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# Development of 3D Printed Autonomous Warehouse Robot Using Mecanum Wheel and Robot Arm

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**ABSTRACT**

Industrial revolution 4.0 has affected many industries, including warehouse management. Warehouse management so far has progressed with the introduction of automation, i.e. using warehouse robots to improve the flow of the warehouse management. This work discusses and builds a 3D-printed warehouse robot prototype in the form of mobile manipulator with mecanum wheel. The mecanum wheel is chosen for better kinematics movement. The prototype warehouse robot is designed to accept command wirelessly through Bluetooth via an Android application. The prototype robot was successfully built and tested. The movement test shows it can move freely in any direction due to the mecanum wheel. However, the robot still has poor repeatability and reliability. Based on the result, the prototype can serve as a basis for an affordable warehouse robot, and the future work to improve the repeatability and reliability of the robot is strongly encouraged.



## Introduction

A warehouse is known as an industrial building that has the main function to store and distribute goods in an efficient manner to the customers [1]. As consumption increases, so does the size of the warehouses. In addition, according to van den Berg and Zijm [2] and Shah and Khanzode [3], 60% of the warehouse costs attributed to Order Picking activities, which around 70% of the activities are attributed to travelling and searching for items. Therefore, increasing efficiency in this section of the warehouse system may save a great deal on the overall operational costs of the warehouse itself. One of the proposed solutions to increase the efficiency in warehouse operational costs is to use automation, such as robots. Several preprogrammed and autonomous robotic technologies have already been studied and even commercialized in warehouse and supply chain industries [4–6].

The autonomous framework and system that currently gains attraction in warehouse is called Robotic Mobile Fulfillment System (RMFS), which was first introduced by KIVA Systems [7]. This system is used in major retailers such as Amazon and Alibaba [8]. In addition, there are also companies that offer RMFS in terms of Autonomous Mobile Robots (AMRs), which use advanced sensors and computation algorithms to plan routes [6,9]. However, most of the solutions or designs offered by these companies use conventional wheel system, which may be restricted in terms of maneuver agilities [10].

Some studies have reported methods to improve restricted conventional wheel system. These improved wheel systems are usually called omnidirectional wheels that allow the robot to move in any direction without reorientation [11]. Mecanum wheel is one of the typical omnidirectional wheel designs. Mecanum wheels have rollers that are typically positioned ± 450 [12], which allows it to have 3 degrees of freedom (DoF), namely steering drive, roller motion, and vertical axis turning slip. This allows the system to have better maneuvers than that of the conventional system, especially in tight spaces. However, this

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wheel system may also have disadvantages, which other studies have tried to solve.

A study by Mutalib and Azlan [13] presented the kinematic and the dynamic modelling of the mecanum wheels. It showed several improvements compared to other studies to solve problems in the mecanum wheels, such as slippage, mass and friction, and noise of the sensor. Sun, et al. [11] had proposed improved control schemes to solve tracking accuracy and control robustness for a system that uses this wheel system. In addition, Leng, et al. [14] proposed another design called a Flexible Spoked Mecanum (FSM) wheel. This design allows the robot to have unique movements that could be used in unstructured terrain. With these advantages and improvements, a mecanum wheel system can be used as the main wheel system to allow it to have superior maneuver in tight space in warehouse.

Besides RMFS, another technology that may be used in the warehouses or manufacturing industries is robotic arms. Robotic arms can be equipped with modules that can be used according to the user's requirements. One of the modules that can be equipped to the arms is picking module to pick and place objects, as demonstrated in [15–17]. Chih-Hsing Liu, et al. [15] designed a topological improvement of compliant fingers to pick vulnerable objects that fabricated by a 3D printing. Sobhan and Shaikat [16] designed an automated scheme that uses a 5 DoF robotic manipulator equipped with pick and place module for warehouses. Another study that uses pick and place module is by Wang, et al. [17] who designed a sorting system that uses RRT-connect algorithm for the robot's motion planning. Studies have shown that robotic arms with pick and place modules can repetitively perform tasks with high degree of precision.

Both RMFS and robotic arms technology give improvements to warehouse technologies have reportedly improved the efficiency of the robot application in the warehouse. However, these systems are usually implemented individually. Therefore, a robot with a mecanum wheel system as the main wheel system to have superior maneuver in tight space in warehouse combined with robotic arm having pick and place module is developed. This paper foresees the combination provide the advantages of both RMFS and robotic arms into one system. The robot is then tested for its performance by calculating the repeatability and reliability. The robotic arm on the robot allows the robot to grab an object, and the RMFS system allows it to transport while carrying the object. Besides, the use of the mecanum wheels allows the robot to maneuver better in tight spaces than that of the conventional wheels.

