CasteriX: A Wheel Configurable Caster Wheel-Based Prototype Design for Electric Wheelchair Motion Dynamics Research

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***Abstract*—While Electric Wheelchairs(EW) usage is rising in the modern world, challenges related to insufficient motion precision are becoming more prominent. Therefore, it's crucial to analyze EW's motion dynamics behavior with different wheel configurations. When considering EWs with non-reconfigurable caster wheels, most prior studies rely on a particular wheel configuration type EW for each study. Thus, understanding those EW's motion dynamics for different wheel configurations while keeping other parameters constant is challenging. Hence, it's notable that to overcome that issue, a wheel configurable EW research platform needed to be designed. Although there is an attempt to design a wheel configurable EW platform, it didn't have configurability in caster wheel arrangements. In order to solve that issue, this paper proposes a prototype wheel configurable modular robot research platform named CasteriX, which can be used for EWs with non-reconfigurable caster wheel motion dynamic analysis studies. CasteriX provides configurability in caster-wheel sizes and in both caster and drive-wheel positions while featuring a scalable, low-cost, modular design. It supports 212 wheel configurations covering the three major EW types and can be extended to robot wheel configurations with more than four caster wheels. To align with the quantitative characteristics of the reference Jazzy EW, the scale ratio is preserved throughout the design process. Moreover, to validate the qualitative characteristics, two main motion studies were conducted. The first one is to compare the reference Jazzy Air EW model and CasteriX motion studies, and the second one is to understand the complexity of motion studies by operating CasteriX under selected wheel configurations.**

***Index Terms*—Mobile robots, Prototype design, Electric wheelchairs, Caster wheel dynamics, Wheel configurable**

I. Introduction

With the increase in the elderly population, electric wheelchairs (EWs) are becoming essential for elderly people in the modern world. Not only that, there are EWs that are modified and used as EW robots by adding robotics components like sensors, autonomous navigation, or programmable control. EWs contain caster wheels to maintain stability. Although casters support the stability of EWs with non-reconfigurable caster wheels, certain studies show that having multiple casters in caster-included EWs causes issues in precisely controlling the EWs in the desired direction [1]. Therefore, to control EWss, properly studying the combined caster wheel's effect on EWs is very important.

But the major issue with these is that there are several wheel configurations on modern EWs. Despite the availability of commercial 4WD drive EWs (e.g., WHILL Model CK2 [1]) and reconfigurable caster EWs (e.g., ibot® PMD [2]), this study focuses only on EWs with non-reconfigurable caster wheels, such as Jazzy Air® 2 [3] and Go Chair® MED [4]. Although three major wheel configurations have been identified for those type of EWs, including Front Wheel Drive (FWD), Mid Wheel Drive (MWD), and Rear Wheel Drive (RWD), conducting real-world experiments to analyze the combined caster effect on EW motion remains challenging. This difficulty arises in these experiments, while the configuration of the caster and driving wheels is changing, researchers have to keep other specifications of the EW the same as they are.

Lots of EW caster-based studies have been done and tested on a single caster or a particular EW wheel configuration type for that reason. And others were tested on simulation platforms. Additionally, there are some attempts to develop wheel configurable models for EWs. Although [2] and [3] have examined the parameters influencing single caster wheel dynamics, their work does not fully address the interactions of multiple casters in EWs. So Wolm [4] analyzed the dynamics of an FWD wheelchair and designed a control system to mitigate instabilities. Similarly, Lenker and Paquet [5] used an RWD EW for their study to check the reference directional stability. To design a controller to compensate for the initial

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[1]https://whill.inc/gb/model-c2
[2]https://mobiusmobility.com/learn-more/
[3]https://www.pridemobility.com/jazzy-power-chairs/jazzy-air-2/
[4]https://www.pridemobility.com/jazzy-power-chairs/go-chair-med/

misalignment of the caster wheels of an EW, Lee et al. [6] used an RWD for their research. Moreover, by using an MWD wheelchair, Baudry et al. [7] analyzed the wheelchair kinematics and developed a transfer function to model its behavior. Also, Emam et al. [8] have tried to analyze the caster effects via modifying an existing RWD wheelchair by attaching encoders to caster wheels. However, the issue is that these studies focused on a specific wheelchair type. Levy and Nelson [9] developed a model of a variable position mid wheel drive system for power wheelchairs. Using this model, the dynamics of the EW can be studied by varying the positions of the control wheels. However, that model didn't focus on different caster wheel configurations and sizes.

