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A Robust QR and Computer Vision-Based Sensorless Steering Angle Control, Localization, and Motion Planning of Self-Driving Vehicles

SAMIA ABID[1,2], BASHIR HAYAT[3], SARMAD SHAFIQUE[1], ZAIN ALI[4], BILAL AHMED[1], FAISAL RIAZ[1], TAE-EUNG SUNG[5], AND KI-IL KIM[6]

[1]Control, Automotive and Robotics Lab, National Center of Robotics and Automation (NCRA HEC), Mirpur 10250, Pakistan
[2]Department of Computer Science and Information Technology, Mirpur University of Science and Technology (MUST), Mirpur 10250, Pakistan
[3]Institute of Management Sciences, Peshawar 25000, Pakistan
[4]Department of Electrical Engineering, HITEC University, Taxila 47080, Pakistan
[5]Department of Software, Yonsei University, Wonju 26493, Republic of Korea
[6]Department of Computer Science and Engineering, Chungnam National University, Daejeon 34134, Republic of Korea

Corresponding authors: Tae-Eung Sung (tesung@yonsei.ac.kr) and Ki-Il Kim (kikim@cnu.ac.kr)

ABSTRACT Autonomous path following has gained tremendous popularity during the last few decades. Numerous researchers have contributed to the development of highly automated navigation systems using different types of sensors and their combination. However, their proposed approaches do not provide a cost-efficient solution because of the deployment of exorbitant and sophisticated sensors, which remains a challenging problem for customized vehicles used in academic research. To overcome this issue, this study presents an economically efficient sensorless steering angle approach that employs a single camera for steering control and quick response (QR) based localization of a vehicle. Moreover, we used SONAR for object detection in a defined route to avoid possible collisions. The proposed technique combines a Probablistic Hough Transfrom for lane detection and QR codes, which helps the vehicle stay in its lane for stabilized control. To prove the efficiency of our approach, we tested it on our developed prototype vehicle named EMO. To validate the proposed approach through in-field testing, we designed a customized test track within the campus. The experimental results show the benefit of our proposed approach compared to existing methods available in the literature.

INDEX TERMS Sensorless steering angle control, localization, lane detection, quick response.

I. INTRODUCTION

Lane-keeping is essential for the smooth navigation of a self-driving car on a predefined path. For this purpose, considering the safety requirements, the accurate estimation of the steering control angle plays a vital role in keeping a vehicle in its lane. However, the steering control module requires accurate feedback to locally plane the motion of a vehicle under different road conditions. Motion planning and decision-making of autonomous vehicles under different situations allow a self-driving vehicle to find the safest and most suitable and beneficial route. Although such sophisticated mechanisms are available for well-developed automation industries, when used for customized vehicles and academic research they are extremely grueling and exorbitant to develop. In this regard, numerous researchers have contributed to propose steering angle sensors to continue their research withstanding the above-mentioned challenge which helps to determine an order of effective arrangement to help move a vehicle from a source to a destination.

Localization is an essential aspect of optimal navigation systems used in self-driving cars [1]. It requires an accurate estimate of the environment when inquiring about the concerns of an ego vehicle in terms of the questions "where am I?" and "what is around me?." For this purpose, the state estimation of a self-driving car plays a critical role in deciding the next move for the local motion planning of an ego vehicle. In the field of robotics, estimating the position of a mobile vehicle in a practical manner is a challenging task that helps in the appraisal and development of an accurate and efficient localization solution [2].

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Although a wide range of solutions to localization have been proposed in the literature using a variety of sensors [3]–[7], a vision-based localization method that uses image processing and QR codes generally provides a more efficient and simpler approach for an accurate state estimation of the ego vehicle. In this regard, Alberto *et al.* [8] proposed the use of 3D LIDAR to employ in a regression method called minimal trashed squares (MTS) for ignoring scenes, as opposed to applying temporary filters and spline fitting methods. Balázs and Benedek [9] presented a lidar-based real-time and precise self-localization system for self-driving vehicles. Furthermore, Ryan and Eustice [10] proposed a high-speed multi-resolution scan match for self-driving cars to localize a vehicle within the non-rural domain.