## Research Methodology

Figure 1 shows the flowchart of the methodology used for the present work. The methodology used in the present work was adapted and modified from Dejan [18]. Each of the methodological steps are explained in their respective subsections.

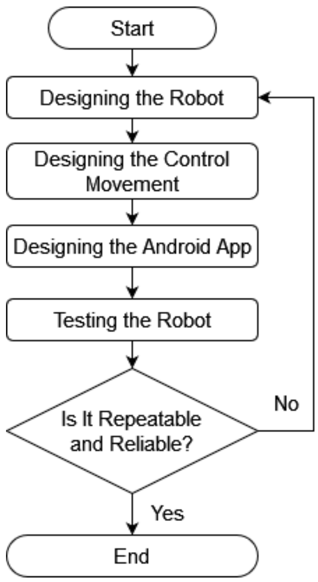


**Figure 1**. The flowchart of the research methodology of the present work

## Adapted Design

To achieve the purpose of the study, the author has adapted some of the design process from Shigley's Mechanical Design book with few changes in the name of the process. The processes include problem definition, research and literature review, prototyping, analysis and experiment, and evaluation [19]. In this our initial study of the warehouse robots, we adapted the design of Dejan [18] with a few modifications to make the prototype work properly to account for the mechatronics components with the wiring system. The robot is divided into two main parts, which were 3D-printed for fast prototyping [20]. The first is the base which is the body of this mobile robot. The body served two functions, the compartment for the Arduino controller and electronics parts, as well as the frame to mount the stepper motors to motorize the mecanum wheels. The second main part is the robot arm. The modified adopted design of the complete mobile robot arm is illustrated in Figure 2.

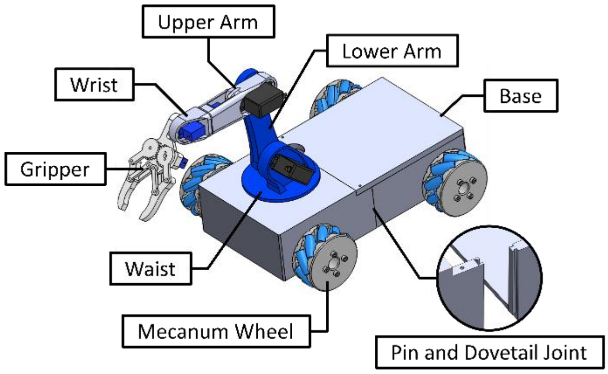


**Figure 2**. Mobile arm robot

The common design of mecanum wheel that is already available in the market and created first by Bengt Ilon was used. The mecanum wheels were 3D printed using fused deposition modelling (FDM) 3D printing in order to lower the cost of purchasing [20]. The conventional design of the mecanum wheel was employed. It used the common 45-degree angle between each roller and the central axis, and the rollers can move freely [21]. In detail, the exploded view of the mecanum wheel design can be seen in Figure 3.

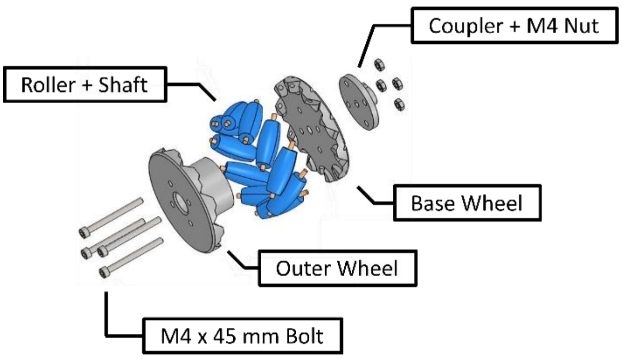


**Figure 3**. Exploded view of the mecanum wheel design

**Control Movement**

The configuration of the mechatronics system played an essential role for the robot. The main microcontroller chosen for the project was an Arduino Mega 2560 with a CNC Shield V3 module attached and four DRV8825 modules to control the motors. The motor used to control the movement of each wheel was NEMA 17 stepper motor. Besides, six servos were used to control the movement of the robotic arm. There are two types of servos used for the robotic arm, which were micro and standard size servos. The micro servos were used for the gripper and wrist of the robot, while the standard servos are used in upper arm, lower arm, and waist.