As a conclusion can see that even though these studies analyzed the dynamic motion of the EWs via their approaches, their research platforms lack the ability to analyze the dynamic motion for different control wheel configurations combined with different caster wheel configurations. Therefore, creating a customizable wheel prototype platform that is both easy to develop and cost-efficient is crucial for researching the EW robot's motion dynamics. To solve this challenge, this paper presents the work done to design a caster and control wheel configurable robot named CasteriX.

The structure of this paper is as follows. Section II provides an overview of the CasteriX robot, including its features, components, and wheel configurations. It also presents the system architecture and describes the localization system in detail, addressing each aspect individually. Section III describes the capabilities and features of the reference model Jazzy Air Wheelchair robot. Then, in section IV, describe the design process briefly. Section V explains the experiment setup that was used to run the robot in selected trajectories with a selected wheel configuration. Section VI provides the results obtained from the experiments and discusses them. Section VII presents the conclusion, demonstrating that the developed robot platform is well-suited for caster-related motion dynamics studies. Finally, section VIII concludes the paper and suggests directions for future research.

II. CASTERIX ROBOT OVERVIEW

To be a proper research robot prototype dynamics research in the area of EWs with non-reconfigurable caster wheels, it should accurately describe the motion characteristics of the reference wheelchair robot and represent all major wheel configuration types used in wheelchair robots. The prototype should faithfully replicate the physical features of the reference model relevant to this research area, while being designed for easy modification, extension, and part swapping. Furthermore, it should be built using cost-effective methods, be straightforward to test and measure, and be reproducible to allow others to replicate the research.

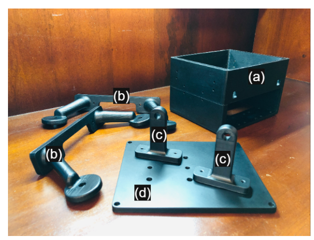
While being a prototype of the Jazzy Air Wheelchair, CasteriX comes with several additional key features. Those are as follows,

- Able to replicate the wheel configuration of major wheel configurations
- Further extended to accommodate studies involving diverse multiple-caster-wheel robotic platforms while supporting a maximum of 6 caster wheels.
- Support two different sizes of caster wheels.
- Can go up to a total of 212 variations of wheel configurations
- Support maximum motor speed of 140rpm
- Operable using the joystick or external systems connected to the same network

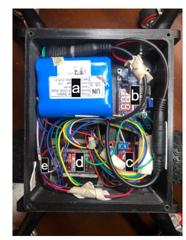
A. Components

As shown in Fig. 1a, the CasteriX structure consists of two base parts, double and single caster wheel attachments, and a cover component.

This robot moves by using 2 control wheels, and each control wheel is attached to JGB37-520 model motors, which can reach a maximum speed of 178 rpm while handling a maximum of 6.5 kg·cm of load torque. Moreover, the robot is equipped with incremental encoders on each motor, providing measurements of up to 616×4 pulses per second. To provide the necessary steady power for the motors and the ESP32 controller, the robot utilizes a 4000 mAh Li-ion battery for long-lasting performance. Fig. 1b shows the internal hardware layout of the robot.



