IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 5 December 2023, accepted 3 January 2024, date of publication 12 January 2024, date of current version 19 January 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3353616

RESEARCH ARTICLE

Outdoor Tests of Autonomous Navigation System Based on Two Different Reference Points of PurePursuit Algorithm for 10-ton Articulated Vehicle

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This work was supported by The Royal Swedish Agricultural Academy (SLO-Foundation).

ABSTRACT This work presents outdoor test results of autonomous navigation system based on two different reference points of PurePursuit algorithm for a 10-ton articulated research platform. PurePursit is commonly used simplified tracking algorithm based on geometric calculation of desired steering angle by pursuing certain number of points/distance ahead on given path from a fixed reference point of vehicle. Choice of fixed reference point effects the tracking accuracy particularly for articulated/center-steered vehicles. In this experimental work, PurePursuit algorithm with a virtual reference point (PPV) and commonly used front-axle reference point (PPF) is evaluated for heavy duty articulated vehicles in outdoor experiments. Experimental data shows that choice of reference point in PurePursuit algorithm for articulated vehicle has impact on tracking accuracy in terms of crosstrack errors and heading errors. Navigation tests were performed on a flat asphalt surface for paths of sharp complexities i-e a path with continuous curvature (circular path) and a path with sharp turns (zigzag path) with different initial conditions i-e initial position of vehicle. In general, it can be concluded that PurePursuit algorithm with front reference point (PPF) produced fewer crosstrack errors while PurePursuit algorithm with virtual midpoint reference (PPV) produced fewer heading errors.

INDEX TERMS Autonomous navigation, articulated vehicle, outdoor experiments, PurePursuit algorithm, virtual mid reference point, front-axle mid reference point.

I. INTRODUCTION

In area of autonomous navigation, several methods are being explored based on use of one or multiple sensors such as GPS, cameras, lidar, radar and other dead reckoning methods [1] depending on applications. One recent research has utilized deep neural networks for vison-based navigation in unknown indoor environments [2]. Another studied energy efficient motion planning of forklifts transportation utilizing Deep neural networks (DNNs) [3]. For underwater navigation application, model predictive control-based velocity controller was verified for trajectory tracking in simulation [4]. A research study investigated online replanning for wheeled-legged robots using behavior tree in cluttered simulation environment [5]. Another recent study proposed steer guidance using pure pursuit algorithm (PPA) which is also assisted by vector field histogram (VFH) based on 2-dimensional light detection and ranging (LiDAR) sensors data for obstacle avoidance [6]. A study has presented experiments industrial-grade service robots with regulated PurePursuit adjusting linear velocities with particular focus on safety in constrained and partially observable indoor spaces [7]. A related study has applied MPC based lookahead distance optimization for pure pursuit tracking control to

The associate editor coordinating the review of this manuscript and approving it for publication was Junho Hong.

improve cutting corner problems in simulation and experiments on various roads, including handling course, double lane change, and 90-degree turn [8].

The work presented in this paper is based on results of outdoor tests of our previously evaluated simulation-based autonomous navigation system built on two versions of Pure-Pursuit algorithm for an articulated vehicle platform [9].

PurePursuit algorithm is one of the preferable choices for low-speed navigation applications due to its platform independency and simplicity and has been widely investigated for various systems since its inception e.g., in cars, articulated vehicles [10] and six wheeled skid steered robot at CMU [11]. Several studies have evaluated PurePursuit algorithm for various reference points, lookahead distance and various initial positions mostly in simulation environment or for regular vehicles [8], [12], [13], [14]

With regards to implementation of Pure Pursuit algorithm for articulated vehicles; following the early work of [15] and [16], on path tracking of articulated vehicles using pure pursuit tracking algorithm, a test study of pure pursuit tracking algorithm on small-scale articulated vehicle was carried out for various paths, speeds and control pulses and measured the accuracy of the task [17]. [18] further studied navigation accuracy of Pure Pursuit based path tracking for a multi-purpose centered-articulated rover for cotton field operation. In 2006, [19] carried out simulation study on accuracy evaluation of proposed path tracking algorithm ''follow the past'' with existing PurePursuit and follow the carrot algorithm for an articulated vehicle.

