Mobile Manipulator for Container Loading and Unloading: A Proof-of-Concept Study

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***Abstract*—The manual loading and unloading of carton boxes from truck containers is a crucial operation in warehouse logistics that puts worker health at risk and takes a lot of time. In this paper, a robotic system for automatically loading and unloading carton boxes of various sizes and weights is proposed. The proposed solution involves a mobile manipulator with an end-effector integrated together with other essential components. Static and dynamic stability analyses backed with simulations are used to evaluate the system's stability and reachability. In addition, a software framework is created that can accommodate different box sizes and weights. With the objective to reduce the challenges of manually loading and unloading carton boxes from containers, this paper offers a promising solution.**

***Index Terms*—Mobile manipulation, Container loading, Container unloading, Motion planning, MoveIt, Carton-box detection.**

I. Introduction

Container loading and unloading constitute major challenges in terms of time, labor, and costs. These processes account for a large portion of shipping expenses and represent critical bottlenecks in logistics operations. The need for container transportation is anticipated to increase as international trade grows, underlining the need for more effective and affordable alternatives. Robotic systems have the potential to automate these jobs, but they still face challenges including handling a variety of commodities, maintaining stability, and maximizing performance in various settings.

To address this challenge, this study presents an autonomous loading and unloading mobile manipulator system designed for containers. The system integrates the functionalities of mobile robots and industrial manipulators to accomplish container handling tasks with minimal human intervention, thereby improving operational efficiency and cost reduction. This paper provides a detailed account of the system's design and development, as well as the outcomes of conducted testing and simulations that substantiate the efficacy of the proposed approach. The findings validate the transformative potential of autonomous mobile manipulator systems in revolutionizing container handling and logistics, with far-reaching implications for the shipping industry and related domains.

The review of the literature reveals a number of commercially viable options for container unloading. In order to ensure proper docking and efficient operation, the Siemens Remote Under Belt Unloading System (RUBUS) [1] requires some setup from the operator. With a mobile base and suspended bridge, the Bastian Solutions Ultra [2] is only useful for single-size parcels and is impractical for mixed-size parcels. Another mobile base with a robot on board, TEUN [3], is simple to deploy but only works with fixed-size containers due to its enormous footprint. The Copal automated container unloading system [4] accounts for different sizes of goods using a scanner and suction End-of-arm tool (EOAT) on a cantilevered slider, but due to space limitations, it might not be able to pick up items on the highest level. Because of how quickly the boxes move along the conveyor, the Honeywell robotic unloader [5] may not be appropriate for fragile items. It uses a kicker roller at the bottom and a suction EOAT at the top of the container. The Boston Dynamics Stretch [6] is a mobile manipulator that can pick up packages of different sizes using a scanner and suction EOAT, but it is only useful for unloading. The Mujin TruckBot [7], which has scanners on the left and right sides, can only be used for unloading but can retrieve mixed parcels. The Pickle robot [8] can unload 600 boxes per hour when equipped with a suction EOAT, but it is unclear how it recognizes boxes inside the container. Finally, the Daifuku-Wynright robotic truck unloading [9] employs a mobile manipulator with adjustable EOAT and a vision system, but does not specify that it can handle containers with mixed box configurations.

In addition to market available solutions, there is also ample of literature available in the research domain. Two different autonomous container loading solutions [10] are proposed which focus on heavy sack and loose goods unloading. A modular software framework is also proposed to address the challenges. A planning, learning and decision making framework is developed [11] to address the challenges of real-time motion planning, decision making and real-time execution for robot truck unloading. Another autonomous handling system [12] is evaluated and a generalized method is proposed for estimating unloading performance. Dynamic stability is the most important aspect of mobile manipulators especially in manipulating heavy objects. A new measure of dynamic stability moment-height stability (MHS) is introduced in [13] to evaluate toppling during maneuvers. An autonomous unloading system kinematics is presented [14] which is suited for all kinds of goods from a container. Navigation of mobile base is also an important part as the whole system should autonomously navigate inside the container while performing obstacle detection and avoidance [15]–[17]. Optimal motion planning using interval analysis [18] is also explored for navigating mobile base from start goal to end goal. It is desired to achieve real-time performance in navigation. An embedded approach towards mobile robotic navigation tasks such as motion planning, collision avoidance and localization is also presented [19]. Precise motion control of the manipulator is dependent on varying payloads. A motion controller [20] is proposed which compensates the effect of varying payloads guarantees position accuracy. Sensing the arrangement of carton boxes is an important aspect in unloading scenarios where 3D vision plays a crucial role. The detection of carton boxes using 3D vision sensor is presented in [21]. A novel projection based 3D-point cloud segmentation technique [22] is presented on detection of objects and their orientation in the container. Deep learning plays an important role in carton box detection. A technique to generate synthetic dataset for carton boxes [23] is proposed which can be used as test cases for box detection techniques.