(a) 3D printed parts



(b) Internal hardware layout

Fig. 1. Overview of CasteriX components. Subfigure (a) shows 3D printed parts with labels (a) 2 base parts, (b) double caster wheel attachments, (c) single caster wheel attachments and (d) cover part. Subfigure (b) shows the internal hardware layout with labels (a) 4000 mAh Li-ion battery, (b) LM2596S DC-DC Buck Converter, (c) L298N Motor Driver Module, (d) NodeMCU ESP32-WROOM, (e) 3V Mini Buzzer.

Furthermore, having a feature to extend the robot vertically emphasizes the extendability of this robot for future use. So if anyone wants to extend this platform vertically, they can remove the cover part of the robot and 3D print their own 3D base and attach it to the middle base part of the robot. The middle base part supports utilized space for internal circuits and sensors, its top cover supports more sensor attachments, such as a mobile phone, a small stereo camera, or a small RGB camera as a visual input for the robot.

B. Wheel Configuration

This robot is designed to represent major wheel configurations of EVs (FWD, MWD, RWD) by making it possible to attach control wheels to related positions. In terms of caster wheel positioning, the robot replicates the reference model by allowing attachment of the two components of the double caster wheel assembly. Furthermore, this robot provides a versatile platform suitable for accommodating studies involving diverse multiple-caster-wheel robotic platforms that have more than four casters. In that case, it can go up to 6 caster wheels with two different sizes of caster wheels. Including those control wheel changeability and caster wheel changeability with their position and sizes, this robot can go up to a total of 212 variations. In Table I, the configuration types are denoted using the following abbreviations, RM – Rear Middle, FM – Front Middle, RL and RR – Rear Left and Rear Right, and FL and FR – Front Left and Front Right. Here, Rear Middle or Front Middle indicates that the component shown in Fig. 1a (c) is attached to the rear or front side of the base, respectively. Similarly, Rear Left and Rear Right or Front Left and Front Right indicate that the components shown in Fig. 1a (b) are connected to the corresponding rear or front sections of the base.

TABLE I
WHEEL CONFIGURATION TYPES AND AMOUNTS

Control wheel position	Parts	Amount of configs (with different caster sizes)
Front	RM	2
	RM + FM	4
	RM + RL & RR	4
	RM + FL & FR	4
	RM + FL & FR + RL & RR	8
	RM + FM + FL & FR	8
	RM + FM + RL & RR	8
	RM + FM + FL & FR + RL & RR	16
	RL & RR	2
	RL & RR + FM	4
	RL & RR + FL & FR	8
	RL & RR + FL & FR + FM	8
Rear	FM	2
	FM + RM	4
	FM + FL & FR	4
	FM + RL & RR	4
	FM + RL & RR + FL & FR	8
	FM + RM + RL & RR	8
	FM + RM + FL & FR	8
	FM + RM + RL & RR + FL & FR	16
	FL & FR	2
	FL & FR + RM	4
	FL & FR + RL & RR	4
	FL & FR + RL & RR + RM	8
Middle	RM + FM	4
	RM + FM + RL & RR	8
	RM + FM + FL & FR	8
	RM + FM + RL & RR + FL & FR	16
	RL & RR + FL & FR	4
	RL & RR + FL & FR + FM	8
	RL & RR + FL & FR + RM	8
	RL & RR + FM	4
	FL & FR + RM	4
Total		212

C. System Architecture

CasteriX robot's internal system architecture (Fig. 2) facilitates the main core functionalities of the robot, such as WiFi communication, encoder reading, joystick communication, motor control, beep sound control, and PID tuning for speed control. Each of the functionalities is bound with a subsystem, and each of the subsystems is loosely coupled for modularity via using message queues. The robot uses an ESP32 as its main controller board. In here, RTOS is used for scheduling and coordinating tasks, while encoder feedback is handled through interrupts to ensure accurate pulse counting. Here are important details of the main subsystems and their core functionalities.