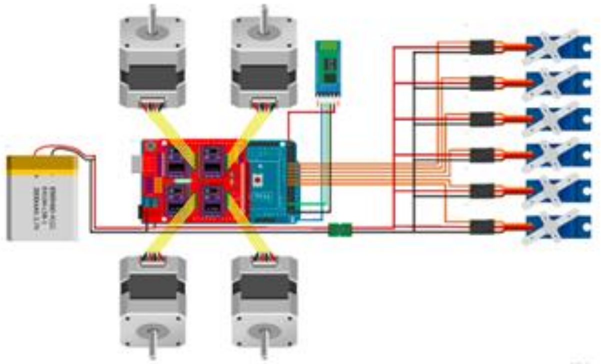

**Figure 4**. Circuit diagram for the warehouse robot

Besides the components to control the movement, there were also components to allow the user to control the robot. We used HC-05 Bluetooth Module to control the movement of all the components. This module allowed wireless communication through Bluetooth from the user's machine, such as smartphone to the Arduino Mega 2560 controller. Lastly, the electronic component required for the project is the battery. The battery chosen for this project was a Lithium-Polymer (Li-Po) battery with 11.1 Volt rating. The circuit diagram of each component used in this project is presented in Figure 4.

**Android App Design**

An Android app was developed to ease the user in controlling the robot. This app was designed to control the robot with Bluetooth signal which was connected between the Arduino board and the app from a smartphone. This app was developed by using online freeware software developed by Massachusetts Institute of Technology (MIT), called AppInventor. The base code of the app was taken from template created by Dejan, a creator of How-to Mechatronics website [18], which was modified to match the system of warehouse robots. The designed user-interface for the Android app is shown in Figure 5. Each button from the app represents a specific signal that is sent from the smartphone to the Arduino board inside the robot through Bluetooth signal. This signal is received by the Bluetooth module on the Arduino and converted to an electrical signal that commands the action.

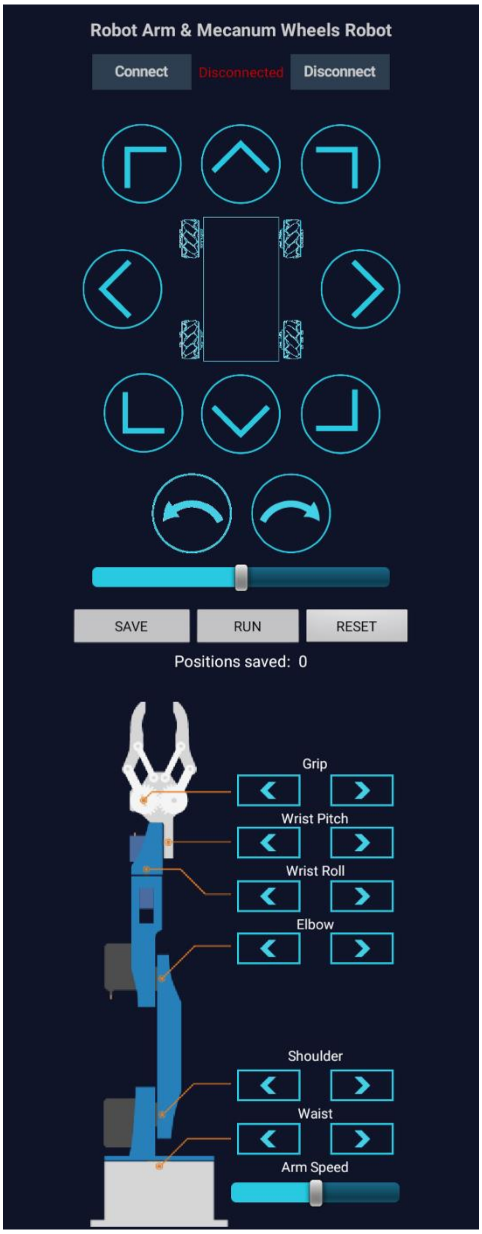


**Figure 5**. App interface when run in smartphone

### Repeatability and Reliability Calculations

In order to measure the robot performance, the repeatability and reliability of the robot movements were performed. The robot was given a task, moving from a fixed start point to a fixed end point. The travelled distance $x_i$ were recorded. The task was repeatedly few times, where the $i$ signifies the number of repetition index and $N$ is the number of repetition test. From the result, the standard deviation $s$ and relative standard deviation $\%RSD$ were calculated. The lower of both values were considered the better. The formulas for calculating standard deviation and relative standard deviation were presented in equations (1) and (2), respectively. Both standard deviation and relative standard deviation required average distance value of the measurements, which described in equation (3).

