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Evaluation of Differential Steering Performance in VRU Testing Platforms: Accuracy and Reliability Analysis Across Varying Speeds and Circular Trajectories

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ABSTRACT – *This study investigates the performance of differential steering systems in navigating circular trajectories at varying speeds using a small Vulnerable Road User (VRU) testing platform. The platform, designed with two 600W Brushless Direct Current (BLDC) hub motors and a differential steering mechanism, was evaluated for its accuracy and reliability in following designated paths with radii of 4, 8, and 12 meters. The evaluation was carried out at two motor speeds 5 000 and 10 000 rpm. Significant deviations from the intended path were observed, with deviations ranging from 14.0% to 32.3%, particularly at higher speeds and larger radii. The primary cause of these deviations was identified as wheel slippage on the asphalt surface, worsened by centrifugal forces during turns. Despite these challenges, the steering system demonstrated good reliability, maintaining deviations within 10%. The study underscores the need for optimizing wheel materials and refining control algorithms to reduce slippage and improve maneuverability. These findings offer valuable insights into enhancing the accuracy of differential steering systems in VRU testing platforms, contributing to the development of more effective Advanced Driver-Assistance Systems (ADAS).*

KEYWORDS: Differential steering, VRU platform, ADAS evaluation

1. INTRODUCTION

Malaysia recorded more than half a million reported road accidents each year. Selangor, Johor, and Kuala Lumpur were the states with the highest number of accidents, with Selangor also reporting the highest number of fatalities (Soo, 2023). According to the Malaysia Road Fatalities Index by the Ministry of Transport, motorcyclists were involved in the majority of fatalities, accounting for around 60 percent of the total, followed by passenger car occupants at around 20 percent. Pedestrians and bicyclists together accounted for 12 percent of the total fatalities (MOT, 2023). These statistics indicate that vulnerable road users (VRUs), including motorcyclists, pedestrians, and bicyclists, constitute the highest proportion of fatalities.

In Malaysia, road accidents are primarily attributed to several factors, with human error being the most significant. Approximately 20 to 30 percent of accidents are caused by drivers exceeding speed limits (Mahat et al., 2020; Ab Rashid et al., 2021). Distracted driving, such as using mobile phones while driving, contributes to about 20% of accidents. Driving under the influence of alcohol or drugs accounts for approximately 15% of accidents, while reckless driving is responsible for around 10%. Non-human factors, including adverse weather conditions (10%), vehicle malfunctions (5%), and poor road conditions (5%), also contribute to the cause of accidents (Mahat et al., 2020; Kurnia Insurans, 2022).

Vehicle manufacturers have focused on enhancing vehicle safety features to mitigate the impact of collisions. Modern vehicles are equipped with safety features such as multiple airbags, improved seatbelt designs, and crumple zones designed to absorb impact energy during a collision. However, these features primarily address safety during an impact. With advancements in technology, there has been a significant shift towards developing solutions aimed at preventing accidents altogether. Advanced Driver-Assistance Systems (ADAS) have been introduced, incorporating features like automatic emergency braking, lane-keeping assist, and adaptive cruise control (Mansor et al., 2020). These systems are designed to prevent accidents by alerting drivers to potential hazards and, in some cases, by taking corrective actions autonomously (Bosurgi et al., 2023). Despite the benefits of ADAS, the technology is still in its nascent stages, with challenges such as sensor limitations, system accuracy, inconsistency, and calibration issues. Consequently, evaluating ADAS systems, especially concerning VRUs, is critical.

To enhance the effectiveness of ADAS in detecting VRU movements, it is important that these systems accurately mimic the movements of pedestrians, motorcyclists, and bicyclists on the road. However, replicating such movements is highly complex. In the Euro NCAP evaluation, a testing platform equipped with VRU dummies is used to simulate these movements (Euro NCAP, 2023). This platform must precisely follow a standardized evaluation path at a specific speed while being robust enough to withstand impacts without damaging the vehicle under testing. However, the standardized evaluation path in Euro NCAP is a straight path, whereas, in reality, VRU movements can be far more complex.

