The unloading time of a complete row varies between rows at the top of the container and the remaining rows. Because unloading starts at the top, the approach task time due to the distance traveled to the next layer of parcels affects the total unloading time. Overall, unloading time per row is shorter for small parcels since the distance traveled by the platform increase with parcel size. At the bottom, the parcel size affects the approach time only to a small extent since the motion consists of a translation and tilting of the platform, with the tilt independent of the distance traveled. Hence, the bottom-most row has an almost identical unloading speed for small and large parcels. For small parcels, the second-highest row has a significantly lower unloading time because the unloading at the top utilizes a combination of tilting and moving of the platform.

As described above, the measurements scatter little for the unloading time of the bottom row. For the center rows, the approach time of small and large parcels varies more since it's directly affected by the distance traveled, equivalent to the parcel height. The top row has the most variation between parcel sizes because this task is even more affected by parcel size since the chassis motion is slower than the platform motion. Figure 9 presents the individual task time and the total unloading time for rows at the container's bottom, center, and top. The most significant difference between the top and the remaining rows is the approach time. Therefore, we propose to change equation (1) to account for unique characteristics happening between layers. With an unloading time of t_r per row and an additional time t_x for each new layer, the total unloading time t becomes

$$t = n_x(t_x + n_z t_r) + t_{system} \quad (3)$$

where t_{system} are additional times needed for system boot and shutdown before and after the unloading process. As in equation (1), n_x is the number of layers and n_z the number of parcels per layer. Table 3 presents the mean values of the unloading time per row and the approach time for a new layer for large and small parcels.