In general navigation of articulated vehicles is viewed from truck-trailer perspective [17] where the wheels are steerable in yaw during translational motions. However, vehicles with articulated steering, as being studied in this paper, has major differences in control relationship among front and rear part of the vehicle. In such systems, the wheels are non-steerable in yaw and instead, the steering action is done by rotating the entire front and rear end of the vehicle around a hitch point or articulation point. When implementing the PurePursuit, the midpoint of the front-axle of articulated vehicles are typically used as reference for the navigation. However, this reference point is not independent of the steering angle (as in wheel steered vehicles) and thus, a steering action by itself induces positioning errors which in turn affects the navigational accuracy. To avoid this problem, a virtual-midpoint being less dependent on the steering angle have been proposed and verified through simulations [9]. A related work of [20] also examined motion stability by choosing such an intermediated point for reverse and forward maneuverability of articulated vehicle. However, there is a lack of experimental validation of virtual-midpoint based PurePursuit algorithm of full-scale heavy duty articulated vehicles. Thus, the objective for this paper is to experimentally determine the navigational accuracy when using virtual-midpoint as reference for PurePursuit algorithm in comparison to the front-axle midpoint reference of articulated vehicles. The articulated vehicle platform used for validation has equal distance between the wheel axles and hitch point and the experiment were conducted at low speed with full traction.

II. METHODOLOGY

To evaluate the navigation accuracy based on two versions of PurePursuit algorithm for an articulated vehicle, full scale outdoor experiments were performed.

The two choices of reference points i.e., the traditional front-axle-midpoint (abbreviated as PPF) and the proposed virtual-midpoint (abbreviated as PPV) were deployed separately from Simulink© models to the target machine (UEISim). Two global paths of different complexity were created on flat surface i.e., one circular and one zigzag patterned.

First, global waypoints were obtained from satellite images in terrestrial coordinate system which then were converted into cartesian coordinates. Path smoothening was then applied to make sure that the vehicle's kinematic constraints (max turning radius) are fulfilled. The path smoothing was carried out using the built-in ''navPath'' function in MATLAB© that incorporated the limitations in heading and turning radius into path generation. The navPath function then interpolated the reference paths with predetermined distance into uniformly spaced path points using stateSpaceDubins (state space composed of state vector [x, y, θ]) and produced a smoothened path that a vehicle can follow (See Figure 8. & Figure 9.). This smoothened path was used as ground truth for the accuracy measurements.

A proportional controller with same parameter was used for regulation of error response calculated by means of Euclidean distance between the smoothened path and the real path travelled by machine (measured by RTK-GPS sensor). In addition, the deviations between the planned and real heading at each path points were measured.

Performance analysis of autonomous navigation of the two version of PurePursuit algorithm (PPF and PPV) was performed with same preconditions e.g., terrain, regulation settings, speed etc. However, different lookahead distance was required between PPF and PPV to make sure that the transient response had a similar behavior.

III. TWO VERSIONS OF PUREPURSUIT NAVIGATION SYSTEM

A. PurePursuit WITH FRONT REFERENCE POINT (PPF)

From the geometry for the front reference (F) shown in Figure 1. below, the wanted steering angle can be derived [9] Thus, for a chosen look-ahead point (LP), look ahead angle (α), distance (l_d) from front-axle midpoint reference(F), and length (L) of vehicle front part to articulated joint, following expression can be computed,

$$\beta = \tan^{-1} \frac{2L \sin \alpha}{l_d} \quad (1)$$

and the wanted steering angle $\gamma = 2\beta$.

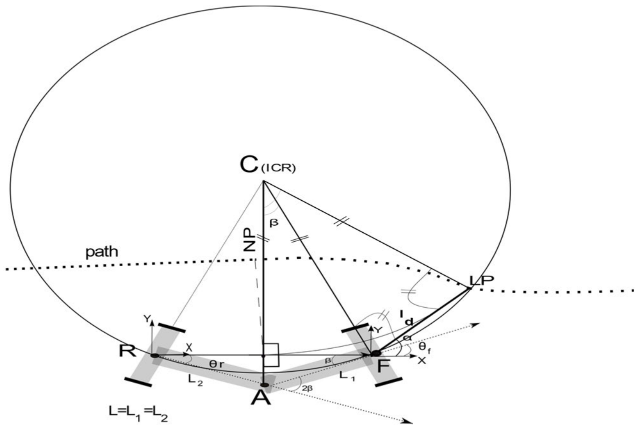

FIGURE 1. PurePursuit geometric representation for articulated vehicle with front-axle midpoint -PPF [9].