To enable the testing platform to navigate complex paths, an effective steering mechanism is crucial. Steering mechanisms can be classified into several categories based on their design, functionality, and application. One of the most common mechanisms is Ackermann steering, where all wheels are linked to a common point and turn about different radii. When the vehicle turns, each wheel follows a unique path, with the inner wheels turning at a sharper angle than the outer wheels (Choi et al., 2008). Ackermann steering is optimized for smooth turns at higher speeds but may exhibit limitations in maneuverability, particularly at low speeds or in confined spaces. Due to the fixed geometry of the steering linkage, vehicles with Ackermann steering may struggle to navigate tight turns or perform complex maneuvers. Despite these drawbacks, Ackermann steering remains a popular choice due to its proven effectiveness in providing smooth and predictable steering behavior, especially in conventional passenger cars and commercial vehicles.

Another well-known steering system is differential steering, which involves independently controlling the speeds of the left and right wheels to steer the vehicle. By varying the wheel speeds, the vehicle can turn by rotating around its central axis (Wu et al., 2013). Differential steering is simple and cost-effective, making it a popular choice for small robotic platforms and vehicles. However, maintaining straight-line tracking can be challenging, particularly at higher speeds or on uneven terrain. The differential nature of the steering system can cause the vehicle to drift or veer off course, necessitating constant corrections from the operator or control system to maintain a straight trajectory. Although this mechanism is effective in certain contexts, it also has limitations in terms of maneuverability, particularly in tight spaces or when precise turning is required.

Skid steering is an enhancement of differential speed steering. Also known as tank steering or track steering, skid-steering involves independently driving the left and right sides of the vehicle or robot using tracks or wheels. To turn, one side of the tracks or wheels slows down or reverses while the other side continues moving forward. This system offers excellent maneuverability and is well-suited for navigating confined spaces or rough terrain. However, it can be less efficient on flat or low-friction surfaces and may lead to excessive tire wear due to skidding.

Recent technological advancements have led to the development of omnidirectional steering systems (Ueno et al., 2009). These systems utilize multiple wheels or rollers arranged in specific configurations to achieve motion in any direction without changing the vehicle's orientation. Omni-directional steering offers unparalleled maneuverability, allowing the vehicle to move sideways, diagonally, or rotate in place. This makes it ideal for applications requiring precise positioning and navigation in tight spaces, such as warehouse automation, robotics, and material handling systems. However, omnidirectional steering systems often require specialized components, such as omnidirectional or mecanum wheels, as well as sophisticated control algorithms and sensors. The increased complexity and cost of these systems may be prohibitive for some applications. Additionally, the unique structure of mecanum wheels may present limitations in terms of load capacity and payload capabilities.

Each of these steering mechanisms offers distinct advantages and is suitable for specific applications, depending on factors such as vehicle size, environment, maneuverability requirements, and cost considerations. Selecting the appropriate steering mechanism is essential for achieving optimal performance and efficiency in autonomous systems.

This paper aims to evaluate the effectiveness of the differential steering system in terms of its performance in path-following at varying speeds, with a particular focus on navigating circular trajectories for a small VRU testing platform.

2. METHODOLOGY

2.1 VRU Platform

A small VRU testing platform was developed using a 40 x 40 mm aluminum profile as the main structural framework. The platform measures 0.3 meters in length and 0.8 meters in width. Two 600 W Brushless Direct Current (BLDC) hub motors were mounted on the rear side of the platform. In these hub motors, the BLDC motor and the wheel are integrated into a single unit. Both the hub motors and the front freewheel have a diameter of 0.075 meters. The hub motors are connected to a VESC FSESC 6.7 dual motor speed controller board. The VESC controller is equipped with proprietary software, VESC Tools, which allows for direct tuning of the motor parameters. To power the VESC controller and the hub motors, a 10S2P-36V battery was utilized. The final configuration of the platform is illustrated in Figure 1.

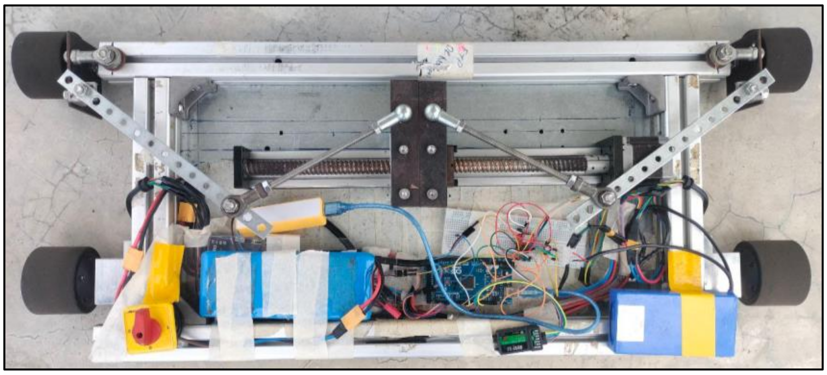

FIGURE 1: The developed VRU platform

For wireless speed regulation, a FLYSKY FS16 remote control was utilized. This remote control includes an integrated sender-receiver board. The receiver from the remote control was connected to an Arduino Mega board, which was then linked to the VESC controller via UART communication.