$$s = \sqrt{\frac{1}{N}\sum(x_i - \bar{x})^2} \quad (1)$$

$$\%RSD = \left(\frac{s}{\bar{x}}\right) \times 100\% \quad (2)$$

$$\bar{x} = \frac{1}{N}\sum x_i \quad (3)$$

### Result and Discussion

This section covers the prototype test with control and movement test, then proceeds with the calculation of repeatability and reliability of the robot.

### Tested Prototype

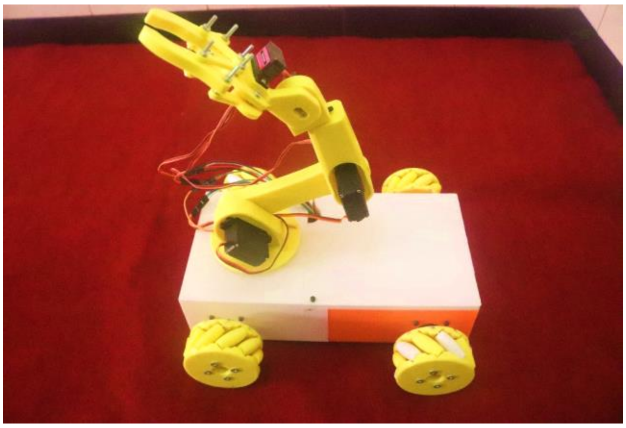

**Figure 6**. Assembly prototype of the robot

The assembled prototype of the robot is shown in Figure 6. The body, robotic arm, and the wheel of the robot were 3D printed using polylactic acid (PLA) material. The body, specifically, was divided into two parts due to the limited capability of the printer. These parts later were joined by employing sliding dovetail joint to minimize the needs of mechanical fastener due to dovetail joint's simple and strong design [22,23].

### Control and Movement Tests

There were several tests performed on the robot. These tests were mainly divided into two, which were control and movement, and repeatability and reliability tests for the robot. This section explains the control and movement tests. The control tests were conducted through the Android app which also tests the Android app, the Bluetooth signal, and the capability of the robot to response to the signal.

Subsequently, the tests were performed to examine the mecanum wheels and robotic arm movements as intended by the controller.

The control of the robot, as previously stated, was achieved by the Android app wirelessly, by sending Bluetooth signal. From the conducted test, the Android app could signal the microcontroller to control the movements of the robot. Besides, the Android app also had the capability to record the path of the robot mobility, as well as the robot arm specific movement. This allowed the robot to repeat the saved path and arm movement without user input. These had already been successfully tested with the Android app. The next test was to test the movement of the robot of the mecanum wheel and the robotic arm.