The remainder of this paper is structured as follows. In Section II, we describe the system components and design, including the mobile manipulator and end-effector for box handling. Section III presents the system architecture, outlining the hardware and software components and their interactions. In Section IV, we present the simulation and stability analysis results, demonstrating the feasibility of our approach. Section V concludes the paper and discusses potential future work to further enhance the proposed solution.

II. System Components Description

The mobile loading and unloading system, as illustrated in Fig. 1, is integrated into the loading and unloading process of carton boxes from a container. The system receives the boxes and facilitates their movement onto a palletizing and depalletizing system, where the boxes are arranged into pallets. These pallets are then transferred to a forklift for further storage and unloading. Next we describe various system components.

Fig. 1: Illustration of loading and unloading operation

A. Mobile base and manipulator

The mobile base and manipulator are the core components of the autonomous loading and unloading system. The mobile base is responsible for moving the manipulator to the desired location within the container. The manipulator, on the other hand, is responsible for picking up and placing carton boxes in the container. The manipulator is integrated with the mobile base to enable seamless movement and positioning of the manipulator.

The mobile base used in the system is MIR1350 [24], which is a popular mobile robot platform used in various industrial applications. The MIR1350 has a payload capacity of up to 1350 kg, and can travel at speeds of up to 2 m/s. The manipulator used in the system is ABB IRB4600 [25], which is a high-performance industrial robot designed for heavy-duty applications. The IRB4600 has a payload capacity of up to 60 kg and a reach of up to 2.5 m.

During the design and development of the mobile base and manipulator, several challenges were encountered. These challenges included ensuring seamless integration between the two systems, optimizing the performance of the manipulator, and ensuring safe and efficient operation in a dynamic environment.

B. End-of-arm Tooling system

The End-of-Arm Tooling (EOAT) is a crucial component of the developed autonomous loading and unloading manipulator system. The EOAT is a vacuum-based system that has been developed in-house. It consists of two parts, each with a vacuum plate that has multiple vacuum cups. One vacuum plate is stationary, while the other vacuum plate is movable and rotates by 90 degrees as shown in Fig. 2. The EOAT has three configurations to pick up boxes using the front surface with bottom support, front and top surfaces or pick up multiple carton boxes from the top with multiple vacuum plates.

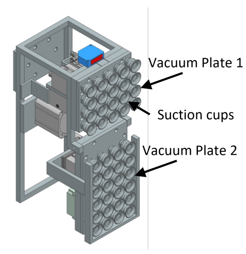


Fig. 2: End-of-arm tool design

The EOAT system has been designed to provide flexibility and adaptability in handling different types of carton boxes. By using multiple vacuum cups, the EOAT system ensures a strong and reliable grip on the carton box surface during loading and unloading operations. The movable vacuum plate allows the EOAT to adjust its position and orientation for different configurations, increasing the system's overall versatility.

C. Vision system

The vision system used here is critical to the successful implementation of the robotic system for unloading container boxes. A modular vision solution is developed to enable container space identification and detection of carton boxes inside the container. The solution consisted of a compact and lightweight 3D camera, the Basler Blaze 101 [26], which was integrated with the advanced vision software product Halcon for picking and placing the carton boxes. The camera is mounted on the end-effector of the mobile manipulator system.