To implement the differential steering command, both rear wheels must maintain the same speed when moving forward or backward. During cornering, one wheel is slowed down relative to the other, based on a specific ratio determined by the desired turning radius. The speed ratio is calculated using the geometry of the differential steering mechanism, as outlined by Shamah (1999) and illustrated in Figure 2.

According to Shamah, the speed ratio of the motorized wheels for a specific turning radius considering that no slipping occurs can be obtained using

$$\frac{v_0}{v_i} = \frac{R + \frac{B}{2}}{R - \frac{B}{2}} \quad (1)$$

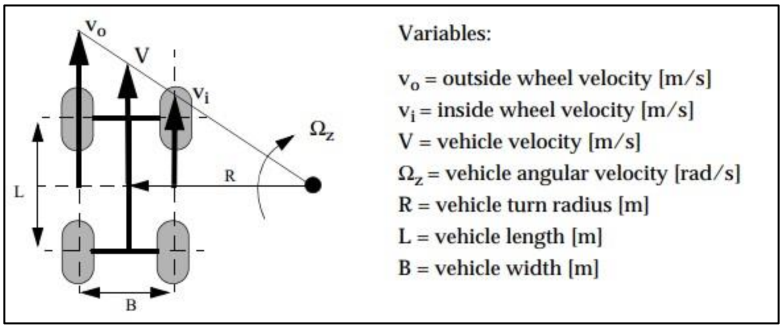

FIGURE 2: Differential Steering geometry (Shamah, 1999)

2.2 Maneuverability Analysis

Three cornering radii were arbitrarily selected: 4 m, 8 m, and 12 m. For each designated turning radius, the speed ratio of the rear wheels for differential steering was calculated based on Equation 1. The speed of the hub motors was expressed in revolutions per minute (rpm) rather than meters per second (m/s) to exclude loading factors. Two initial speeds were chosen: 5,000 rpm and 10,000 rpm. The calculated ratios corresponding to the selected radii and speeds are presented in Table 1. The speed of the hub motors was adjusted by controlling the motor parameters using VESC tools, as shown in Figure 3.

TABLE 1: Ratio for differential steering systems and the speed of the outer motor (Mo) and inner motor (Mi)

Width (m)	Radius (m)	Ratio	Mo (rpm)	Mi (rpm)
0.8	4	1.22	5,000	4,098
			10,000	8,197
	8	1.11	5,000	4,505
			10,000	9,009
	12	1.07	5,000	4,673
			10,000	9,346

FIGURE 3: BLDC motor parameters setting using the VESC tools software

The Sensor Logger mobile application was employed to collect data on positioning and speed using the embedded GPS and IMU sensors (Google, n.d.). One advantage of using the Sensor Logger application is its continuous updates on measurement accuracy, which helps ensure the reliability of the collected data.

3. RESULTS AND DISCUSSION

The GPS data recorded by the Sensor Logger application were translated into X-Y coordinates, where the X and Y coordinates represent longitude and latitude, respectively. These coordinates were manually processed and converted into meters. The recorded positional data, along with comparisons to reference points, are presented in Figures 4 and 5, as well as in Table 2.

TABLE 2: CRS list in at least three countries

Speed (rpm)	Radius (m)	Mean Radius (m)	Deviation (%)
5,000	4	4.6	14.0
	8	9.5	18.4
	12	15.0	24.8
10,000	4	5.0	24.2
	8	10.1	25.9
	12	15.9	32.3

Based on Table 2, significant deviations were observed across all cases, with the lowest being 14.0% and the highest 32.3%. One contributing factor to these deviations was slippage. The wheels used on the platform were made of Polyurethane (PU), which is prone to slipping on asphalt surfaces. PU wheels, commonly found on skateboards, rollerblades, or scooters, are designed to reduce friction. As noted by Shamah (1999), Equation 1 assumes no slippage occurs, hence using wheels with higher friction, such as those made of rubber, could potentially reduce deviations.