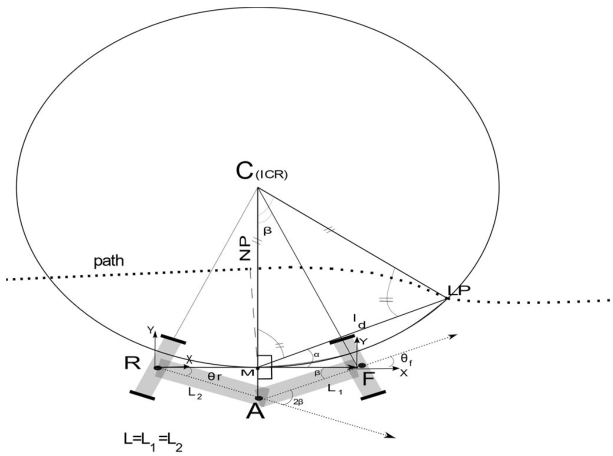

FIGURE 2. PurePursuit geometric representation for articulated vehicle with virtual-midpoint heading (M)-PPV [9].

B. PurePursuit WITH VIRTUAL MIDPOINT (PPV)

For the virtual midpoint reference, the geometry shown in Figure 2. below gives that

$$\frac{2L\sin(\alpha)}{l_d} = \frac{\tan(\beta)}{\cos(\beta)} \tag{2}$$

where for a chosen look-ahead point LP, (α, l_d) are lookahead angle and distance from front reference, (L) is length of vehicle front part front to articulated joint. The wanted steering angle is $\gamma = 2\beta$.

IV. MECHANICAL PLATFORM

To test PurePursuit navigation with the two chosen reference points, an articulated research vehicle platform shown in Fig. 3 was used. The platform consists of rear and front vehicle bodies which are connected by centered positioned articulated joint. The drive train consist of a 129-kW combustion engine powering two tandem mounted hydraulic pumps with variable displacement. One pump is used for the hydro static motors driving the vehicle and the other pump used

FIGURE 3. Test articulated vehicle.

to drive pendulum arm cylinders, steering cylinders, auxiliary equipment etc. The primary components and systems comprising the core of the machine used in the physical experiments was designed entirely from scratch at Luleå University of Technology, but some subsystems have been purchased such as the entire drivetrain, hydraulic components, and computers. The overall dimensions of the machine are characterized by a length of 5.5 meters, a width of 2.3 meters and a weight of 10 ton. The articulated joint of the machine is actuated using two hydraulic cylinders working in series. The hydraulic pressure in those cylinders is, in turn, regulated by a hydraulic proportional valve overseen by a Parker IQan amplifier. The Parker IQan retrieves a UEISIM I/O output between 0 and 5 VDC to set the current level sent to the proportional valve. The platform is instrumented with a Novotechnik analogue Rotary sensor Series RFD4000 that measures the articulate joint angle, having a repeatability at 0.1deg. The UEISIM I/O logs this sensor with a 18bit input board at a sampling rate of 60000 samples/s. To transmit output signals to the Parker IQan amplifier, a 16bit UEISIM output board with a precision measure at $+-$ 2.44mV is used, set at a timestamp of 0.01s.

V. COMPUTING AND COMMUNICATION HARDWARE

The articulated vehicle is equipped with UEISIM & NVIDIA®Jetson™ computing hardware to deploy and perform autonomous functionalities.

UEISIM & NVIDIA® Jetson™ are the main data acquisition & computing unit of vehicle; accessed through Laptop's terminal program over secure local Wi-Fi connection. Pure Pursuit based navigation models are compiled in MATLAB Simulink©and deployed in UEISIM. Once the models are built and compiled, they are deployed in the UEISIM and activated by human command to run the machine autonomously.

Figure 4. shows an overview of the hardware architecture including the internal communication flow.

The navigation control is deployed to the UEISIM through TCP connection as shown Figure. 4.

