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Introducing *autoCARGO* – A Fully Autonomous Robot-Assisted Vehicle for Last-Mile Parcel Delivery

autoCARGO – Ein vollständig autonomes, roboterunterstütztes Fahrzeug für die Paketzustellung auf der letzten Meile

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The future of urban logistics, particularly in last-mile delivery, is set to transform through advancements in autonomous driving and robotics. This paper introduces *autoCARGO*, an autonomous electric vehicle developed within the *UNICARagil* project for efficient parcel delivery and pickup in urban areas. The vehicle integrates a robotic arm, advanced vision systems, and cloud-based communication to handle parcels autonomously. The paper details the hardware and software components, highlighting the successful demonstration of a fully automated parcel delivery system. *autoCARGO* exemplifies the potential of autonomous vehicles in urban logistics, offering a scalable and efficient solution for the future of parcel delivery.

[Keywords: Autonomous vehicle, Urban logistics, Last-mile delivery, Robot, Parcel delivery]

Die Zukunft der urbanen Logistik, insbesondere auf der "letzten Meile", wird durch Fortschritte im autonomen Fahren und in der Robotik revolutioniert. In dieser Arbeit wird *autoCARGO* vorgestellt, ein autonomes Elektrofahrzeug, das im Rahmen des *UNICARagil*-Projekts für effiziente Paketzustellung und -abholung in städtischen Gebieten entwickelt und gebaut wurde. Das Fahrzeug integriert einen Roboterarm, fortschrittliche Kamerasysteme und eine cloudbasierte Kommunikation, um Pakete autonom zu handhaben. Diese Arbeit beschreibt die Hardware- und Softwarekomponenten und hebt die erfolgreiche Demonstration eines vollautomatisierten Paketzustellsystems hervor. *autoCARGO* zeigt das Potenzial autonomer Fahrzeuge in der urbanen Logistik und bietet eine skalierbare und effiziente Lösung für die Zukunft der Paketzustellung.

[Schlüsselwörter: Autonomes Fahrzeug, Urbane Logistik, Letzte Meile, Roboter, Paketzustellung]

Figure 1. *The autoCARGO vehicle platform combines a purpose-built level 5 autonomous car with a fully automated parcel delivery system.*

1 Introduction

The rapid growth of e-commerce has significantly increased the demand for efficient last-mile delivery solutions. Traditional delivery methods face challenges such as traffic congestion, high delivery costs, and environmental impact. These issues have been extensively discussed. For example, Boysen et al. provide an extensive overview of current and innovative concepts [1]. They conclude, however, that there is still a significant amount of research required. Some concepts such as autonomous delivery drones are already nearing real-life application [2], [3]. Similarly, autonomous delivery robots are being rolled out in pilot projects [4], [5].

These solutions all have various limitations though. Drones, for example, have a very limited capacity whereas robots bound to the sidewalk move at very low speeds, only slightly increasing the efficiency of the delivery process.

Autonomous driving might alleviate some of these issues and with the first self-driving taxi cabs being deployed in various American cities [6], [7], it is worth looking into how autonomous vehicles could be utilized for last-mile delivery.

Alverhed et al. review the impact of self-driving autonomous delivery robots on last-mile deliveries, highlighting the potential benefit these systems might have in the future [8]. However, they emphasize the need for real-world case studies as most studies on these topics have been theoretical in nature. There have been some publications presenting a real-life prototype of an autonomous delivery vehicle. E.g. Ochs et al. fitted an autonomous shuttle with a cargo hold that effectively turns the vehicle into a mobile parcel station [9]. While this concept adds a lot of automation to the delivery process, a human is still required to manually pick up the parcel which blocks the vehicle from further deliveries. Heinrich et al. retrofitted a stock delivery vehicle with the hardware required for autonomous driving as well as automated parcel delivery using an on-board robot [10]. This allows fully autonomous delivery of parcels to roadside parcel stations where the parcels can be picked up by the customer asynchronously. Due to the system being based on a stock vehicle not intended for automated driving and the limited movement of the robot, the cargo capacity of the prototype is very limited.

autoCARGO improves upon existing approaches by combining a purpose-built level 5 vehicle with a large loading container and a delivery robot. This allows for fully autonomous parcel delivery while maximizing the space and carrying capacity of a large delivery vehicle.