However, the above-mentioned steering control, motion planning, and localization techniques are remarkably reliant on expensive hardware and sensors such as 3D LiDAR and angle sensors, which are extremely expensive computationally. The utilization of such sensors requires a heavy GPU-based computing machine, which ultimately increases the cost of the system by approximately 60%. Moreover, GPS-based solutions rely on online services; Accuracy is also an important concern in these solutions. To overcome these limitations, we propose a cost-effective computer vision-based localization and sensorless steering angle control and motion planning technique. The proposed technique utilizes an angle-sensorless QR-based approach for localization, steering control, and motion planning of a self-driving car. The proposed technique can be used in indoor and outdoor environments. However, we have only tested it in outdoor environments owing to the luminosity conditions. It is obvious that indoor environments are not vulnerable to such luminosity constraints.

The remainder of this paper is organized as follows. Section II presents a literature review of existing studies on this topic. Section III then presents the proposed methodology. The practical experiments and the corresponding results are provided in Section IV. Finally, our approach is presented in section V.

II. RELATED WORK

Localization, steering control, and local motion planning are critical problems in studies on autonomous vehicles. For estimating the state of the vehicle at time t, which in turn assists the vehicle during local motion planning, localization helps the vehicle answer the question "Where Am I?" Moreover, adjusting the steering angle under different road conditions is an important challenge for autonomous vehicles. Researchers have used different methods to address this important challenge in accurately estimating the state of the vehicle.

Vehicle localization is a significant and critical problem in current research on driving support and autonomous driving. Numerous researchers have attempted to address these issues. In this regard, Bailey *et al.* [3] discussed a recursive Bayesian formulation of the simultaneous localization and mapping (SLAM) problem in which the probability distribution and estimation of the absolute or relative locations of signs and vehicle suffixes are obtained. They focused on three main areas: computational complexity, data association, and environmental representation. SLAM is utilized for robot localization, where a mobile robot can build an environment map, and at the same time, can compute its location using the generated map. By contrast, Buyval *et al.* [4] introduced a method for classifying and locating road signs in a 3D environment using a neural network and obtained the point cloud from a laser range finder (LIDAR). In addition, they collected a dataset to achieve this task and train the neural network (which is increasingly based on a region-based convolutional neural network (CNN) architecture). A trained confusion network is used as part of a robot operating system (ROS) node, merging the acquired valuation, camera data, and learning measurements. In another study, Yoneda *et al.* [5] presented an image-based localization technique for an autonomous vehicle. This method uses a mono camera and an inertial measurement unit to approximate the position of the vehicle. The authors implemented localization using a map-matching technique between the reference digital map and the sensor watch. However, this study focuses on the fusion of mono-cameras and lidar-based maps.

Moreover, Lundgren *et al.* [6] presented a localization algorithm based on a map generated using multiple sensors. With this method, a GPS receiver, a gyroscope, wheel speed sensors, a camera providing information regarding lane markings, and radar are used for localization. Acharya *et al.* [7], by contrast, proposed a visual localization approach to eliminate the need for an image-based reconstruction of an indoor environment using a 3D indoor model. The results of the experiments indicate that the proposed approach can be used for indoor localization of a mobile robot with an accuracy of approximately 2 m in real time. Furthermore, Wolcott *et al.* [11] proposed a method for reporting problems occurring with map-based visual localization in urban environments for autonomous vehicles. They used a single monocular camera to build a 3D prior ground map generated by a survey vehicle equipped with 3D LiDAR scanners. In this study, as an information source for visual localization in a 3D LIDAR map, a single monocular camera is used. Zhang *et al.* [1] also proposed a method through which QR codes are used as benchmarks. The location of the robot is stored in QR codes that are intentionally placed in the operating environment. A mobile robot with an industrial camera is used to read the QR codes at high speed. The position of the robot is projected according to the positional relationship between the QR codes and the robot. In a review paper, Lynch *et al.* [12] suggested the use of barcodes or QR-codes for the state estimation and navigation of a ground vehicle. In addition, Lee *et al.* [2] proposed a QR code-based localization technique for mobile robots. For this purpose, they strategically placed QR codes in their operating environment. In their study, they used QR codes to provide reference points to estimate the location of the robot. In [13], the researchers proposed a cost-effective localization technique, utilizing QR codes to estimate the position and heading measurements of the robot.