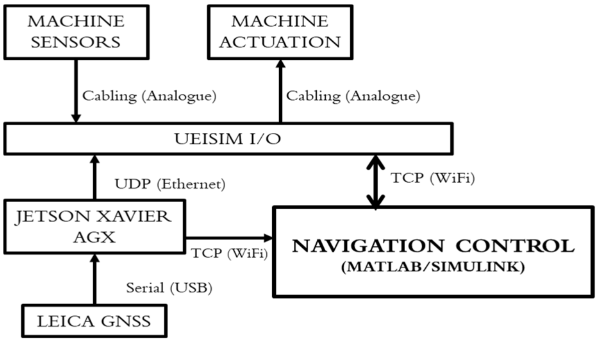

FIGURE 4. Hardware & communication architecture.

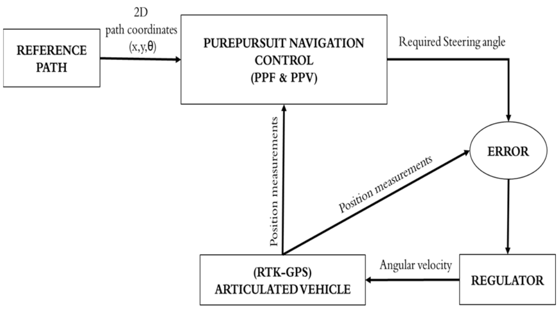

FIGURE 5. Navigation control system.

VI. NAVIGATION CONTROL SOFTWARE

In Figure 5., the general information flow of the navigation control software built in MATLAB Simulink is shown.

A. POSITION MEASUREMENT

RTK-GPS was used to measure pose information of vehicle. Two RTK-GPS sensors mounted on front frame of vehicle as shown in Figure 3. were used to calculate the reference point position and heading. In case of PPF, this heading is defined by the front part heading while in the PPV case it is defined as the direction of the vector between rear axle midpoint and the front axle midpoint (see "R" and "F" in Figure 2.). RTK-GPS position coordinates were acquired through python script running in Jetson Computer on machine and converted into cartesian coordinates.

Error between wanted and actual steering angle was used as input to a proportional regulator function written in MATLAB which output the steering command. To compensate the estimated delay by hydraulic action of the vehicle, an estimated constant named as epsilon was introduced in the regulator equation.

VII. TEST ENVIRONMENT

Tests were performed on a dry flat asphalt surface at the end June 2023, 36km away from Luleå city on an area approx.17253sqm, of total of traveled length of 407m as shown in Figure 6. & Figure 7. Vehicle was position at fixed starting point outside the reference path.

A. REFERENCE PATHS/ GROUND TRUTH

Reference paths were generated offline in typical manner using static satellite images which then were saved and used as input to navigation system at test location. These reference paths are further used as ground truth when calculating the navigation accuracy. Alternatively, ground truth can also be created online by human operator by driving the machine with remote control and recording the traveled path which then can be used as ground truth for autonomous tracking.

Ground truth generated offline was then fed into path smoothing function developed in MATLAB©to generate a realistic path that a machine can follow given its kinematic constraints (in this case i-e minimum turning radius & required heading). This smoothened path was then provided as reference path or ground truth to navigation system to let the machine run autonomously. Figure 8. shows the smoothened circular reference path with a diameter of 50m while Figure 9. shows the zigzag reference path. The zigzag pattern consists of repetitions of 25 m straight road followed by a 45-degree left turn, another straight road and then a 45-degree right turn.

FIGURE 6. Satellite Image of outdoor test location [65.810000, 21.692528].

FIGURE 7. Snapshot from experiment site.

B. FIXED TUNING PARAMETERS

1) NUMBER OF LOOKAHEAD POINTS

Number of lookahead points were determined by choosing similar transient response behavior of PPF and PPV

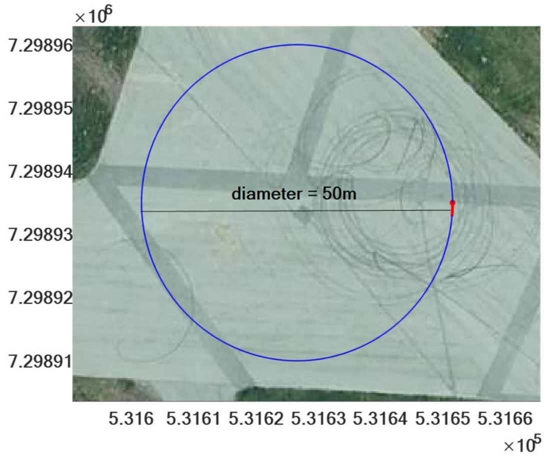

FIGURE 8. Circular smooth path generated offline at test location coordinates.