2 System Overview

Both passenger transport and urban logistics on the so-called “last mile” will look different in the future. These changes will benefit from research and developments in autonomous driving and robotics. As part of the *UNICARagil* [11] project, four autonomous electric vehicles were developed and built from scratch.

Figure 1 depicts *autoCARGO*, an autonomous vehicle for parcel delivery and pickup, that operates electrically, is locally emission-free, and is designed for urban spaces. It makes receiving and sending parcels independent of the presence of its customers, reducing the need for human intervention and increasing efficiency. Connected with other vehicles and information systems, *autoCARGO* can respond flexibly to traffic disruptions. Various fleet and order management systems work in the cloud in the background for this purpose [11].

The route targets all parcel stations where shipments need to be delivered to or picked up from. Various private and public parcel stations can accommodate individual or even very large numbers of parcels. For this purpose, an underground parcel storage facility can be connected to the parcel station. In this way, urban space can be used as efficiently as possible.

The associated *autoCARGO* app can be used to order the dispatch of parcels. The desired parcel station can be selected individually, easily and flexibly for each shipment (dispatch or pickup). The app informs about parcels ready for pickup just as reliably as about the delivery to the recipient.

In a parcel center, parcels are stacked in a container arranged to optimize routing and accommodate anticipated acceleration forces during the transport. This container is then moved into the autonomous parcel delivery vehicle which is then routed to deliver the parcels while being able to pick up parcels on the way as well.

Overall, *autoCARGO* is more than a research vehicle that drives autonomously and picks up and delivers parcels on its own. *autoCARGO* is a logistics system consisting of:

- the actual vehicle with exchangeable parcel storage, the loading container,
- the parcel center,
- private and public parcel stations for the delivery and collection of parcels by customers and
- the *autoCARGO* app.

autoCARGO's storage system is geared to the current volume ratio of deliveries and collections. The B2C sector dominates, with significantly more parcels being delivered than picked up [12]. Accordingly, the loading container is significantly more voluminous than the shelves next to the container in which picked-up parcels are stored.

Just like the other *UNICARagil* vehicles, *autoCARGO* combines various innovative technologies. These include up to 90-degree steering angles allowing sideways movements, a modular sensor setup, and a state-of-the-art software pipeline for autonomous driving. However, this work focuses on the delivery system of *autoCARGO*, as presenting the entire vehicle would be out of scope for this publication. A full list of publications highlighting various aspects of the *UNICARagil* project can be found at [13].

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3 THE VEHICLES OF *UNICARAGIL*

The *UNICARagil* project uses the latest findings from research into electromobility and automated and connected driving to develop autonomous electric vehicles for a wide range of future application scenarios. It borrows from the IT industry with its rapid development cycles and update mechanisms. The basis is a modular and scalable vehicle concept consisting of utility and drive units that can be flexibly adapted to a wide range of applications in logistics and passenger transportation. The core element of the research and development work is the functional vehicle architecture, which is networked with the cloud, the road infrastructure, drones as flying sensor clusters and a control station for remote control and supervision. Other focal points are the development of generic sensor modules for environment detection, a flexibly expandable and updateable software and hardware architecture as well as an innovative wheel design. The latter includes steering and acceleration of individual wheels allowing for new and innovative forms of movement in road traffic such as turning on the spot or moving sideways. These driving maneuvers enable precise approaches to shuttle stops or parcel stations.

The goal was to build four level 5 autonomous driving vehicles from scratch. Aside from a temporary seat used during the development phase, there was no driver seat in the final version of the car meaning the cars were deployed without a safety driver during the final demonstration. *autoCARGO* is being developed as part of the *UNICARagil* research project funded by the German Federal Ministry of Research and Development. Four autonomous vehicles are being developed in this project. While three vehicles are used for passenger transport, *autoCARGO* fulfills parcel logistics. *autoCARGO* shares with the other vehicles a common chassis and vehicle automation system but differs in its interior layout and equipment.