Moreover, Wolcott *et al.* [14] reported a fast multi-resolution scanner for localization of self-driving cars. The latest approaches to vehicle localization used to achieve centimeter-level accuracy rely on observing road surface reflections through 3D light detection and ranging (LIDAR) scanners., They presented a common method for localizing an autonomous vehicle equipped with a three-dimensional (3D) LIDAR scanner. Thrun *et al.* [15] proposed an algorithm that relies on the combination of an extended Kalman filter (EKF) and an extended information filter (EIF) for robot localization. However, Turgay *et al.* [16] presented a method for global vehicle localization that combines stereo visual odometry, satellite images, and road maps. This approach typically focuses on vehicle localization scenarios for urban and rural environments without the use of a global positioning system. The key points of this approach are the use of road maps using stereo reconstruction, presenting accurate top views, and matching these views with satellite imagery to obtain accurate global localization.

However, such localization solutions are remarkably reliant on expensive hardware sensors, that is, 3D LiDAR, which is extremely expensive computationally. Furthermore, a heavy GPU-based computing machine is required for point cloud computations, which ultimately increases the cost of the system by approximately 60%. Moreover, GPS-based solutions rely on online services. Accuracy is also an important concern with these solutions.

Motion planning allows autonomous vehicles to find the safest and most convenient path from source to destination in a different environment. For local plains, the vehicle motion is achieved using different methods. For example, Frazzoli *et al.* [17] proposed an architecture to address the dynamic constraints on the vehicle motion. The proposed algorithm can be applied to vehicles whose dynamics have been described. However, Kuwata *et al.* [18] presented a real-time motion planning algorithm based on the rapidly exploring random tree (RRT) method appropriate for autonomous vehicles operating in an urban environment. Moreover, Li *et al.* [19] proposed a motion planner for autonomous parking. This method describes various types of parking cases, that is, parallel and perpendicular or echelon. The authors formulated a time-optimal dynamic optimization problem with vehicle kinematics and collision-avoidance conditions, and strictly described the mechanical constraints.

In an autonomous vehicle, steering angle control plays a vital role in keeping the vehicle in the center of the road or within the boundary lanes to meet serious safety requirements. To control the steering angle of an autonomous vehicle, a number of studies have been conducted by different researchers. For example, to improve the accuracy of steering angle control, Valiente *et al.* [20] used many sets of images shared between two autonomous vehicles. They presented an architecture to predict the steering angle automatically by using long short-term memory (LSTM). With this method, convolutional neural networks (CNNs), LSTM, fully connected (FC) layers, and both present and future images are used as inputs to control the steering angle. Du *et al.* [21] presented a complete control strategy for active return-to-center (RTC) control for electric power steering (EPS) systems. They first created a mathematical model of an EPS system and then analyzed the source and influence of the self-aligning torque (SAT). This is based on the feedback signals of the steering column torque and the steering wheel angle. The then designed the RTC controller, which depends on the feedback signals of the steering wheel angle and angular velocity. However, Yasuda *et al.* [22] proposed a control method for sensor-based path planning and steering control of mobile robots. This method is based on environmental information learned using an external sensor. With this technique, a genetic algorithm is used for path planning. Moreover, Park *et al.* [23] described a steering control system for the path tracking of autonomous vehicles. For this method, the steering control system consists of a path tracker and a primitive driver. The authors installed a servo motor to control the steering handle and transmit the steering force using a belt and pulley. Further, Lee *et al.* [24] proposed a scheme consisting of a multirate extended Kalman filter (EKF) and state feedback control. The multi-rate EKF estimates the vehicle states at a fast rate using multi-rate sensing, which is a slow vision-based lane detection approach using a camera and fast motion detection achieved through inertia sensors.

However, because the above-mentioned steering control techniques depend on expensive hardware, they do not provide a suitable solution. Furthermore, the above-mentioned approach is based on different sensors used to control the steering of the vehicle, which ultimately increases the cost, as well as the accuracy of the system, which is also an extremely important concern.