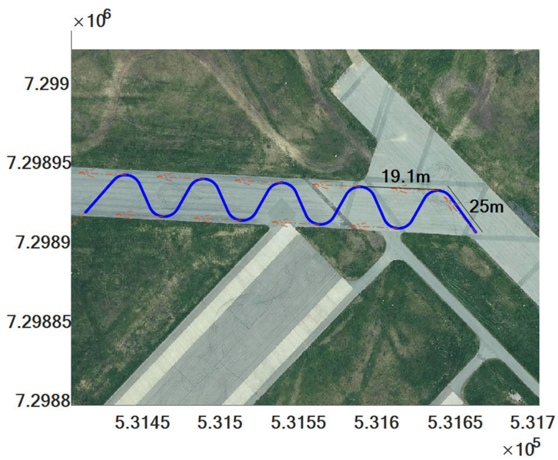

FIGURE 9. Zigzag smooth reference path generated offline at test location coordinates.

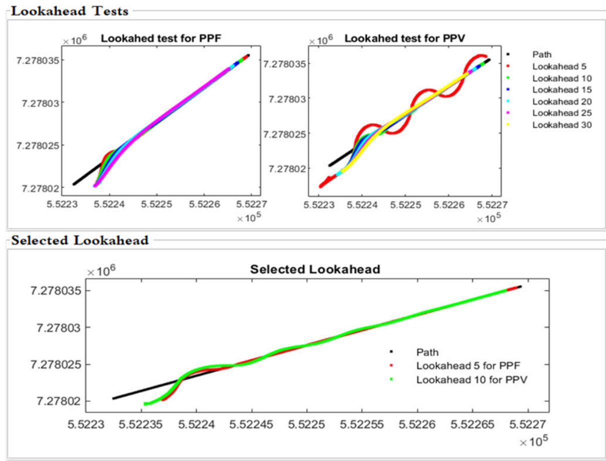

FIGURE 10. Test for Selected lookahead distance/number of points-Test for PPF (Top left), Test for PPV (Top right), Selected lookahead number (Low).

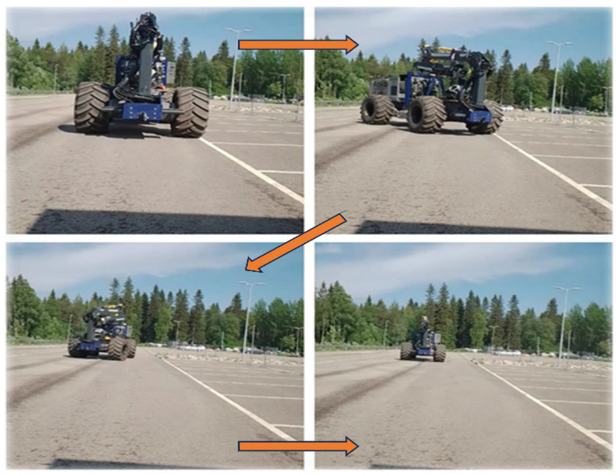

FIGURE 11. Experimental setup for look ahead point selection.

algorithms. the tests were conducted by starting from a fixed initial position of 2m sideway vehicle offset from the initial straight-line point as shown in Figure. 10 (Top left & right)

This procedure was repeated for 5 to 30 number of lookahead points in steps of 5 both for PPF and PPV. It was found that 5 lookahead points for PPF and 10 for PPV (corresponding to a lookahead distance from the reference point of 1m and 3m) show similar transient response behavior and was thus selected for the navigation tests. Figure 10. (Low) shows the transient response of PPF and PPV with the selected number of lookahead points. Figure 11. below shows snapshot of test environment and machine motion at different instants. Machine was set at standstill at close offset distance (Top left figure in Figure 11.) path to converge to straight line input for varying lookahead points/distances for both PPF & PPV.