4 DESIGN GOALS

Parcels come in many shapes and sizes. To be able to plan, develop and construct *autoCARGO*, we set the following goals: Parcels have a maximum size of 50 cm x 40 cm x 30 cm and a minimum size of 20 cm x 20 cm x 5 cm, a rectangular shape and a maximum weight of 6 kg. The system should accommodate between 36 and 1000 parcels of various sizes. Since *autoCARGO* is based on the *UNICARagil* chassis, the overall size of the system was predetermined and we aimed to exploit the space as efficiently as possible without exceeding the maximum permissible payload weight.

5 HARDWARE

This chapter explains the hardware used by the *autoCARGO* logistics concept which was developed in parallel to the vehicle platform. To achieve this, an identical mockup of the vehicle interior, called *CARGOlab*, was built. The available space was determined by the project and the vehicle design. Based on this, the subsequent design, the choice of an interchangeable loading container, and the automation using a collaborative robot could be developed. Additionally, this means that the material handling hardware is largely independent of the vehicle hardware. Specifically, there is a dedicated computer that enables the control of all cameras and allows the software to be developed and operated in isolation. Figure *2* depicts the inside of *autoCARGO* giving an overview of the built-in hardware components.

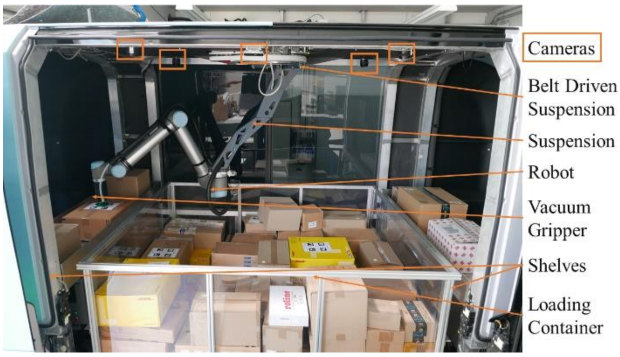

Figure 2. *The interior of autoCARGO. Next to the large loading container are the shelves for parcels picked up on route. They are handled by the mounted robotic arm, which is guided using the multi-camera setup.*

5.1 ROBOT WITH SUSPENSION

A lightweight robot (UR10) with a reach of 130 cm and a load capacity of 10 kg was selected for parcel handling. However, the workspace of the robot was insufficient to cover the entire storage area within the vehicle, necessitating an extension. To facilitate the suspension of the robot on a circular track above the loading container, an optimized robot boom was designed. This boom connects the base of the robot to the slewing ring mounted on the ceiling of the vehicle. The design had to fulfill several critical requirements: high stiffness, crash safety, minimal weight, and a geometric configuration optimized for the following: maximum freedom of movement for the robot, comprehensive coverage of the required gripping locations, and compatibility with the test driver's workspace even when the robot is installed.

Kinematic simulations of the articulated robot were employed to iteratively determine the available installation space for the robot suspension. This space was further constrained by the presence of a driver during test drives. Based on the identified available space, load paths within this area were determined using topology optimization for the sheet metal construction. Following the conceptual design phase, the resulting stresses were analytically evaluated. To further minimize the weight of the suspension, additional topology optimization of the sheet metal structure was conducted. The optimized design was simulated, and the results were evaluated. The sheet metal construction was subsequently tested for weight, deformation, stress distribution, and natural frequencies under specified loading conditions. Ultimately, the suspension was manufactured and successfully tested in the *CARGOlab*.

Figure 3. *The suspension connects the robotic arm with the vehicle. The additional degree of freedom significantly increases the reach of robot.*

The integration of the suspension with the robot and the suction gripper seen in Figure 3 enables the robot to reach and pick up parcels both within the vehicle and at parcel stations outside of the vehicle. For safety considerations, the motor control of the slewing ring was interfaced with the UR10 control system, ensuring its linkage to the emergency shutdown mechanism.