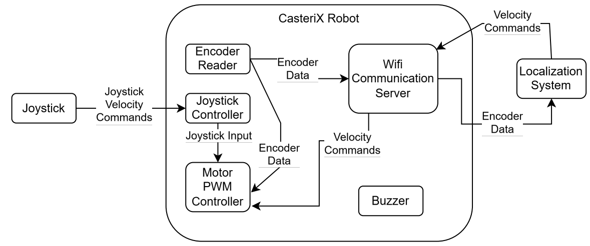


Fig. 2. System Architecture

1) WiFi Communication Server Subsystem: Used for sending each wheel encoder counts, their directions and rpm rates to external systems and to receive wheel velocity commands from either external systems or direct user input. In this, a Web Socket communication system is implemented to enable real-time data exchange.

2) Encoder Reader Subsystem: Read the encoder tick counts, their directions, and motor rpm rates. Furthermore, that data will be sent to the WiFi Communication Server Sub System using a queue.

3) Joystick Controller Subsystem: Helps with the robot being controlled via a PlayStation 4 Dual Shock Joystick. In addition, this system sends those user commands to the Motor PWM Controller Sub System by using a queue. The joystick buttons are mapped to provide full motion control of the robot. The triangle button with R2 drives the robot forward at constant velocity, while the circle and square buttons adjust the speed, and the X button stops the robot. For finer control, the analog stick combined with R2 enables proportional speed and orientation control based on the stick's magnitude and direction.

4) Motor PWM Controller Subsystem: This subsystem's main functionality is to control each of the motors according to speed commands that come from the Joystick Controller Subsystem or from the WiFi Communication Server Subsystem. Here, to ensure precise motor control based on the received commands, a PID controller was employed. Additionally, this communicates with the Joystick Controller Subsystem and the WiFi Communication Server Subsystem by using queues.

5) Alert Notifier Subsystem: This subsystem is responsible for alerting the user when the robot turns on and using a buffer when the controller gets connected to the WiFi and when the Joystick Controller Subsystem and the Encoder Reader Subsystem get initialized.

D. Localization System

The localization system was implemented on the laptop, which is connected to the same WiFi network that connected to the CasteriX robot. For localization, a box that has Apriltags on all four sides has been used. That Apriltag attached box was then attached to the cover part of the CasteriX robot. For the detection of Apriltags, a mobile camera is placed using a Tripod Fig. 3a and connected to the laptop via a USB cable. The AprilTags positions and camera position relative to the world have already been given. Moreover, when the camera detects multiple AprilTags, it gets its relative position in the world by utilizing all those multiple tag detection outcomes via using the Linear Least Squares method. Then the pose was smoothed by using an Exponential Moving Average filter.

III. Reference Robot

When discussing the robot's reference model, the Jazzy Air Wheelchair, which is an MWD EW (see specifications[5]), was used to design the CasteriX robot. It is capable of reaching a maximum speed of 4 mph without seat elevation, and 3.5 mph when elevated. Additionally, control of the robot is provided either through the joystick supplied with the robot or via a custom motor controller. Regarding the localization system of the Jazzy Air Wheelchair, the same localization setup used in CasteriX has been implemented (see Fig. 3b).

(a) Localization System of CasteriX (b) Localization System of Jazzy Air

Fig. 3. Localization Systems of both robots

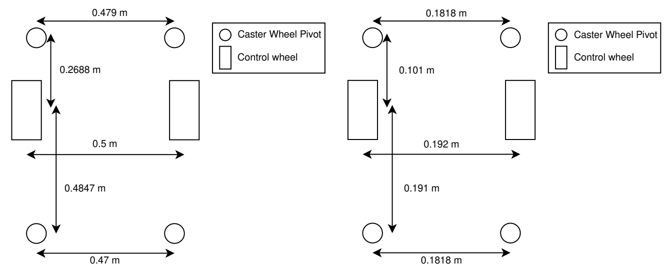
IV. Design Process

A. Software

For the 3D modeling of the CasteriX robot, SolidWorks software is used.