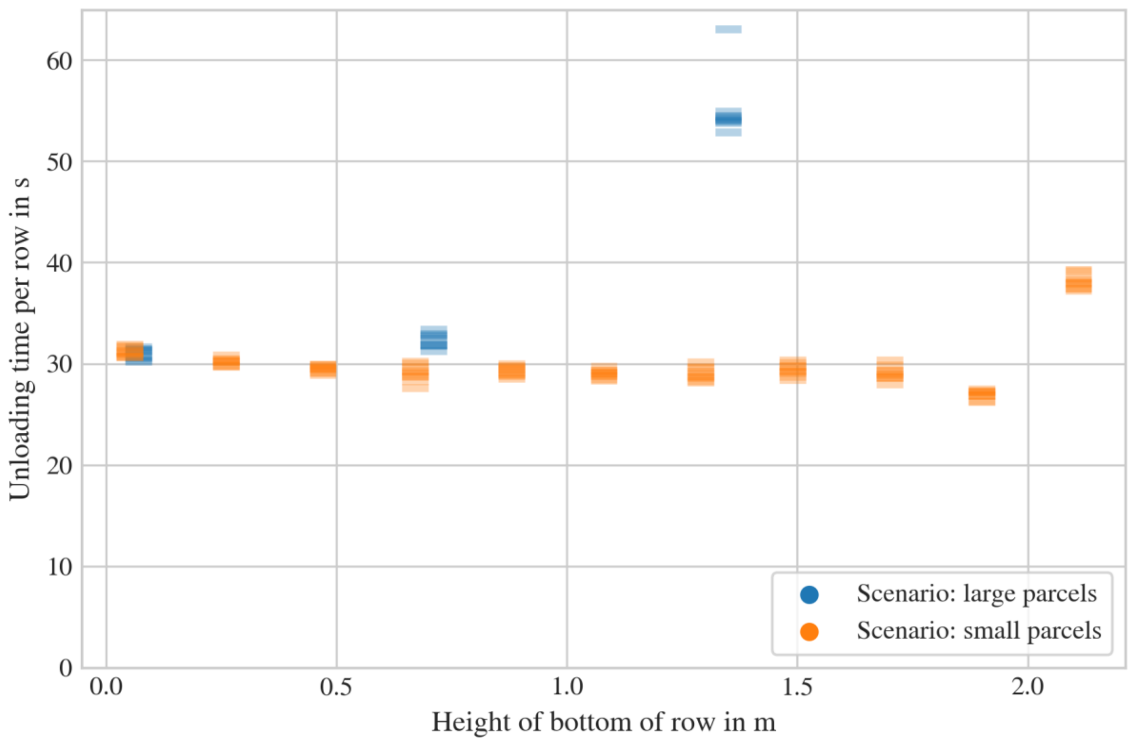

Figure 8: Total unloading time for a row depending on the height of the bottom of the row. Each horizontal line displays one unloading event, with darker colors representing multiple events at the same place. To improve differentiability, the heights of the two bottom rows were shifted slightly relative to each other.

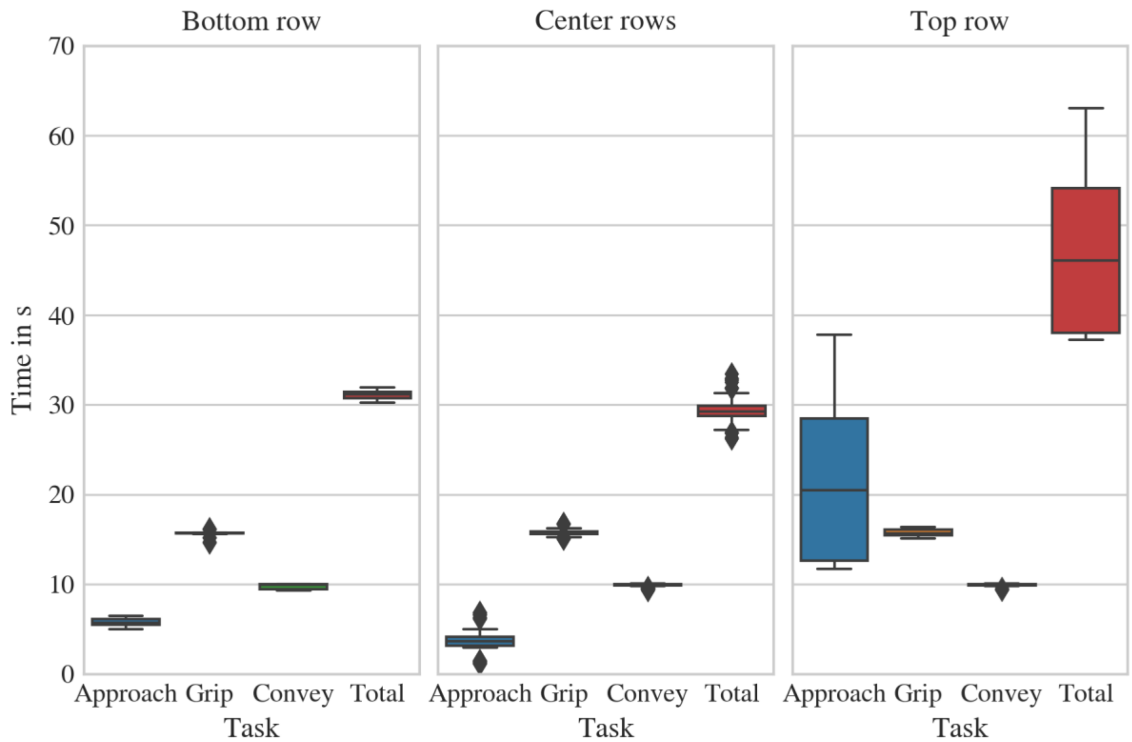

Figure 9: Breakdown of the unloading time for rows at different heights for both parcel sizes. Note that the times for the bottom row have low variation, whereas the approach time, and therefore also the total time, for the center and top rows vary due to the different parcel sizes.

Table 3: Unloading times for the individual steps and the total unloading time for small and large parcels.