5.2 End effector & Vacuum Pump

The end effector integrates a vacuum gripper that can handle parcels of 6 kg and an RGB-D camera system for the measurement of new parcels as described in 6.1.3. As vacuum pumps are quite loud by nature and ready-made industrial soundproof housings are too large for installation in the delivery vehicle, a new one was developed. Since the air sucked in by the vacuum gripper must also leave the soundproof box, a multi-folded channel was designed and integrated for this purpose. The entire box, as well as the channel, is lined with sound-absorbing foam. The two pumps, each with 65 watts, heat up accordingly during operation, but due to the short duty cycle of the pumps, no additional cooling measures are necessary to prevent the pumps from overheating.

5.3 Loading Container & shelf

A large, exchangeable loading container was selected for parcel storage to ensure optimal use of space and maximal storage capacity and so to allow us to meet our design goals. Parcels are stacked according to the planned route such that the topmost visible parcels can always be delivered without the need to rearrange the parcels. Additionally, shelves next to the container were added for parcels picked up from the parcel stations. They are smaller than the loading container, since it is assumed that more parcels will be delivered than picked up. Conceptually, additional shelf levels or conveyor belts could be integrated for extended storage of collected parcels. At the end of the route, the robot loads the parcels collected and placed on the shelves into the exchangeable container, which is then unloaded at the parcel center.

5.4 Parcel station

For fully automated parcel delivery, a station is required to serve as an interface between the user and *autoCARGO*. The mockup station developed for this purpose (see Figure *4*) features two distinct openings: one for the user and one for the vehicle. The user opening is at an ergonomic height, allowing the user to open the flap and load parcels using the app. This side is equipped with a camera that reads QR codes from the app for identification. The vehicle opening, facing the street, can move the parcel closer to the vehicle to facilitate access for handling with the on-board robot. The wing doors provide additional protection against external interference. A scale for measuring the weight of unidentified parcels was installed between the deposit area and the pull-out mechanism. In addition, an underground storage facility for parcel management is planned to be connected to the parcel station. The parcel stations will be strategically located near a shuttle stop so that users can drop off or pick up parcels before or after a trip.

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Figure 4. *Model of the parcel station for demonstration purposes, which is shown with the side facing the vehicle. It is depicted in the opened and fully extended state.*

5.5 CAMERA SETUP

On top of the sensor suites for autonomous driving used by all vehicles of the *UNICARagil* platform, *autoCARGO* employs a multi-camera setup to ensure continuous detection and tracking of parcels inside and outside the vehicle. Four high resolution greyscale cameras are strategically mounted on the ceiling, each pointing downwards to provide comprehensive coverage of the interior space. This arrangement ensures that all parcels are continuously monitored from multiple angles, facilitating accurate detection and tracking. Additionally, an RGB-D camera is installed above the door, oriented to face outward towards the parcel station. This camera plays a crucial role in perceiving the delivery environment, enabling precise interaction with the station where parcels are exchanged. It is also used for intrusion detection to prevent parcel theft and accidents with the robotic arm. Complementing this setup, another RGB-D camera is affixed to the end effector of the robot. This camera provides detailed close-up views of previously unknown parcels, allowing the system to initialize and file these parcels accurately at the beginning of the delivery process. Together, these cameras create a robust perception system that enables autonomous parcel handling.

6 SOFTWARE

The software chapter details the different software components of *autoCARGO*. On top of the main software stack of the UNICARagil vehicles, autoCARGO features some additional modules controlling the material handling system, including:

- the camera-based vision system to detect and track the parcels
- the robot control
- the communication interface to the external cloud
- the sequence control that coordinates all activities of these modules

6.1 VISION

The vision stack of the software is divided into several parts, each dedicated to a specific task. They are outlined as follows:

Inside the vehicle, several monochrome cameras identify the parcels in the loading container and shelves and estimate their respective 6D poses. To facilitate precise localization, parcels are equipped with ArUco markers [14]. Optimal gripping points are determined based on the known position of these markers on the parcels. An initialization process, that uses a depth imaging camera, determines the dimensions of the parcels as well as the position of the markers. Additionally, a depth imaging camera monitors the area between the vehicle and the parcel station to prevent third-party interference and to determine the pose of the parcel station relative to the vehicle.