The vision solution is predominantly used for the unloading application and is performed in a cyclic manner. The box unloading cycle starts from a pre-defined location. Once the camera captures the boxes, the point cloud information is sent to the vision algorithm, where the boxes are identified and segmented based on their orientation to generate the grasp poses. The information on the position and orientation is then sent back to the motion controller in the form of coordinates to unload the boxes. Once the boxes within the camera FOV are picked, the cycle is repeated.

D. Loading Optimization

Efficiently utilizing space and arranging carton boxes in a way that prevents damage during transportation is crucial in the loading process. The container loading optimization module is designed to address these concerns, particularly in situations where the details of the carton boxes are unknown. This is common when boxes are loaded directly from a conveyor belt, with sizes and shapes that can vary widely.

The module takes into account the sizes of the boxes and the available space inside the container to determine the optimal placement for each box. Using online optimization techniques, the module continuously adjusts the placement of incoming carton boxes as they are loaded into the container. This ensures that space is utilized effectively and boxes are arranged to minimize the risk of damage during transit. The buffer space inside the container serves as a temporary storage area for boxes that cannot be immediately placed in their final position.

III. System Architecture

This section describes the system architecture of an independent loading and unloading system intended for warehouse use. The system is composed of multiple hardware parts and software modules that operate in unison to automate the loading and unloading process. The succeeding subsections provide a comprehensive outline of the system architecture, highlighting the role of each hardware and software component and their interconnections.

A. Overview

The autonomous loading and unloading system consists of several interconnected software and hardware modules. To ensure the proper functioning of the system, these modules are connected through various communication interfaces. The different modules are integrated using the ROS framework based behaviour tree, which provides a robust and flexible platform for building and controlling complex robotic systems. In the following sub-sections, we will provide a detailed description of each module and its functionalities.

B. Hardware module

The system consists of five hardware modules: mobile base, industrial robot, conveyor for loading and unloading of boxes, 3D camera and EOAT. The mobile base is responsible for

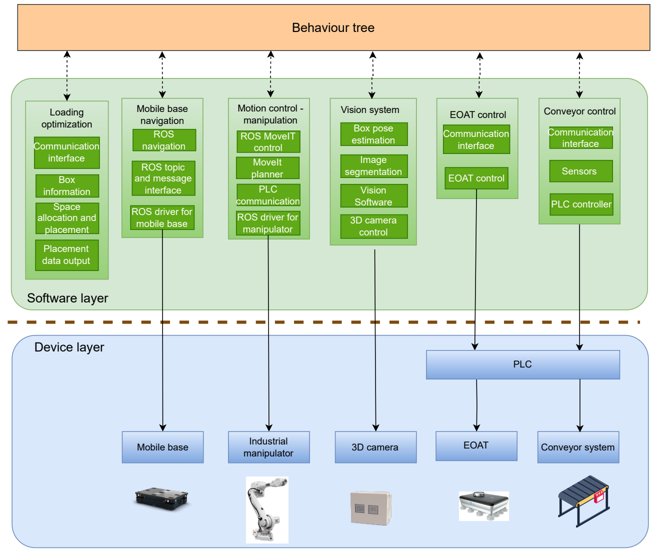


Fig. 3: System Architecture

the movement of the entire system. The industrial robot is mounted on the mobile base and is used for the manipulation of boxes. A conveyor is connected to the system and is used for loading and unloading of boxes. The 3D camera is mounted on the robot end effector and is used for capturing the images of the boxes for pose estimation. The EOAT is responsible for the gripping and releasing of boxes during the loading and unloading process.

C. Software modules

The system architecture comprises six software modules, each responsible for a specific function. The mobile base navigation module is responsible for the movement of the mobile manipulator and its interaction with the environment. This module is composed of three sub-modules: ROS Navigation, ROS topic and message interface, and ROS driver for the mobile base. The ROS Navigation sub-module utilizes the ROS Navigation stack, which provides a set of packages that implement robot navigation capabilities such as localization, mapping, and path planning. The ROS topic and message interface sub-module is responsible for publishing and subscribing to ROS topics and messages, which allows the communication between the mobile manipulator and other modules. The ROS driver provides a software interface to control the mobile base through ROS. The manipulator motion control module controls the manipulator's motion and is composed of four sub-modules: ROS MoveIt control, MoveIt planner, Programmable Logic Controller (PLC) communication, and ROS driver for the manipulator. The ROS MoveIt control sub-module is responsible for controlling the manipulator's movement using the MoveIt software package. The MoveIt planner sub-module generates a motion plan for the manipulator based on the desired goal and the current state of the robot. The PLC communication sub-module establishes communication with PLC, which controls the EOAT. The