III. PROPOSED METHODOLOGY

To overcome these problems, we propose a computer vision-based technique for localization and steering control that helps in the local motion planning of a vehicle. Our proposed solution applies QR codes and advanced lane detection-based techniques to localize the vehicle and control the steering without employing an angle sensor. QR codes assist in localizing the vehicle and contribute toward steering control in curved road segments while fusing with the detected lanes. This approach helps in estimating the steering angles of a vehicle on both straight and curved roads in a controlled environment. The data acquired from lane detection and QR-based localization are provided to the motion planner to control the steering and locally plan the motion of the vehicle.

A. AGENT ARCHITECTURE

Figure 1 shows the agent architecture of our system, representing the flow of our proposed solution. Using a perception module, our system applies ultrasonic sonar and an HD camera to take visual and sensor-based data. Ultrasonic sonar

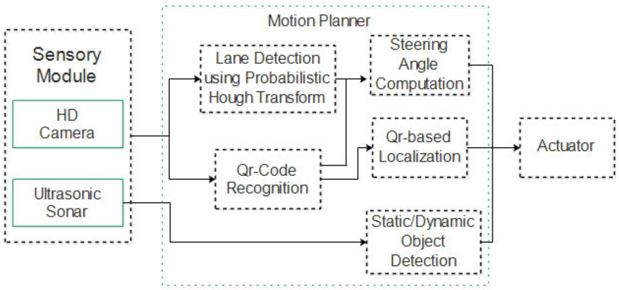
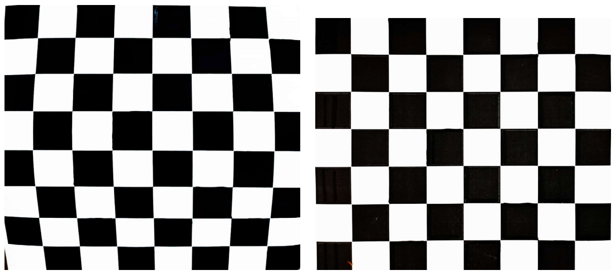


FIGURE 1. **Agent architecture of the proposed methodology.**



(a) Original image (b) Corrected image

FIGURE 2. **Camera calibration on chessboard images.**

passes such data to the object detection module, which helps the vehicles detect dynamic and static objects on the road. Moreover, the HD camera provides visual data to the lane detection and QR code recognition modules. The information acquired from the camera is passed to the angle computation and QR-code recognition modules, which work in combination and pass the angle and current position of the vehicle to the motion planner. The motion planner module passes such data to the actuator module for the vehicle actuation.

B. ADVANCED LANE DETECTION

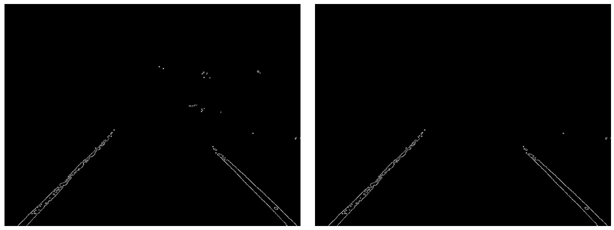
For steering control, it is essential to obtain the boundaries of the road to keep the AV in its lane. For lane detection, we prefer computer vision over deep learning-based solutions because these techniques do not require class-specific knowledge. With computer vision techniques, lanes can be detected more efficiently, following simple lines of code, than deep learning-based techniques, which require extensive training as well as a large number of data specific to the environment. Our proposed lane detection approach comprises the steps outlined in the subsequent subsections.

1) CAMERA CALIBRATION

First, we computed the camera calibration matrix to remove the problem of a radial distortion from the original image. For this purpose, OpenCV was used on the chessboard images to compute the accurate camera calibration matrix and distortion coefficient. To eliminate distortion, we selected the inside corners within the image to undistort it. The original and corrected images are shown in Fig. 2.

(a) Contrast Enhancement (b) Color conversion from RGB to HSV

FIGURE 3. **Preprocessing.**



(a) Edge Detection (b) Region of Interest

FIGURE 4. **Color-based Edge Detection.**

2) IMAGE ACQUISITION

The process starts with image acquisition, and we collected a video dataset by mounting a camera on top of our vehicle and navigating it through the test route. Image frames were extracted from the collected video dataset, which has three RGB color channels with a pixel resolution of 1280×720.