2) ADAPTED REGULATION

Euclidean distance error regulation was done by fixed values of proportional gain in regulation control function chosen by hit and trail test on straight path. P value then was set 0.5 and 0.3 for PPF and PPV respectively based on similar stable evident behavior.

3) PERFORMANCE MEASURES

After retrieving the stored measurement data, the performance of PPF & PPV was evaluated in terms of **CrossTrack errors, Heading errors, Steering effort analysis & Steering errors**.

CrossTrack or lateral errors are computed as Euclidean distance between nearest path point and tracked position by vehicle while heading errors are computed as angular difference between heading of nearest path point and heading of tracked position by vehicle. Further, steering effort is analyzed in terms of change in steering command over time before regulation and after regulation. Unregulated steering command is the computed steering angle generated by Pure-Pursuit navigation algorithms.

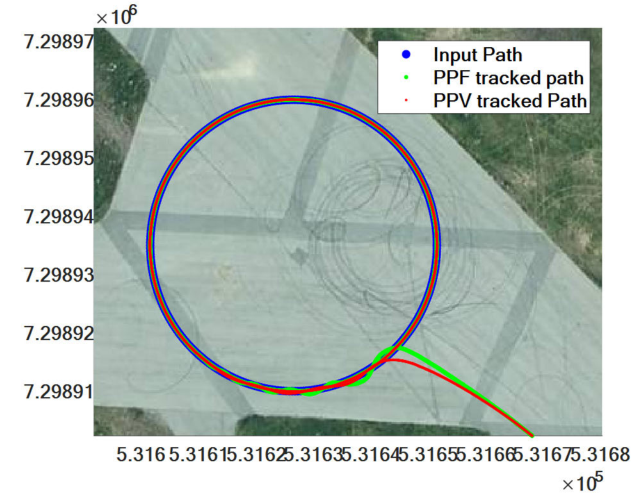

FIGURE 12. Tracked Circular path: input path (Blue), PPF(Green), PPV (Red).

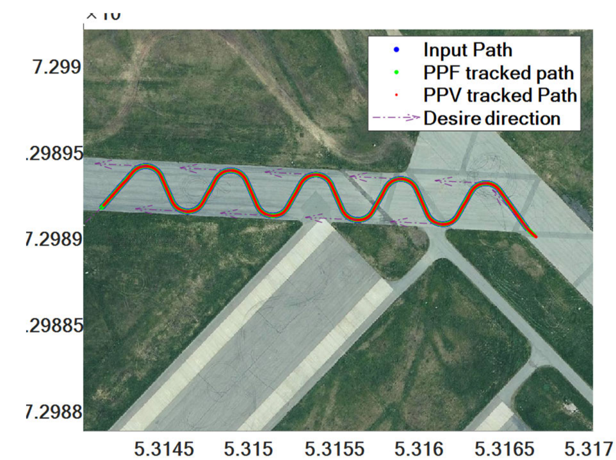

FIGURE 13. Tracked Zigzag path: input path (Blue), PPF(Green), PPV(Red).

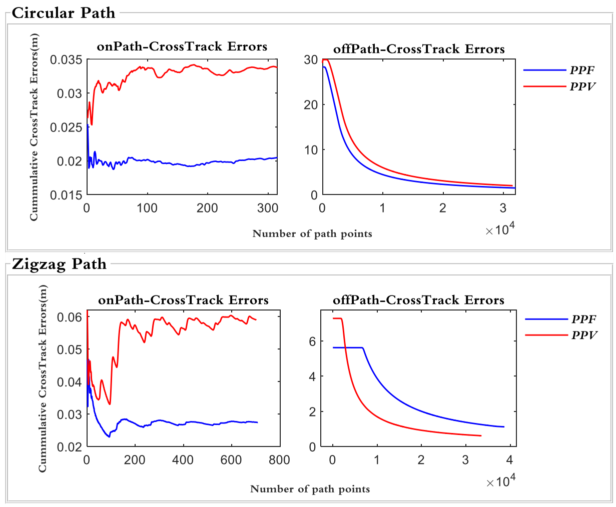

FIGURE 14. On path(L) & off-path(R) cumulative CrossTrack errors for Circular(upper) & Zigzag (Lower) paths: PPF(Blue), PPV(Red).