ROS driver for the manipulator sub-module provides a software interface to control the manipulator through ROS. The conveyor control module is composed of three sub-modules: communication interface, sensors, and PLC controller. The communication interface establishes communication between the conveyor system and other modules. The sensors are responsible for detecting the boxes on the conveyor. The PLC controller communicates with the PLC, which controls the operation of the conveyor system. The vision system module is responsible for capturing images of boxes and determining their position and orientation. This module is composed of four sub-modules: box pose estimation, image segmentation, Halcon vision software, and 3D camera control. The EOAT control module controls the EOAT and is composed of two sub-modules: communication interface and EOAT driver for control which establishes communication between the EOAT and other modules and the EOAT driver controls the EOAT. The loading optimization module optimizes the placement of boxes in the container. The box information is given to space allocation and placement sub-module which optimizes the placement of boxes in the container based on their dimensions and weight.

To enable efficient communication and coordination between the software modules, a combination of wired and wireless communication interfaces are used. The mobile base navigation module utilizes the ROS navigation stack and communicates with the mobile base through a wired LAN. The manipulator motion controller communicates with the industrial robot via a wired LAN and PLC communication. The conveyor control module communicates with the conveyor system through a wired LAN connection and sensors for efficient control. The vision system module employs a 3D camera for image acquisition and communicates with the system via a wired LAN connection. The EOAT control module is connected to the PLC and communicates with the system through a wired LAN. Finally, the loading optimization module is connected to the system via a wired LAN and utilizes the collected data for optimal space allocation and placement. Overall, the software modules are interconnected through ROS topic and message interfaces, enabling seamless communication and coordination between the modules. The communication between the modules and the hardware components is achieved through various communication interfaces, including USB, wired LAN, and serial interfaces.

IV. Simulation and Stability Results

The proposed mobile loading and unloading system involves a complex integration of various hardware and software components to achieve efficient loading and unloading of carton boxes. Before implementing the system in a real-world scenario, it is essential to validate its stability and reachability. In this section, we present simulation results and stability analysis of the system.

A. *Simulation results*

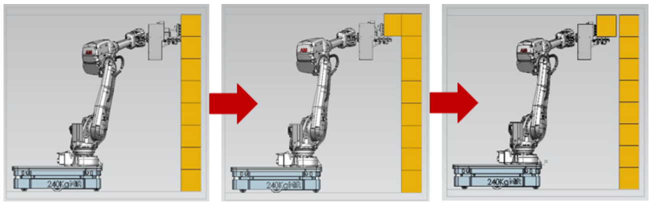
Simulation testing was conducted to evaluate the end-of-arm tool (EOAT) of the mobile manipulator for the loading and unloading of carton boxes from containers of varying sizes and shapes. A 3D model of the container was created, and carton boxes were placed in different layers inside it to test the EOAT's grasp capability. The results of the simulation were then used to optimize the design of the EOAT, ensuring its effectiveness in the actual operation of the mobile manipulator.

ProcessSimulate [27], developed by Siemens, is the simulation environment used here. The carton boxes used in the simulation varied between $200\ \mathrm{mm}$ and $500\ \mathrm{mm}$ in size, and a maximum weight of $15\ \mathrm{kg}$ was considered. In Fig 4, the simulation results for emptying carton boxes from the top layer of the container are illustrated. The EOAT for picking up carton boxes from different layers in the container was tested in the simulated environment. The grip capability of the EOAT was evaluated for several circumstances, and the results were used to improve the EOAT's design for efficient loading and unloading of carton boxes. The removal of carton boxes from the top layer of the container by the EOAT is shown in Fig 4(a). The front surface of the carton boxes are picked up by the EOAT utilizing vacuum plate 1, and the bottom surface of the box is supported by the bottom support bar attached to vacuum plate 2. In order to pick up carton boxes from the middle layers, the EOAT uses vacuum plate 1 to pick up the front surface of the box and vacuum plate 2 to support the top surface of the box. This process is shown in Fig 4(b). Fig 4(c) depicts the removal of carton boxes from the container's bottom layer. Here, the EOAT can use vacuum plates 1 and 2 to lift a maximum of two carton boxes from the top surface.