B. Wheel configuration dimensions down scaling

During the design process, the wheel configuration of the CasteriX robot was carefully scaled to match the reference model, ensuring quantitative consistency in all dimensions. For that, as shown in Fig. 4a, front caster pivot to control wheel center, control wheel center to rear caster pivot, wheelbase, front caster pivot spacing, and rear caster pivot spacing distances were taken from the Jazzy EW. By using ratios as shown in Table II, those values are down-scaled for CasteriX dimensions and designed as shown in Fig. 4b while keeping the same shape. Despite the fact that the ratios are not identical, they were kept approximately equal, taking into account practical design considerations such as including optimum chassis dimensions and caster pivot placement requirements.



(a) Jazzy EW Wheel Configuration Dimensions (b) CasteriX Wheel Configuration Dimensions

Fig. 4. Wheel Configurations of Reference and Prototype Robots

TABLE II
Jazzy EW & CasteriX Wheel Configuration Ratios Calculation

Distances	$\frac{\text{Prototype Distance}}{\text{Reference Distance}}$	Value
front caster pivot to control wheel center	$\frac{0.101}{0.2688}$	0.3757
control wheel center to rear caster pivot	$\frac{0.191}{0.4847}$	0.3941
wheelbase	$\frac{0.192}{0.5}$	0.3840
front caster pivot spacing	$\frac{0.1818}{0.479}$	0.3795
rear caster pivot spacing distances	$\frac{0.1818}{0.47}$	0.3868

C. Caster wheels and caster tire material

Furthermore, attention was given to ensuring that the material of the caster wheel tire behaves similarly to the Jazzy Wheelchair. To achieve that, similar to the Jazzy wheelchair caster wheel's tire material, the CasteriX robot caster wheels have been glued to a rubber sheet, which was taken from old bicycle tubes. The reason to follow that kind of approach is to maintain the same qualities of the tires as the Jazzy wheelchair. The major reason for that is that it's an easy and cost-effective method instead of going for completely rubber-tire expensive casters. Moreover, at that moment, it was difficult to find a completely rubber tire caster that has a similar texture to the jazzy wheelchair caster tire. Furthermore, that method enables other researchers to build this robot easily.

D. Weight distribution

In this situation, maintaining consistent weight characteristics in the CasteriX robot was essential. A major reason for that was that all wheels having proper contact with the floor is important. Not only that, the motion of the wheelchair relies on that weight distribution. To match the weight characteristics, 1 kg, 500 g, and 200 g standard weights were added to the top of the CasteriX robot. Their amounts and positions were chosen based on the Jazzy wheelchair's weight and center of gravity calculated from its 3D model.

[5] https://www.pridemobility.com/pdf/owners_manuals/us_jazzy/infinfb3432_us_ca_uk_au_jazzy_air_specifications.pdf

V. Experiments

A. Testing arena

To validate the CasteriX suitability for EW Motion Dynamic studies, two major motion experiments were done. The first one was for proving the qualitative similarity of the motion of CasteriX with Jazzy EW and the second one is for showing how the motion changes with changing CasteriX's physical parameters. Here, the same floor was used throughout those two experiments. However, the floor of the testing area had slight variations in height between tiles, resulting in small hills and valleys. Although the surface was relatively smooth, it was not perfectly uniform. The reason for using this floor is that its minor surface variations simulate realistic indoor conditions. It should be noted that, for all experiments, the caster angles are measured clockwise relative to the robot's forward heading.

B. Assumptions

In these experiments, assumed that the control wheels were always in contact with the ground. Because for CasteriX, having a total of 3.71 kg and for Jazzy EW having 91 kg of weight is enough to push the robot to the ground. Furthermore, because of the low speed, it was assumed that the air drag was negligible in this experiment.