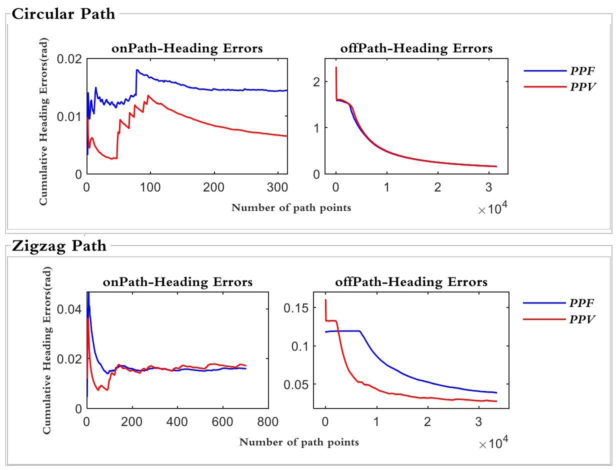

FIGURE 15. On path & off-path cumulative Heading errors for Circular(upper) & Zigzag(lower) paths: PPF(Blue), PPV(Red).

Regulated steering command is steering angle generated by P-regulator function. In addition, steering error is computed as angular difference between desired steering command and GPS based tracked orientation of vehicle.

VIII. TEST RESULTS AND ERROR ANALYSIS

To test the performance of virtual-midpoint based PurePursuit algorithm (PPV) in relation to conventional one (PPF) on the research vehicle platform, outdoor experiments were performed. Figure 12. shows tracked paths for input the circular path and Figure 13. shows tracked paths for the input zigzag path.

A. CROSS TRACK ERROR ANALYSIS

Cross track error was calculated for both circular and zigzag path by finding distance between nearest path point with respect to tracked path and represented as cumulative error. The upper half of Figure 14. shows on path- (L) and off path (R) crosstrack errors for PPF (blue) and PPV (red) for the circular reference path while the lower half of Figure 14. shows the same results for the zigzag path.

Figure 14. shows that the tracking errors when vehicle is on the path is similar for both PPF and PPV for both circular and zigzag path. However, path tracking errors when vehicle initial position is outside path are somewhat less for PPV for zigzag path.

B. HEADING ERROR ANALYSIS

The upper half of Figure 15 shows on path- (L) and off path (R) heading errors for PPF (blue) and PPV (red) for the circular reference path while the lower half of Figure. 15 shows the same results for the zigzag path.

Figure 15. shows that heading errors when vehicle is on the circular path is less for PPV while similar for zigzag path. The heading errors when vehicle initial position is outside path are

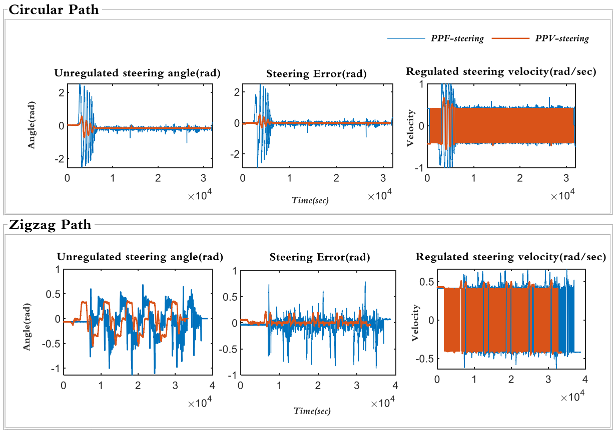

FIGURE 16. Unregulated & regulated steering effort for Circular and Zigzag paths: PPF(Blue), PPV(Red).

less for PPV for the zigzag path and similar for the circular path.

C. STEERING EFFORT & ERROR ANALYSIS

Steering effort & errors were calculated for both circular and zigzag path by finding angular difference between steering command and articulation angle of the machine. Figure 16. shows steering angle, steering error, and regulated steering for PPF (blue) and PPV (red) for Circular and Zigzag path, respectively.