3) PREPROCESSING

The calibration information was applied to the images acquired at runtime for distortion correction. Furthermore, the undistorted images are preprocessed to eliminate lightning distortion or noise, which can affect the lane detection. We conducted a color conversion of the extracted frames from RGB into HSV and then applied a contrast enhancement to rectify the brightness issues and enhance the features of the image.

4) COLOR-BASED EDGE DETECTION

Edge detection is the most important step in the critical vision application used in lane detection. Sharp changes define the edges in an image. By detecting the edges, a region can be defined based on color.

5) LANE DETECTION

We used the Canny edge detector for determining thin and sharp lane edges, lead to an efficient lane detection. Based on the extracted edges, lanes are detected using a probabilistic Hough transform (PHT). The lanes detected by the standard Hough transform are relatively rough, demonstrating its applicability within this vision-sensitive domain. A PHT offers flexibility and the possibility of more accurate detection while providing a computationally efficient detection.

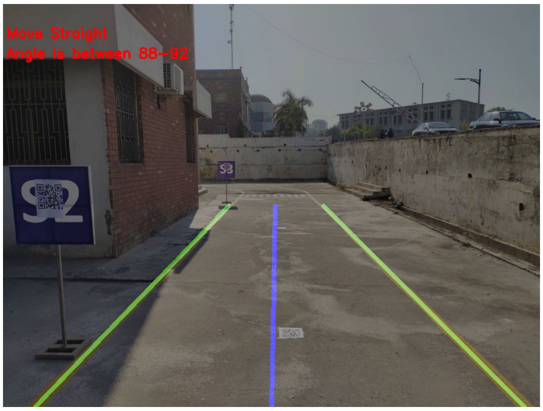


FIGURE 5. Lane Detection using PHT.

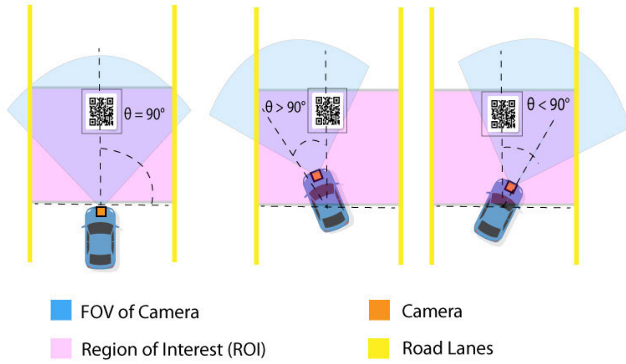


FIGURE 6. A QR-based angle sensor less steering control and localization.

C. QR-BASED SENSORLESS STEERING ANGLE CONTROL AND LOCALIZATION

The core requirement of smooth navigation is accurate steering angle estimation and localization, which restricts a vehicle within the drivable region of the road. For this purpose, the local motion planning and decision-making of an autonomous vehicle in different environments empowers a self-driving vehicle to find the safest and most convenient and beneficial route from the source to destination. Used alone, lane detection and QR codes cannot provide accurate estimates of the steering angle under complex road scenarios, that is, curved roads. For this reason, we proposed a fusion of QR and an advanced lane-detection-based approach for steering control and localization of autonomous vehicles without employing an angle sensor. Figure 6 shows our lane detection approach, which employs QR codes and road lanes that assist the vehicle during decision making and motion planning, that is, when the vehicle decides to take a turn, apply the brakes, or select an optimal route, in which cases our proposed solution supports autonomous vehicles without the use of an angle sensor. Information regarding the current position and steering angles is programmed into the QR, which helps the vehicle achieve local motion planning on the road along with the detected lanes.