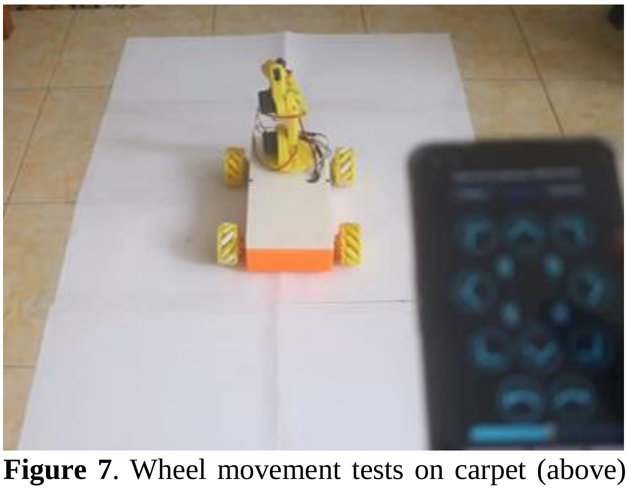

**Figure 7**. Wheel movement tests on carpet (above) and paper (below) surfaces.

The test for the mecanum wheels was to test the maneuverability due to their unique steering system. In order to turn or rotate, the combinations of the four mecanum wheels must be achieved. Hence, the surface and the four-wheel traction play an important role for the steering system to work [11–14]. The test was conducted on a carpet and a paper as they had different surface roughness's, as shown in Figure 7. The speed used for the test was 250 steps/second of the stepper motors. This employed the rate of 200 steps per revolution or 1.8° per step. The test was performed by moving the robot forward, backward, sideway, and diagonal. The result of the test showed that the carpet gave a better grip compared to the paper, as the wheel was slipping in paper when performing the diagonal movement. However, since the carpet was soft, uneven and might get folded, it disturbed the wheel movements as it might also clog the rollers of the mecanum wheels. Therefore, it was recommended to use the robot on rough but rigid surfaces, such as concrete floors. The 3D–printed rollers also contributed to the poor traction. Rubber roller is strongly recommended, due to rubber's viscoelasticity and friction that can increase traction and grip [24–26].

In addition to the mecanum wheels, the movement and function of the robotic arms were also tested. When tested through the app, each of the servos acted accordingly to the controlled input. However, the standard servos did not response as well as the micro servos. This happened due to insufficient power supply since the single battery was used to supply electricity to all electrical components in the robot, as each of the servo required 5V with minimum of 1000 mA DC current to work [27,28]. Therefore, it is recommended to use a bigger and more suitable power source for the robot to work properly. This project also tested the gripper performance. However, since the surface of the gripper is smooth, then it only can grip object with certain roughness.

### Repeatability and Reliability Tests

As previously stated, there were two main types of tests in this project, namely control and movement test, and repeatability and reliability test. The repeatability and accuracy tests were performed by moving the robot one meter forward by using saved path data. It was then measured the offset. The tests were performed three times with ten cycles in each test. The test results are presented in Table 1.

**Table 1**. Repeatability and reliability test results

| | 1st Test | 2nd Test | 3rd Test |
|---|---|---|---|
| $\bar{x}$ | 4.850 mm | 5.436 mm | 3.027 mm |
| $s$ | 1.827 | 2.979 | 1.485 |
| $\%RSD$ | 37.67% | 54.80% | 49.06% |

As shown in Table 1, the first test shows the lowest relative standard deviation, which means that that specific test has the highest repeatability among other tests [29–31]. However, since each test gives wide ranges of relative standard deviation among each other, we conclude that the robot has poor mobile reliability as the reliability itself referred to as the consistency of the results of the test [29,32].

There are two solutions that can improve the repeatability and reliability of the robot as the extension of the study. The first extension is to study the kinematic movement and improve the formulation of the kinematic movement itself. The improvement of the kinematic formulation can improve the accuracy and precision of the movement [11]. There are several studies that have been done on the improvement of kinematic formulation and algorithm [11,13,14,33]; however, it may not be suitable for this specific case. The second extension is to study the signal from the Android app to the microcontroller through Bluetooth. This may include the study of how the signal can be improved, the latency can be decreased, and the reliability of the signal.

## Conclusions

This paper tried to develop an automated robot to optimize these activities by using the robotic arm with mecanum wheels for easy mobility. The adopted design prototype was 3D–printed using PLA material. The user could use an Android app that was designed to control the robot sending Bluetooth signal. Several tests were performed on the robot: the app, the movements, and the repeatability and the reliability. The tests showed that the movement of the robot was successfully controlled using the Android app. The movements include forward, backward, sideway, and diagonal. However, diagonal movement of the robot has poor performance, due to slipping in some surfaces. Besides, the movement and gripping performance were also tested for the robotic arm, which resulted in difficulties gripping objects with low roughness. The repeatability and reliability of the robot mobility showed poor performance due to wide ranges of relative standard deviation between tests. To improve wheel traction, rubber rollers and rigid surfaces are strongly recommended. Besides, it also recommended to extend the study by studying the kinematic formulation for the specific case and signal send from the Android app to the microcontroller through Bluetooth to improve the accuracy and precision of the robot.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

[1] Richards, Gwynne. 2017. “Warehouse Management: A Complete Guide to Improving Efficiency and Minimizing Costs in The Modern Warehouse”

[2] Berg, J.P.van den, and W.H.M. Zijm. 1999. “Models for Warehouse Management: Classification and Examples.” *International Journal of Production Economics* 59 (1–3): 519–28. https://doi.org/10.1016/S0925-5273(98)00114-5

[3] Shah, Bhavin, and Vivek Khanzode. 2017. “A Comprehensive Review of Warehouse Operational Issues.” *International Journal of Logistics Systems and Management* 26 (3): 346. https://doi.org/10.1504/IJLSM.2017.081962