Moreover, the trend of deviation increased with radii, indicating that larger radii were associated with higher deviations. This may be attributed to the speed ratio. For the 4 m radius, the speed difference between the wheels is substantial, while for the 12 m radius, the ratio approaches one, indicating a minimal difference. When the speed difference is small, there is less skidding, and the presence of slippage further reduces the platform's ability to perform cornering, leading to larger deviations. According to Equation 1, the speed ratio can be increased by widening the vehicle.

During cornering, the platform generates centrifugal force, which is an apparent force that acts outward on a body moving along a circular path, away from the center of rotation. Centrifugal force is directly proportional to both the speed and mass of the platform and inversely proportional to the turning radius. At higher speeds, a greater centrifugal force is generated, pushing the platform further away from the center of rotation. This phenomenon is evident in the observed deviation trends relative to speed. As shown in Table 2, higher speeds result in greater deviations.

Table 3 presents the reliability of the differential steering system, measured by the amount of deviation from the recorded position relative to the recorded mean radius. The reliability of the steering system is considered good, with deviations between results remaining within 10%. The highest deviation was recorded for the 4 m radius, while deviations for the 8 m and 12 m radii were less than 3%. For a given speed, centrifugal force is stronger during a turn with a smaller radius, as the vehicle changes direction more sharply, requiring more force to maintain the curved path. To ensure the vehicle stays on its intended path during a turn, the frictional force must be equal to or greater than the centrifugal force; therefore, increasing wheel grip can reduce deviation.

The Sensor Logger application also recorded the platform’s speed during testing. The mean speeds are presented in Table 4. For an outer motor speed of 5,000 rpm, the overall recorded mean speed was 6.69 km/h, with a deviation of less than 2%. At an outer motor speed of 10,000 rpm, the recorded overall mean speed was 13.82 km/h, with a slightly higher deviation of 3%. Despite this slight increase, the low deviation indicates that the platform's speed was consistent.

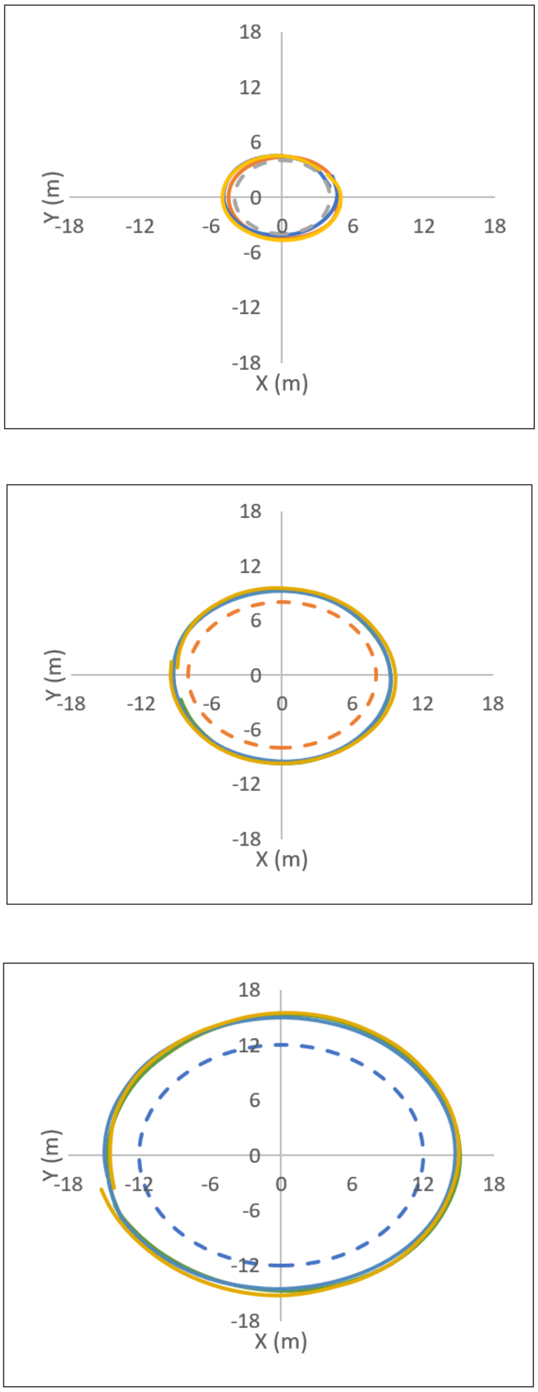

FIGURE 4: The recorded position of the platform with the outer motor speed was 5,000 rpm along a 4 m, 8 m, and 12 m radius path respectively