C. First Experiment

To examine the motion characteristics of CasteriX with the Jazzy Wheelchair, CasteriX was tested by changing the initial caster angles from $\pi/2$ to $\pi/2$ radians before initiating the straight forward motion of the robot. Throughout this experimental setup, two double caster wheel attachments were attached to the CastriX robot base as the front and rear caster handles, similar to the Jazzy wheelchair. When testing CasteriX, 22 trials were conducted for each case, maintaining the same initial caster angle and input speed. To get the motion characteristics of the reference robot, the same experiments have been done on the Jazzy EW, but each trial was run for 13 seconds. Here, a constant wheel velocity input of 40% of the maximum speed of 56 rpm is given for CasteriX and for Jazzy EW constant speed of $0.225\ ms^{-1}$ throughout the trial. However, for the Jazzy EW, for each initial caster angle, 8-10 trials were done and the best performing 5 trials were selected based on the minimum standard deviation.

D. Second Experiment

In this experiment, CasteriX was tested on the given motion path with chosen wheel configurations (Table III). In this experiment, for all the motions as the initial caster angles $\frac{\pi}{2}$ and $\frac{3\pi}{2}$ were used for front and rear casters, respectively. Here, motion variation with control wheel position, caster wheel configuration, and caster wheel sizes was inspected. Here, for each configuration, 10 trials were conducted and the best 5 out of those were selected by using the minimum standard deviation values among them.

The notation in this paper follows the format (control wheel position)_(caster positions)_(caster size), where control wheel position is f = front, m = middle, r = rear; caster positions are a = front left, b = front middle, c = front right, d = rear right, e = rear middle, f = rear left; and caster size is s = small, l = large. All of the configurations of the CasteriX are shown in Fig. 5

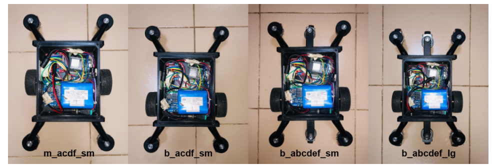


Fig. 5. Wheel configurations on CasteriX for the second experiment

TABLE III
Wheel configurations for the second experiment

Control wheel position	Parts	Caster Size	Notation
Middle	FL & FR+RL & RR	Small	m_acdf_sm
Rear	FL & FR+RL & RR	Small	b_acdf_sm
	MF+FL & FR+RL & RR+MR	Small	b_abcdef_sm
	MF+FL & FR+RL & RR+MR	Large	b_abcdef_lg

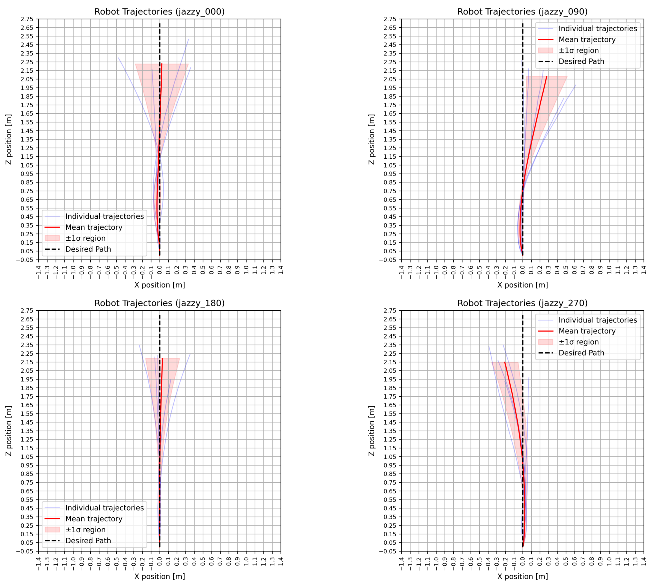
VI. Experiment Results and Discussion

Even though Fig. 6 shows Jazzy Air EW has more drift away from the desired path, CasteriX shows the same qualitative characteristic about the behavior of how motion differs with different caster angles in Fig. 7. That drift magnitude differs between them because it scales with the overall size of the platform. Additionally, in graphs can see that when the initial caster angles are $90°$ degrees and $270°$ degrees, the motion tends to go in that direction for both robots.