[4] Bolu, Ali, and Omer Korcak. 2021. “Adaptive Task Planning for Multi-Robot Smart Warehouse.” *IEEE Access* 9: 27346–58. https://doi.org/10.1109/ACCESS.2021.3058190

[5] Shamout, Mohamed, Rabeb Ben-Abdallah, Muhammad Alshurideh, Haitham Alzoubi, Barween Al Kurdi, and Samer Hamadneh. 2022. “A Conceptual Model for the Adoption of Autonomous Robots in Supply Chain and Logistics Industry.” *Uncertain Supply Chain Management* 10 (2): 577–92. https://doi.org/10.5267/j.uscm.2021.11.006

[6] da Costa Barros, Ítalo Renan, and Tiago Pereira Nascimento. 2021. “Robotic Mobile Fulfillment Systems: A Survey on Recent Developments and Research Opportunities.” *Robotics and Autonomous Systems*. Elsevier B.V. https://doi.org/10.1016/j.robot.2021.103729

[7] Wurman, Peter R, Raffaello DAndrea, and Mick Mountz. 2008. “Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses”

[8] Boysen, Nils, René de Koster, and Felix Weidinger. 2019. “Warehousing in the E-Commerce Era: A Survey.” *European Journal of Operational Research* 277 (2): 396–411. https://doi.org/10.1016/j.ejor.2018.08.023

[9] Azadeh, Kaveh, René De Koster, and Debjit Roy. 2019. “Robotized and Automated Warehouse Systems: Review and Recent Developments.” *Transportation Science* 53

(4): 917–45. https://doi.org/10.1287/trsc.2018.0873

[10] John J. Craig. 2021. *Introduction to Robotics, Global Edition*. 4th Edition. Pearson

[11] Sun, Zhe, Hao Xie, Jinchuan Zheng, Zhihong Man, and Defeng He. 2021. "Path-Following Control of Mecanum-Wheels Omnidirectional Mobile Robots Using Nonsingular Terminal Sliding Mode." *Mechanical Systems and Signal Processing* 147 (January). https://doi.org/10.1016/j.ymssp.2020.107128

[12] Yadav, Pankaj Singh, Vandana Agrawal, J. C. Mohanta, and M. D.Faiyaz Ahmed. 2022. "A Theoretical Review of Mobile Robot Locomotion Based on Mecanum Wheels." *Evergreen*. Joint Journal of Novel Carbon Resource Sciences and Green Asia Strategy. https://doi.org/10.5109/4794163

[13] Mohd Azri Bin Abd Mutalib, and Norsinnira Zainul Azlan. 2020. "Prototype Development of Mecanum Wheels Mobile Robot: A Review." *Applied Research and Smart Technology* 1 (2): 71–82. https://doi.org/10.23917/arstech.vli2.39

[14] Leng, Jie, Haiming Mou, Jun Tang, Qingdu Li, and Jianwei Zhang. 2023. "Design, Modeling, and Control of a New Multi-Motion Mobile Robot Based on Spoked Mecanum Wheels." *Biomimetics* 8 (2). https://doi.org/10.3390/biomimetics8020183

[15] Liu, Chih-Hsing, Chen-Hua Chiu, Ta-Lun Chen, Tzu-Yang Pai, Mao-Cheng Hsu, and Yang Chen. 2018. "Topology Optimization and Prototype of a Three-Dimensional Printed Compliant Finger for Grasping Vulnerable Objects With Size and Shape Variations." *Journal of Mechanisms and Robotics* 10 (4). https://doi.org/10.1115/1.4039972

[16] Sobhan, Nazib, and Abu Salman Shaikat. 2021. "Implementation of Pick & Place Robotic Arm for Warehouse Products Management." In *2021 IEEE 7th International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA)*, 156–61. IEEE. https://doi.org/10.1109/ICSIMA50015.2021.9526304

[17] Wang, Yinghan, Yi Liang, Diansheng Chen, Yongzhan Liu, and Min Wang. 2020. "A Goods Sorting Robot System for E-Commerce Logistics Warehouse Based on Robotic Arm Technology." In *2020 IEEE International Conference on Real-Time Computing and Robotics, RCAR 2020*, 310–14. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/RCAR49640.2020.9303286

[18] Dejan. n.d. "Arduino Robot Arm and Mecanum Wheels Platform Automatic Operation." https://howtomechatronics.com/projects/arduino-robot-arm-and-mecanum-wheels-platform-automatic-operation/