6.1.1 CAMERA CALIBRATION

Accurate interaction between the cameras-based parcel detection and the control of the robot movements requires calibration of the cameras with respect to the reference frame of the vehicle. To maintain high accuracy over time, this process should be done periodically. Therefore, it has been automated. A 3x3 chessboard can be mounted on the base of the robot to serve as a calibration target for the monochrome cameras. The robot rotates by defined angles, while the cameras capture images at each position to solve the perspective-n-point problem accurately. The position of the calibration target within the coordinate frame of the vehicle is calculated for camera calibration, using the reference frame of the robot. The calibration parameters of the RGB-D cameras are calibrated using a larger target mounted on the loading container.

6.1.2 PARCEL DETECTION & TRACKING

Figure 5. *The view from one of the interior cameras looking down into the loading container. Detected markers have been marked and the parcel's coordinate systems are visualized using reprojected axes.*

Accurate 6D pose estimation of each parcel is essential for the robotic arm to achieve precise gripping positions. Parcels are marked with a 2x2 ArUco marker grid as seen in Figure 5. Experiments have shown that compared to single markers, using a marker grid provides higher accuracy with smaller markers. This allows for additional data, such as a human-readable address, to be printed on the parcel. This grid setup also reduces false detections by requiring multiple markers to be detected before confirmation. The 6D pose of each parcel is estimated using all detected marker corner points filtered over time for stability. The same algorithm is used to locate a marker on the parcel station, determining its precise position relative to the vehicle frame when initializing the delivery process.

6.1.3 PARCEL INITIALIZATION

The detection and tracking algorithm tracks the marker pose rather than the parcel itself. To determine the optimal gripping position on the parcel, the relative position and orientation of the marker with respect to the parcel must be known. This is done by initializing each parcel once using the RGB-D camera on the robotic arm while the parcel is located on the tray of the parcel station. The initialized parcel is then recorded in a database.

The coordinate system of the marker is determined using the same algorithm used for detecting parcels described above. The shape and extension of the parcel is computed using the 3D measurements of the RGB-D camera. The parcel is assumed to lie flat on the stations tray which allows us to segment its top face and project it into 2D. Finally, a minimal enclosing rectangle is fitted around this projection which allows us to estimate the center and the dimensions of the parcel. With both, the parcel and the marker coordinate frame available, the relative transformation between the two can be computed and stored for later use.

6.1.4 INTRUSION DETECTION

To ensure safe operation we must prevent that humans interact within the workspace of the robot. The outward-facing camera of the vehicle continuously monitors the parcel delivery process. If a human enters the critical area between the vehicle and the parcel station, measures such as slowing down or stopping the robotic arm and communicating with the person via speakers can be implemented. The control station would then contact the person and release the robot again.

6.2 SEQUENCE CONTROL

The sequence control is based on a behavior tree that manages the material flow process. It processes information from various components and issues decisions and control commands accordingly. The handling service is activated at each parcel station and initiated via the vehicle control system. Before interacting with the parcel station, the sequence control must compare the positions of the vehicle with the parcel station. Depending on the situation, the sequence control can open and close the vehicle and parcel station doors. It also uses the parcel information to determine which parcels need to be stored or retrieved. Camera tracking provides position data for parcel handling, enabling the robot to move precisely to the recognized locations.

6.2.1 ROBOT CONTROL

The suspension of the robot with the slewing ring provides an additional degree of freedom, which describes a circular path with the base of the robot. The robot itself has six degrees of freedom, allowing it to reach any pose within its workspace. The extension enlarges the workspace, but a suitable slewing ring position must be calculated beforehand. This angle is determined based on the current position of the slewing ring and the target position using a sigmoid function with a tolerance range. If the current pose is outside of this range, the nearest upper or lower limit of the tolerance range is selected as the target. This ensures that every pose within the overall workspace can be reached.

Based on the calculated angle of the slewing ring, a synchronous movement of the slewing ring and the robot is planned. The speed is calculated, and the acceleration of the slewing ring is considered to reach the final position within a specified time. Additionally, the robot movement is calculated based on the final pose of the base within the given travel time. Due to the separate movement of the two systems, if the final poses are outside of a defined radius

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from the rotation axis of the slewing ring, the path planning of the robot must be adapted to avoid collisions.