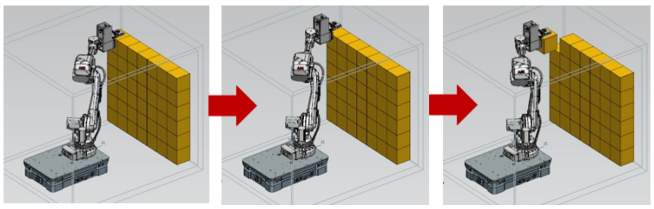
B. *Stability and reachability analysis*

A mobile robotic system's stability and reachability must be considered while building it to load and unload containers. The system's mobile base should offer both static and dynamic stability to keep it from toppling over as the manipulator arm approaches the container's four corners. In this section, we describe the mobile loading and unloading system's stability and reachability analysis.

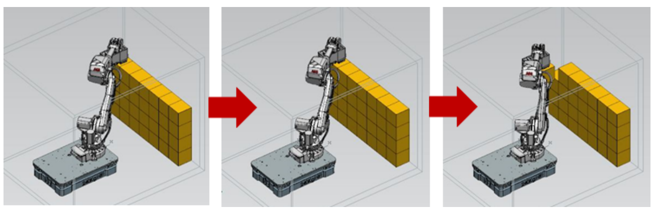
The payload distribution of the mobile base was examined using the MIR1350 manual [24] as shown in Fig. 5 to verify static stability of the mobile manipulator system. In the case of the MIR1350 mobile robot, the payload distribution is assumed to be designed for operation on even surfaces. This assumption takes into account that the robot is primarily intended for use in environments where the ground or floor is flat and level. To make sure it falls within the stable range of the payload distribution, the combined center of mass of the industrial robot with the PLC and other components mounted on the mobile base were analyzed. A study was done to evaluate the static center of mass of the system in two extreme scenarios: when the industrial robot is outstretched in the four corners and when it is in the home position. The study was done because the position of the industrial robot impacts the static



(a) Top layer carton box unloading



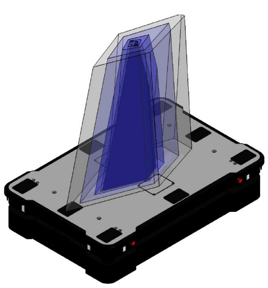
(b) Middle layer carton box unloading



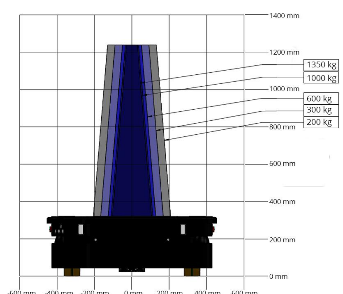
(c) Bottom layer carton box unloading

Fig. 4: Simulation results for EOAT operation

center of mass of the system. For these two scenarios, the system's center of mass was calculated using the CAD model, as seen by red color dot in the Fig 6. According to the analysis, the center of mass lies within the payload distribution's stable range.



(a) 3D Overview

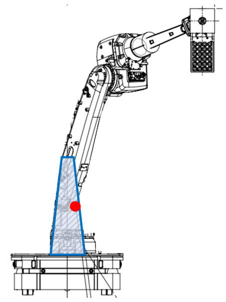


(b) Front View

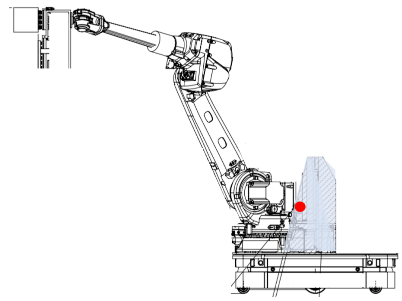
Fig. 5: Payload distribution of MIR1350 [24]

The industrial robot was tested using Gazebo simulation with its arm completely extended forward for the dynamic stability analysis, as shown in the Fig 7. Three distinct speeds of the industrial robot were used to assess the dynamic stability of the system, and it was discovered that the system as a whole is stable for these different speeds and finish the execution within 0.25 sec, 0.5 sec and 1 sec respectively.