$$= \frac{\Delta y}{\Delta x} = tan(\theta) \quad (1)$$

$$r = x.cos\theta + y.sin\theta \quad (2)$$

Equation 1 is used to determine the slope, a positive value of which is for the right line, and a negative value is for the left line. Here, $'\theta'$ represents the angle at which the vehicle deviates from its desired path. In addition, Equation 2 is used to detect line segments in a road environment using PHT. Here, ‘r’ is the length from the origin to the road lanes, and $'theta'$ is the angle at which a vehicle deviates from its origin. For any point (x, y) along this line, ‘r’ and $'theta'$ are constants. In Figure 6, three different scenarios are shown. For the first, a vehicle is driving straight down the center of the road with an angle of 90^o. For the second, the vehicle is driving left of the center of the lane with an angle of greater than 90^o. Under this scenario, our proposed solution provides information that the vehicle is not at the center of the lane and provides an exact angle allowing the motion planner to steer the vehicle toward the right. For the third, if the vehicle is right from the center of the lane, it provides information to the motion planner to move toward the left and stay at the center.

The main purpose of Algorithm 1 is to achieve sensorless steering angle control and localize the vehicle using a QR-based approach. This algorithm provides the state of the vehicle and assists in local motion planning. With this algorithm, the first step is to initialize the camera, which obtains visual data as the input and then initializes the microcontroller to apply the actuation of the vehicle. We used a detector() function to detect the QR code to localize and control the vehicle. The detector function of our algorithm provides the state and distance of a vehicle from its previous position to the next position and provides different angles to control the steering. Moreover, we used the lane() function for lane detection, for which a Canny filter is used to extract the edges to help select the region of interest. Subsequently, lane detection is conducted using the PHT technique. The detected lanes help determine the slope to keep the vehicle at the center of the road.

Furthermore, the results of our experiments indicate that this algorithm accurately determines the state of the vehicle and controls the steering according to the specific requirements. The algorithm is also effective in terms of time and speed, and utilizes less expensive hardware.

IV. EXPERIMENT RESULTS

In this section, we discuss the experiments conducted and the corresponding results generated through the proposed solution. To conduct the experiments using our system, we constructed a dedicated test environment for our self-driving vehicle. The track is built to validate our sensorless steering angle control and localization approach. For this purpose, we further divided the track into different sectors. To control the steering and localize our vehicle, our approach uses a QR-based system that utilizes visual data as an input to

Algorithm 1: Proposed QR-Based Steering Control and Localization Algorithm

```
Initialize camera.
Initialize micro-controller
while True do
    Proc detector()
    Initialize image
    Initialize QR-Code-Data()
    if Qr_code_Data = i then
        State = Sector(i)
        Angle = (using Eq. 1)
    end
    End detector
    Proc lane
    Initialize mask
    Edges = canny filter(mask)
    Return edges
    ROI = region_of_interest(edges)
    Return ROI
    HLS = Hough_line_segment(ROI)
    Return HLS
    SD = slope_data(HLS)
    if SD = 90^o then
        Vehicle_move_straight
    end
    if SD < 90^o then
        Vehicle_turn_right
    end
    if SD > 90^o then
        Vehicle_turn_left
    end
    End lane
end
```

TABLE 1. Computed angles and vehicle movements.

Original angle	Predicted angle	Movement of vehicle	Average error
35	33	Turn left	2%
90	90	Move straight	0%
144	146	Turn right	2%
23	25	Turn left	2%
155	157	Turn right	2%

determine the position of the ego vehicle. The QR codes are strategically placed by utilizing a hit and trial method using multiple distances for the placement of the QR codes. In this way, we found that the proposed approach achieves the best accuracy when the distance between the QR codes is set to 5 m. Moreover, the lane is maintained through the use of an image processing technique and by finding the different angles of the vehicle. The Qr codes and lane detection together help determine the accurate steering angle estimates for the vehicle, thereby keeping the vehicle within the drivable region of the road.

In Table 1, we provide the original and predicted angles, as well as the average error between them. The proposed solution employs these angles for the vehicle movement. According to the information stored in the corresponding QR code and the detected lanes, if the angle is less than 90^o, the vehicle turns left, and if the angle is greater than 90^o, the vehicle turns right. Moreover, when the angle is equal to 90^o, the vehicle moves straight.