[19] Richard G. Budynas, and J. Keith Nisbett. 2020. *Shigley's Mechanical Engineering Design*. 11th Edition. McGraw-Hill Education

[20] Hadisujoto, Budi, and Robby Wijaya. 2021. "Development and Accuracy Test of a Fused Deposition Modeling (FDM) 3D Printing Using H-Bot Mechanism." *Indonesian Journal of Computing, Engineering and Design (IJoCED)* 3 (1): 46–53. https://doi.org/10.35806/ijoced.v3i1.148

[21] Gfrerrer, A. 2008. "Geometry and Kinematics of the Mecanum Wheel." *Computer Aided Geometric Design* 25 (9): 784–91. https://doi.org/10.1016/j.cagd.2008.07.008

[22] Yin, Tianxiao, Chenyue Guo, Zhiqiang Wang, Wei Zheng, and Meng Gong. 2023. "Mechanical Properties of Mortise-Tenon Joints Reinforced by Self-Tapping Screws with Different Insertion Methods." *Construction and Building Materials* 366 (February): 130243. https://doi.org/10.1016/j.conbuildmat.2022.130243

[23] Waleed Mashrah, Zhi-Hua Chen, Hong-Bo Liu, and Mohammed Ameen Amer. 2022. "Experimental, Numerical, and Theoretical Study on Static Behaviour of Novel Steel Dovetail Joint Subjected to Axial Tensile Load." https://doi.org/10.18057/IJASC.2022.18.1.4

[24] Grosch, K. A. 1996. "The Rolling Resistance, Wear and Traction Properties of Tread Compounds." *Rubber Chemistry and Technology* 69 (3): 495–568. https://doi.org/10.5254/1.3538383

[25] Heinrich, Gert, and Manfred Klüppel. 2008. "Rubber Friction, Tread Deformation and Tire Traction." *Wear* 265 (7–8): 1052–60. https://doi.org/10.1016/j.wear.2008.02.016

[26] Lugaro, Carlo, Mohsen Alirezaei, Ioannis Konstantinou, and Abhijeet Behera. 2020.

"A Study on the Effect of Tire Temperature and Rolling Speed on the Vehicle Handling Response." In . https://doi.org/10.4271/2020-01-1235

[27] Ali, Hussein Mohammed, Yasir Hashim, and Ghadah Alaadden Al-Sakkal. 2022. "Design and Implementation of Arduino Based Robotic Arm." *International Journal of Electrical and Computer Engineering (IJECE)* 12 (2): 1411. https://doi.org/10.11591/ijece.v12i2.pp1411-1418

[28] Al Tahtawi, Adnan Rafi, Muhammad Agni, and Trisiani Dewi Hendrawati. 2021. "Small-Scale Robot Arm Design with Pick and Place Mission Based on Inverse Kinematics." *Journal of Robotics and Control (JRC)* 2 (6). https://doi.org/10.18196/jrc.26124

[29] Zeyi Wang, Eric Bridgeford, Shangsi Wang, Joshua T. Vogelstein, and Brian Caffo. 2020. "Statistical Analysis of Data Repeatability Measures." https://doi.org/https://doi.org/10.48550/arXiv.2005.11911

[30] De Bièvre, Paul. 2008. "Measurement Uncertainty Is Not Synonym of Measurement Repeatability or Measurement Reproducibility..." *Accreditation and Quality Assurance* 13 (2): 61–62. https://doi.org/10.1007/s00769-008-0371-0

[31] Bland, J M., and D. G Altman. 1996. "Statistics Notes: Measurement Error." *BMJ* 312 (7047): 1654–1654. https://doi.org/10.1136/bmj.312.7047.1654

[32] Bruton, Anne, Joy H Conway, and Stephen T Holgate. 2000. "Reliability: What Is It, and How Is It Measured?" *Physiotherapy* 86 (2): 94–99. https://dosi.org/10.1016/S0031-9406(05)61211-4

[33] Simarmata, Adven, Tiara Kusuma Dewi, Muhamad Rausyan Fikri, and Kushendarsyah Saptaji. 2023. "Development of Autonomous Robot Using Fuzzy Inference System (FIS) for Indoor Ultraviolet (UV) Disinfection." *AIP Conference Proceedings* 2646 (1): 050018. https://doi.org/10.1063/5.0112788