The industrial robot's capacity to reach objects was tested by having it pick up boxes from each of the container's four



(a) Front view



(b) Side view

Fig. 6: Static stability with CAD model

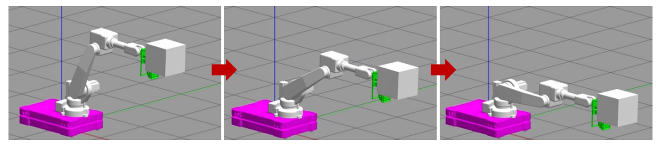


Fig. 7: Dynamic stability using Gazebo simulation

corners, as seen in Fig 8. According to the simulation, the system is able to pick up boxes from even the farthest edges of the container. Based on the findings of the simulation, it was anticipated that the loading speed of carton boxes would be 450 boxes per hour and the unloading speed would be 400 boxes per hour. These results are obtained based on several factors and considerations that determine the system's efficiency and productivity.

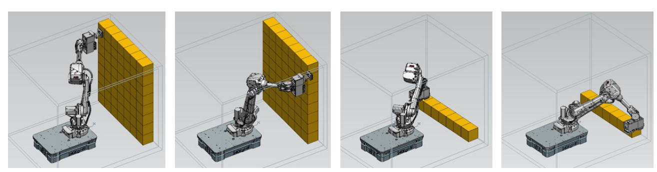


Fig. 8: Simulation results for four extreme corner reach

V. Conclusion and Future Work

This paper presents a proof-of-concept design and simulation verification of mobile manipulator and EOAT procedures for carton box loading and unloading from a container. A mobile base, an industrial robot arm, and a specially developed EOAT for carton box manipulation are all included in the design. Analyses of static and dynamic stability were conducted, and the manipulator's reachability was evaluated.

Future work will involve putting the system into practice and testing it in a real-world environment. The design and control algorithms will be further optimized to increase the system's effectiveness and precision. Additionally, the system's performance will be improved and its intelligence and autonomy will be improved by incorporating machine learning techniques. Overall, this study offers a viable approach to automated material handling in the logistics sector.

Acknowledgment

This research / project is supported by A*STAR under the Supply Chain (SC) 4.0 - Digital Supply Chain Development via Platform Technologies (Award M21J6a0080). Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of the A*STAR.

References

[1] Siemens Logistics GmbH. 2019. "Siemens Revolutionizes Parcel Unloading." 2019. https://www.siemens-logistics.com/en/news/press-releases/siemens-revolutionizes-parcel-unloading.

[2] Bastian Solutions. 2018. "Robotic Truck Trailer – Case Loader/Unloader." Indianapolis. https://www.bastiansolutions.com/solutions/service/industrial-robotics/industrial-robotic-solutions/mobile-robotics/robotic-truck-unloading-loading/.

[3] Vehicle Technologies Inc. 2011. "Automated Container Loaders and Unloaders". http://www.vetexinc.com/applications/teun.html.

[4] Copal Handling Systems. "Copal Automated Container Unloading System". https://www.copalhandlingsystems.com/en/products/copal-c2/.

[5] Honeywell International Inc. 2020. "The robotic unloader". https://sps.honeywell.com/us/en/support/automation/resources/brochures/robotic-unloader.

[6] Boston Dynamics. 2021. "Boston dynamics unveils new robot for warehouse automation." 2021. https://www.bostondynamics.com/new-robot-for-warehouse-automation.

[7] Mujin Corp. 2023. "Introducing TruckBot". https://mujin-corp.com/truckbot-automated-truck-unloader/.