6.2.2 COMMUNICATION

To facilitate information exchange between different instances and to store parcels and user-specific data, a cloud-based communication system was implemented. It stores both process-specific parcel information, such as sender and recipient, as well as parcel-specific information like dimensions and current position, which are relevant for the handling process. The management and control of the parcel stations also take place via the cloud. This allows for querying the position and fill level of the respective parcel stations, as well as controlling the doors. Additionally, user management, which is necessary for the app, is handled here.

6.3 APP

The *autoCARGO* app serves as an interface for the user to the *autoCARGO* system with his parcel stations. It manages all user-centred actions, such as dropping off and picking up parcels at the parcel stations and opening the user door. Additionally, the available parcel stations are displayed on a map.

7 DEMONSTRATION

The *UNICARagil* project, a collaborative endeavor involving 8 universities and various companies, culminated in May 2023 with a demonstration event held at Aldenhoven Testing Center. This event showcased the four autonomous vehicle prototypes (see Figure *6*), driving different routes on the same testing area. This chapter presents the demonstration of *autoCARGO* and how it successfully combined the modules presented in this paper.[2]

Figure 6. *The four UNICARagil vehicles on outer ring of the Aldenhoven Testing Center where the final demonstration took place in May 2023.*

To verify functionality, the test carrier was built and tested. In the first step, a lab was set up as an identical replica of the *autoCARGO* interior. The handling concept was developed and tested there. Different scenarios were tested, including parcel delivery, pickup, parcel initialization, and emergency shutdown of the robot in case of a collision.

The test route on the Aldenhoven Testing Center consisted of a circular route where multiple parcel stations could be approached by *autoCARGO*. Figures (7-10) show some scenes from the testing phase.

Figure 7. *autoCARGO approaching a parcel station sideways.*

In Figure *7*, *autoCARGO* uses its innovative wheel design to approach a parcel station sideways to start the delivery process. While the vehicle can approach the station using traditional steering, this mode allows maneuvering towards hard-to-reach parcel stations in urban scenarios.

[2] A video introducing *autoCARGO* is available at https://www.youtube.com/watch?v=fCzByrbpRAk

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Figure 8. *After the doors opened, the handling system is about to start the delivery process.*

Once the parcel station has been reached, the doors open (see Figure *8*) and the delivery process begins. If parcels need to be picked up, this is done first. After scanning and initializing them, they are moved to the shelves next to the loading container. Figure *9* shows the robot picking up one of the parcels and delivering it to the current parcel station. After delivery is concluded, the parcel can be picked up by a human from the sidewalk-facing side of the station as seen in Figure *10*.

Figure 9. *The robotic arm picking up a parcel to deliver it to the parcel station.*

During the testing phases and the demonstration at the final event, it was shown that it is possible to realize a fully automated system for parcel delivery using a vehicle. During the demonstration day, the focus was on showing the logistics concept. It was crucial that each component was well-coordinated, as the system is vulnerable when any component fails. Specifically, there is a high dependency on the communication system. If the communication to the cloud-based system was interrupted and information about the parcels or remote control was no longer available, the system could not complete deliveries. When all components worked together properly, it was demonstrated that parcel handling with a robotic system is feasible.

Figure 10. *A customer picking up a parcel delivered by autoCARGO*

8 CONCLUSION & FUTURE WORK

The development and successful demonstration of *autoCARGO* highlight significant progress in the field of autonomous urban logistics. By combining cutting-edge hardware and software, including a robot with a custom suspension, advanced vision systems, and a cloud-based communication infrastructure, *autoCARGO* achieves fully autonomous parcel delivery. The system's design, which is tailored to urban environments, maximizes efficiency and flexibility in last-mile logistics. However, the project also underscores the importance of seamless integration and reliable communication between all system components. While the demonstration proved the feasibility of the concept, further refinement is needed to ensure robustness in real-world scenarios. *autoCARGO* serves as a promising step towards automated urban logistics.

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