When discussing the second experiment results, identify that with a different set of wheel configurations motion path varies. Furthermore, comparing m_acdf_sm and b_acdf_sm shows that the robot's motion is highly sensitive to the control wheel placement, resulting in markedly different kinematic responses. Relative to the earlier case, the difference in motion behavior between b_acdf_sm and b_abcdef_sm is reduced, although a noticeable deviation is still present. That gives a sense that caster wheel configuration also affects the dynamics. Although the motion patterns of b_abcdef_sm and b_abcdef_lg appear largely similar, a small deviation is observed in the mid-path region following the first turn. This indicates that the caster wheel size influences the robot's motion dynamics.

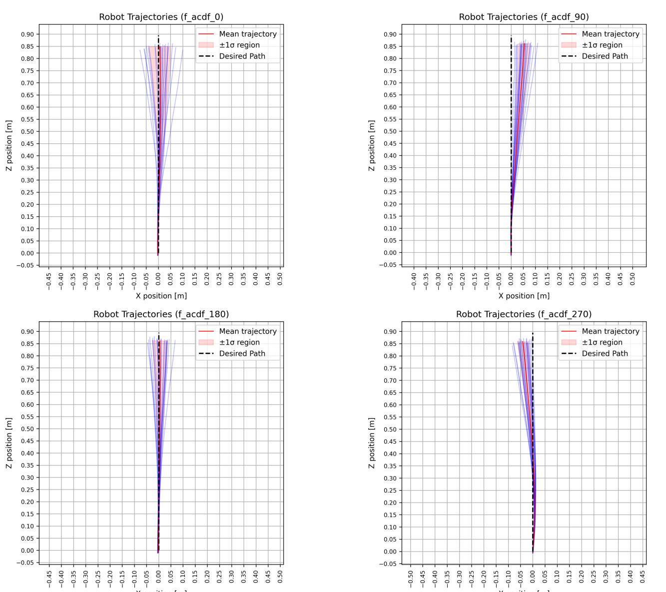
VII. Conclusion

These 3D printable parts and the use of cost-effective sensors and motors reflect the low cost of developing this robot. Also, those caster wheel attachments, which can be attached and detached, show the modularity of this prototype. Not only that, modularity of this robot is greatly enhanced by the loosely coupled behavior of its subsystems. Using scaled-down double caster attachments from the Jazzy Pride Air wheelchair incorporates the scalability of the robot. Moreover, being extendable for future use and supportive of additional



(c) 180° (d) 270°

Fig. 6. Forward straight motion trajectories of the Jazzy EW robot for four different initial orientations



(c) 180° (d) 270°

Fig. 7. Forward straight motion trajectories of the CasteriX robot for four different initial orientations

sensors supports that. Proper scaling of the robot supports the quantitative similarity between the CasteriX robot and the Jazzy EW. Additionally, via the first experiment, the CasteriX robot proves the qualitative motion dynamics similarity with the Jazzy EW. Lastly, the second experiment shows how the complexity of the motion dynamics of an EW varies and the importance of analyzing the motion dynamics of an EW via a prototype while changing the wheel configurations.

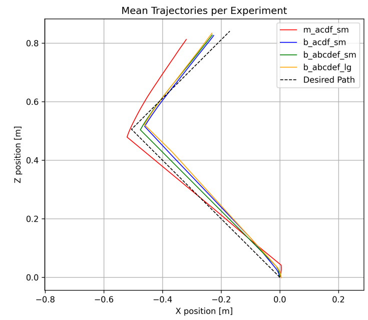


Fig. 8. Motion behavior with different configurations

Therefore, these findings highlight the suitability of CasteriX for EW motion dynamics analysis. It should also be noted that, when downsclaing wheel configuration of the EW, the external forces do not scale down exactly as the ratio. Therefore, the dynamics of the prototype robot won't be purely the same as the EW robot. However, the scaled wheel configuration preserved the qualitative behavior of motion between two robots.

VIII. Future Work

Future researchers can extend CasteriX by mounting absolute encoders on the caster handles to measure caster angles.

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