	Unloading times for a row				Unique times for a new layer		
Scenario	**Platform approach time in s**	**Gripper time in s**	**Convey time in s**	**Time per row t_r in s**	**Platform Approach time in s**	**Chassis Approach time in s**	**Time for a new layer t_x in s**
Large	6.7	15.7	9.9	31.6	7.8	29.3	29.3
Small	3.7	15.7	9.9	29.3	12.2	11.5	12.2

The unloading time for a full row t_r, which is the sum of platform approach time, gripper time, and conveyor time, is between 29.3 s and 31.6 s. The approach time, which is the maximum of the approach time of the platform and the chassis, since both tasks run in parallel, is 29.3 s for large and 11.5 s for small parcels. Following equation (1), this leads to an unloading performance of 261 to 3,014 parcels per hour (Table 4).

Table 4: Unloading performance for different scenarios

Scenario	**Time per row t_r in s**	**Time for a new layer t_x in s**	**Rows per layer**	**Layers per container**	**Unloading time per container in s**	**Number of parcels per container**	**Unloading performance in parcels per hour**	
							Measured	Estimated [21]
Large	31.6	29.3	3	14	1,737	126	261	341
Small	29.3	12.2	9	39	10,760	9,009	3,014	3,252

Figure 10: A collapsed wall of parcels (left) and incurred damage on parcels in detail (middle and right)

4.2. Impact tests

We performed the unloading processes for each scenario ten times using accelerometer sensors to compare the unloading scenarios concerning careful parcel handling (gentleness). For a direct comparison of the three unloading scenarios, the mean shock $\overline{a_{max}}$, determined in the tests, are summarized in Table 5, including their standard derivations $\sigma_{a_{max}}$.

Table 5: Mean and standard deviation of the maximum shock induced into the parcels for the three investigated unloading strategies.

Unloading scenario	$\overline{a_{max}}$ in g	$\sigma_{a_{max}}$ in g
Line-by-Line	0.2	0.1
Manual	7.4	2.1
Bulk	16.1	4.6

In addition to the high shock values determined during the tests for bulk unloading, direct observations could also be made on the packages used for the tests. Figure 10 shows the condition of the parcels after the first bulk unloading test. Considerable damage to two parcels occurred after one drop.

5. DISCUSSION

5.1. Performance, comparison, and limitations

The unloading performance measured in the experiments is roughly 20 percent lower than the estimated performance based on a layer-based calculation presented in [21], which does not consider the necessary movement between layers. Thus, the deviation is explained by the reduced performance for the unloading of top rows due to the increased time for the chassis motion to reach a new vertical layer (Figure 9). The speed of the chassis is limited by the vehicle's acceleration due to the large mass and restricted by the navigation in the narrow surroundings of the container. Unloading a complete row requires a platform or a gripper of a width close to the inner width of the container. This minimizes the possible distance of the robot from the walls, which makes navigation complicated due to the low tolerances.

Nevertheless, as shown in Figure 11, the unloading system has a higher throughput than the previously reported solutions for individual gripping, multi-grip, and manual unloading (c.f. section 2.1). In addition, the latter also entails poor ergonomic working conditions due to the monotonous work and the heavy loads to be handled, as well as the environmental conditions, which in turn results in an increasing challenge of finding workforce. Compared to bulk unloading, however, the system is significantly slower but introduces far less acceleration and shock impact onto the parcels unloaded. Parcel shock with the proposed unloading method is 0.2 g, compared to 7.4 g for manual and 16.1 g for bulk unloading. Thus, the evaluated unloading system provides a reasonable tradeoff between high unloading performance and careful parcel handling (Figure 11).

However, when comparing the results of the above performance characteristics, limitations that were not examined in the tests performed should be considered. Most prominently, we did not assess the robustness and accuracy of the object recognition system. If the stack of parcels and the individual parcel coordinates are detected inaccurately or even incorrectly, the positioning of the system or the platform height becomes inaccurate. This leads to corrective movements being necessary or packages being pulled against the edge of the platform, or incorrect vacuum units being activated. Such failures in parcel recognition would cause time delays and thus have a decisive effect on the overall unloading performance of the system.