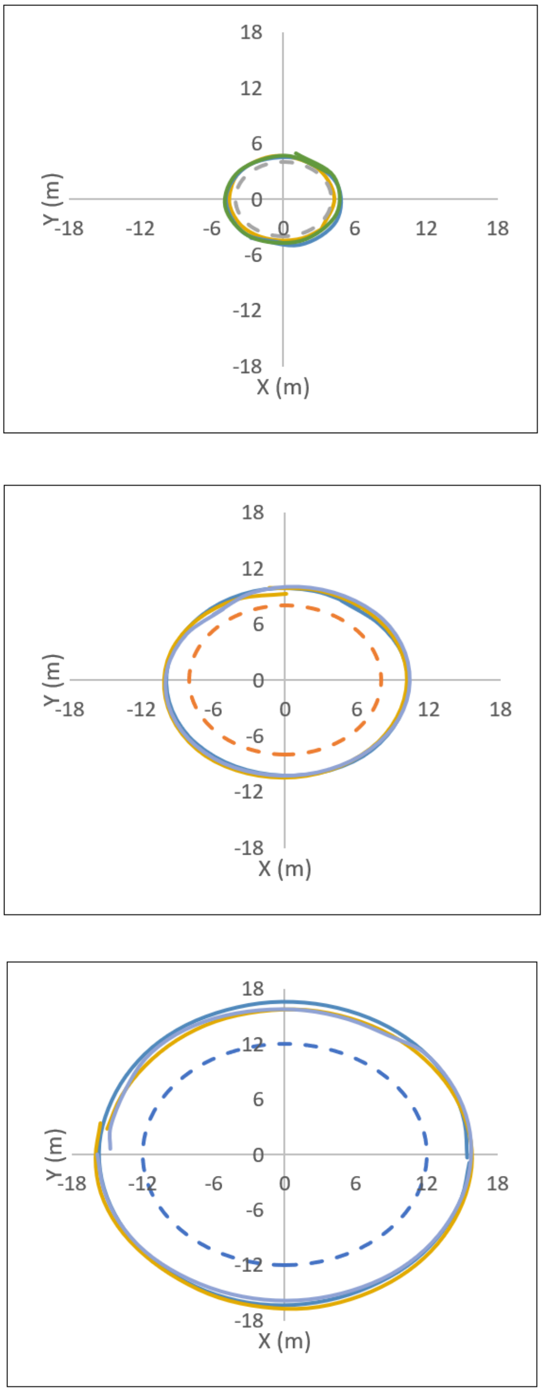

FIGURE 5: The recorded position of the platform with the outer motor speed was 10 000 rpm along a 4 m, 8 m, and 12 m radius path respectively

TABLE 3: Reliability analysis of the platform

Speed (rpm)	Mean Radius (m)	Mean Deviation (m)	Mean Deviation (%)
5,000	4.56	0.40	8.7
	9.47	0.14	1.5
	14.97	0.21	1.4
10,000	4.97	0.50	10.1
	10.07	0.24	2.4
	15.88	0.30	1.9

TABLE 4: Mean speed of the platform during the analysis

Radius (m)	Mo (rpm)	Mean Speed (km/h)	Overall Mean Speed (km/h)	Overall Deviation (%)
4	5,000	6.79	6.69	1.4
8		6.65		0.7
12		6.64		0.8
4	10,000	13.91	13.82	0.7
8		14.13		2.2
12		13.41		3.0

4. CONCLUSION

This study evaluated the effectiveness of differential steering systems in navigating circular trajectories at varying speeds using a small VRU testing platform. The findings revealed that the platform experienced significant deviations from the intended path, with deviation percentages ranging from 14.0% to 32.3%, particularly at higher speeds and larger turning radii. These deviations were primarily attributed to wheel slippage on the asphalt surface, worsened by the centrifugal forces generated during turns. Despite these challenges, the platform demonstrated good reliability, with deviations staying within 10% of the mean radius, especially for larger radii where centrifugal forces were less pronounced. The study highlights the importance of optimizing wheel materials and improving friction to reduce slippage, particularly for tight turns at higher speeds. Additionally, it underscores the need for further refinement in the speed ratio calculation and platform design to enhance path-following accuracy. Future research could explore alternative wheel materials or advanced control algorithms to mitigate slippage and improve the platform's maneuverability. The findings provide valuable insights into the limitations and potential of differential steering systems in VRU testing platforms, contributing to the ongoing development of safer and more reliable ADAS technologies.

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