The figure above shows steering effort performed by PPF and PPV before and after regulation. Irrespective of path complexity, unregulated PPF steering graph shows sharp and high magnitude changes over time whereas unregulated PPV steering graph shows relatively smooth and less magnitude changes which corresponds to similar behavior for steering errors for PPF and for PPV. Since vehicle is center-steered, where rear part of vehicle is led by front part. This particular physical structure makes the PPF more reactive to errors than PPV that results in oscillations and induces more systematic error over time. Steering error for PPF and PPV are regulated by set regulation, however for PPF, small overshoot can be observed for regulated steering velocity. This behavior relates to physical observation of the vehicle making constant steering adjustments, sharp turns, and jerky movements during driving for PPF and relatively smooth behavior during driving for PPV.

Figure 16. shows that for the circular and zigzag paths, PPV generated less steering error in comparison to PPF and therefore less steering effort was required and hence less computational & fuel energy. Additionally, it can be noted that for both paths, PPV has generated a smoother perturbation in comparison to PPF which generated higher magnitude peaks. This also shows that PPF is more reactive to changes.

Table 1 & 2 below shows statistical summary of test results for circular and zigzag path for PPF & PPV. Tracking accuracy is calculated in meter(M) or centimeter (CM) for crosstrack errors and in radian(rad) or degrees(deg) for heading errors.

TABLE 1. Accuracy measure crosstrack error & heading error for circular path for PPF & PPV.

	Circular Path – Cross Track Error		Circular Path – Heading Error	
	Initial Position		Initial Position	
	On path	Off path	On path	Off path
PPF	0.02M or 2CM	1.4M or 140 CM	0.01 rad or 0.5 deg	0.1rad or 5.7deg
PPV	0.03M or 3CM	1.9M or 190 CM	0.006 rador 0.3deg	0.1rad or 5.7deg
Absolute Difference in Accuracy (M/CM)	-0.01M or -1CM	-0.5M or -50CM	0.004 rador 0.2deg	0
% relative Difference in Accuracy	-50%	-35%	40%	0%

TABLE 2. Accuracy measure of crosstrack error & heading error for zigzag path for PPF & PPV.

	Zigzag Path – Cross Track Error		Zigzag Path – Heading Error	
	Initial Position		Initial Position	
	On path	Off path	On path	Off path
PPF	0.02M or 2CM	1.1M or 110CM	0.01 rad or 0.5cm	0.03rad or 1.7deg
PPV	0.05M or 5CM	0.06M or 6CM	0.01 m or 0.5cm	0.02rad or 1.14deg
Absolute Difference in Accuracy	-0.03M or 3CM	1.04M or 104CM	0	0.01rad or 0.5deg
% Relative Difference in Accuracy	-150%	95 %	0%	33%

IX. DISCUSSION

The performance of two different reference points of pure pursuit algorithm (PPF & PPV) was experimentally evaluated for two reference paths of different complexities i-e path with continuous curvature (circle) and a path with sharp turns (zigzag). Performance of PPF & PPV was evaluated in terms of crosstrack, heading and steering errors.

In general, the results show that PPV produced less heading error while PPF has produced less cross track errors for circular as well as zigzag path. The PPF showed 50% reduced (2 cm) cross track error when vehicle 's initial position is on the circular path & 35% (50 cm) reduced cross track error when vehicle 's initial position is off the circular path. On the other hand, the PPV showed 40% (0.2 degree) reduced heading error with initial position on the circular path while same heading error was achieved with initial position on the circular path.

The PPF showed 150% (3 cm) reduced cross track error with initial position on the zigzag path while the PPV showed 95% (104 cm) reduced cross track error with initial position off the zigzag path. While similar heading error was registered for the on path initial position, the PPV showed 33.3% (0.5 degree) reduced heading error with initial position is off the zigzag path. This indicates that PPV could be suitable choice where heading errors are important concern such as bales collection problem studies earlier [1] given the possible roam for minor systematic and human practical errors.

X. CONCLUSION

It is concluded that PPV has reduced transient cross track and heading errors for path of sharp turns such as zigzag. In general, the results indicate that the PPV is more accurate than PPF in terms of heading error while PPF is more accurate than PPV in terms of cross track error. Thus, the suitability of pure pursuit reference point choice (PPV or PPF) for navigation of articulated vehicles depends on the application area.

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