The stacking of the parcels also directly influences the unloading performance of structured line-by- line unloading approaches. A non-continuous horizontal row of packages, i.e., rows with one or more vertical offsets, results in multiple platform movements necessary for height adjustment and the corresponding repeated execution of the tasks grip and convey, reducing the overall performance accordingly by the respective execution times. Therefore, the evaluated

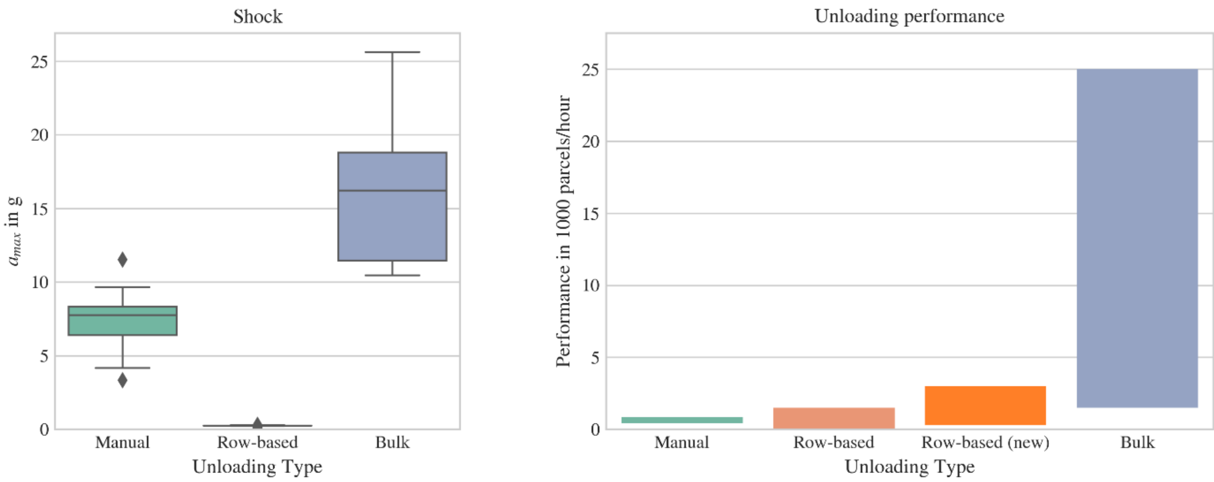

Figure 11: Comparison of maximum induced shock (left) and unloading range of performance (right) for the proposed unloading method (row-based new, bright orange) compared to manual (green), previous row-based approaches based on literature (orange), and bulk unloading (purple).

line-by-line unloading system operates most effectively in scenarios with mainly homogeneous goods in the containers as in the considered parcel contract logistics use case. However, even in such application scenarios, situations may occur in which stacks of parcels are disordered or partially collapsed due to incompletely loaded containers. Such anomalies cannot always be unloaded with the investigated line-by-line unloading system and were not considered in the conducted experiments. However, an economic analysis conducted as part of the requirements analysis prior to system development showed that an autonomous unloading rate of 80 % is sufficient for the investigated unloading system [14]. In the event of significant stacking anomalies, manual unloading can therefore be resorted to. The proposed system still considerably optimizes the required personnel deployment as well as the ergonomic working conditions of the human workforce.

Other unloading approaches are less affected by these two parameters, i.e., the object detection and the order of the parcel stack: especially the manual unloading performance is almost not influenced at all by any anomalies in the stacking of the parcels due to the superior cognitive capabilities and handling flexibility of human workers. Also, bulk unloading is hardly affected by irregularities in parcel stacking and does not require any vision system, thus eliminating a potential factor of uncertainty in the unloading procedure. In single packet unloading, disordered packet stacks also do not significantly affect the unloading performance, since only parcel-by-parcel unloading is possible. In this case, the achievable performance is in principle comparable to the worst performance of line-by-line unloading approaches, which occurs when the rows in the parcel stack are arranged in a staircase-like manner. The sensitivity to inaccuracies in object recognition also influences the system positioning. Still, these may be compensated more easily by the higher degrees of freedom of the end-effectors of some systems during the approach step without significant delays.