[8] Pickle Robot Company. 2022, "Pickle Unloading robot". https://picklerobot.com/unload

[9] Daifuku Corporation. "Robotic Container Unloader". https://global-uploads.webflow.com/621a92e5a8cfda14a3bdc5e3/6258c38d84a95d40b31862cb_RTL(U).pdf.

[10] T. Stoyanov, et al, "No more heavy lifting: Robotic solutions to the container unloading problem." IEEE Robotics & Automation magazine, vol. 23, no.4, pp.94-106, Aug 2016.

[11] F. Islam, A. Vemula, S.K. Kim, A. Dornbush, O. Salzman and M. Likhachev, "Planning, Learning and Reasoning Framework for Robot Truck Unloading", Proceedings of IEEE International Conference on Robotics and Automation (ICRA), pp. 5011-5017, May 2020.

[12] J. Wilhelm, N. H. Hoppe, P. Kreuzer, C. Petzoldt, L. Rolfs and M. Freitag, "Method for the Evaluation of An Autonomous Handling System For Improving the Process Efficiency of Container Unloading", International Scientific Symposium on Logistics, pp. 13-22, 2021.

[13] S.A.A. Moosavian and K. Alipour, "On the dynamic tip-over stability of wheeled mobile manipulators", International Journal of Robotics and Automation, vol. 22, no. 4, 2007.

[14] W. Echelmeyer, M. Bonini and M. Rohde, "From manufacturing to logistics: Development of a kinematic for autonomous unloading of containers", Journal of Advanced Materials Research, vol. 903, pp. 245-251, 2014.

[15] P. Vyas, L. Vachhani, K. Sridharan and V. Pudi, "CORDIC-based azimuth calculation and obstacle tracing via optimal sensor placement on a mobile robot", IEEE/ASME Transactions on Mechatronics, vol. 21, no. 5, pp. 2317-2329, 2015.

[16] P. Vyas, L. Vachhani and K. Sridharan, "Hardware-efficient interval analysis based collision detection and avoidance for mobile robots" Mechatronics, vol. 62, 102258, 2019.

[17] P. Vyas, L. Vachhani and K. Sridharan, "Interval analysis technique for versatile and parallel multi-agent collision detection and avoidance", Journal of Intelligent and Robotic Systems, vol. 98, pp. 705-720, 2020.

[18] A. Chauhan, P. Vyas, L. Vachhani and A. Maity, "Optimal path planning for a non-holonomic robot using interval analysis," 2018 Indian Control Conference (ICC), Kanpur, India, pp. 184-189, 2018.

[19] L. Vachhani, P. Vyas and Arunkumar G. K, "Embedded Control for Mobile Robotic Applications", IEEE Press Series on Control Systems Theory and Applications, John Wiley & Sons, Aug. 2022.

[20] A.B. Epenetus, C.S. Meera, S. Mohan and M.K. Gupta, "Development and motion control of spatial serial robotic manipulator under varying disturbances", World Journal of Engineering, Vol. 16 No. 4, pp. 460-467, 2019.

[21] R. Monica, J. Aleotti and D. L. Rizzini, "Detection of Parcel Boxes for Pallet Unloading Using a 3D Time-of-Flight Industrial Sensor", Proceedings of IEEE International Conference on Robotic Computing (IRC), pp. 314-318, 2020.

[22] D. D. Sredhar, "Detection of objects and their orientation from 3D point clouds in an industrial robotics settings", Thesis, Jul, 2021.

[23] L. Gou, et al, "Carton dataset synthesis method for loading-and-unloading carton detection based on deep learning", The International Journal Advanced Manufacturing Technology, vol. 124, pp. 3049–3066, Feb 2022.

[24] Mobile Industrial Robots A/S, "MIR1350 Specifications", https://www.mobile-industrial-robots.com/solutions/robots/mir1350/.

[25] ABB robots, "IRB 4600 Specfications", https://new.abb.com/products/robotics/robots/articulated-robots/irb-4600.

[26] Basler AG, "Basler blaze 101 specifications", https://www.baslerweb.com/en/products/cameras/3d-cameras/basler-blaze/blaze-101/#specs.

[27] Siemens AG, "Process Simulate brochure", https://www.plm.automation.siemens.com/en_gb/Images/7457_tcm642-80351.pdf.