5.2. Potentials for system improvement

Furthermore, the results show that the unloading performance is non-linear with height (row of parcels). In principle, placing larger parcels at the top would increase performance, as this would reduce the platform movement time. However, the results have shown that the platform movement time is relatively short compared to the chassis movement. Hence, the latter is more critical for the overall system performance. Thus, increasing the speed and acceleration of the entire unloading system would have a much more significant positive impact on unloading performance than changing the parcel stacking.

In addition, to simplify navigation and reduce the time for required adjustments, either optimization of navigation algorithms or a slightly narrower system design could improve times for chassis motion. Moreover, the control logic offers further optimization potential regarding even greater parallelization of the individual tasks. For example, the steps of conveying and approaching could be executed simultaneously, which would increase the system's unloading performance.

Furthermore, while performing the experiments, we encountered limitations with respect to the lowest bottom row since the platform must be strongly inclined for the platform tip to reach the container bottom (compare Figure 3b). On the one hand, the angle between the suction cups and the parcel wall can lead to problems when grabbing the parcels. On the other hand, the parcels must overcome this incline during pulling, which can also negatively influence the system behavior if the suction cups are in non-ideal contact with the parcel surface. Mechanical optimization of the hardware would have to be carried out here to increase the system's robustness and performance.

5.3. Needs for a general methodology for unloading performance assessment

Evaluation with the method presented in [21] demonstrated its applicability for the analysis of line-by-line unloading approaches and assessing such systems' unloading performance. As follows from the results, the measured difference in unloading performance depending on the parcel size (see Table 4) underlines the need and importance of a systematic method for assessing system performance as presented in this and our previous work [21]. For other approaches, such as bulk unloading, most of the tasks, i.e., detection, platform motion, gripper motion, and vacuum control, would be irrelevant and could be neglected, thus having only the parcel size and initial chassis motion as parameters for structured performance evaluation. However, as we demonstrated in our shock impact tests, the impact in bulk unloading compared to line-by-line unloading approaches is dramatically higher, and, consequently, only low-susceptible goods can be handled in this manner. Therefore, we suggest that in addition to throughput, the shock load on the packages should also be taken into account when evaluating unloading systems. This provides interested customers with more relevant parameters to make an informed decision on selecting an unloading system that meets their specific requirements.

To further increase the transparency of throughput performance data, extending the proposed method to include a performance evaluation as a function of the degree of ordering of the parcel stacks could help benchmark the throughput of respective systems for different application scenarios in a more targeted manner.

6. CONCLUSION AND OUTLOOK

This paper evaluated the unloading system presented in [24] and compared the results to the method proposed in [21]. The unloading performance based on laboratory tests is lower than the theoretical estimation. The reason for this is the reduced performance in unloading the top row due to the chassis motion. The system is only slightly smaller than the container it moves in, so navigation is a critical and slow task. Reducing the system's width or increasing the chassis speed while maintaining unloading characteristics could potentially improve performance up to the estimated values. Additionally, we measured the acceleration and derived the shock on the parcels for the proposed method and two competing approaches, manual and bulk unloading. Unloading through the presented system is much smoother than in the other analyzed methods without compromising efficiency.

The evaluated system presents the first step towards smooth and efficient container unloading by facilitating a unique line-by-line unloading method. Based on the results achieved so far, the method should also be transferred to other processes, such as loading. Also, it should be extended by considering different, representative degrees of the order of parcel stacks. In the future, we want to further increase the performance of the developed unloading system by improving navigational speed. An improved human-machine interaction will also increase the robustness of the solution in hard-to-detect environments.

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