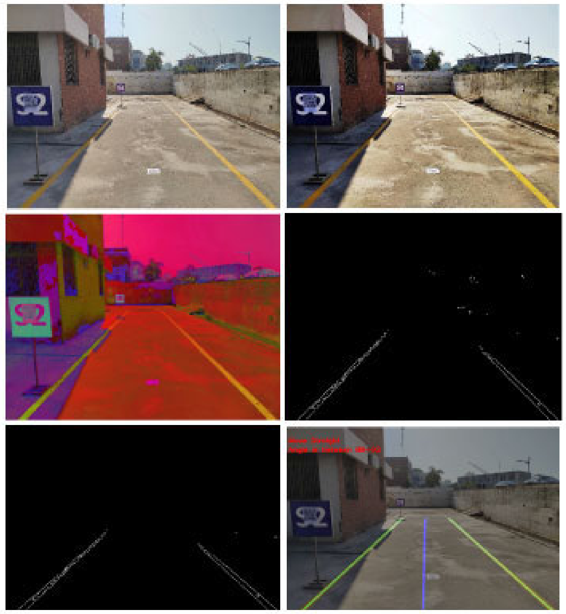


FIGURE 7. Lane detection on straight road.

TABLE 2. Case A: Experiments conducted on straight road.

No	Speed (RPM)	Error	Accuracy
1	20	2%	98%
2	30	2%	98%
3	40	2%	98%
4	60	4%	96%

$$\epsilon = \frac{1}{2}(P_A - O_A)^2 \qquad (3)$$

Equation 3 elucidates the error between the original and predicted angles. Here, ϵ represents this error, whereas PA represents the predicted angle and OA is the original angle.

A. DIFFERENT TEST CASES

In this subsection, we discuss the different test cases based upon which we conducted the experiments. In test case A, we conducted experiments on a straight road, and in test case B, we conducted experiments on roads with different curvatures.

1) TEST CASE A: STRAIGHT ROAD

As the name suggests, this subsection provides details of the experiments conducted on a straight road. Figure 7 represents the steering angle estimation approach using the advanced lane detection technique described in the previous section. In Table 2, we provide the error rate and accuracy of our sensorless steering angle approach at different vehicle speeds

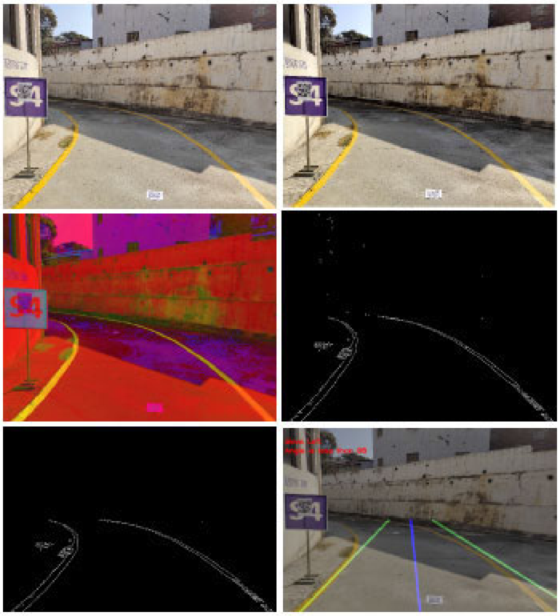


FIGURE 8. Lane detection on curved road scenario.

TABLE 3. Case B: Experiments conducted on curvature.

No	Speed	Curvature	Error	accuracy
1	20	60^o	2%	98%
2	30	60^o	2%	98%
3	40	60^o	5%	95%
4	60	60^o	7%	93%
5	20	80^o	2%	98%
6	30	80^o	2%	98%
7	40	80^o	5%	95%
8	60	80^o	7%	93%

during experiments conducted on a straight road. It can be seen that the error rate is significantly affected by the speed of our vehicle. A low RPM results in a greater accuracy than a higher RPM. However, at 60 RPM, the accuracy of the system, i.e., 4%, is sufficient to operate the vehicle under confined straight road conditions.

2) TEST CASE B: CURVED ROAD

We also tested our approach under curved road scenarios. Figure 8 shows detected lanes, which help provide accurate estimates of the steering angle. Table 3 shows the error rate and accuracy of our sensorless steering angle approach with different vehicle speeds from experiments conducted under different curvatures. From Table 3, although it can be seen that the error rate is slightly affected by the speed of the vehicle, the curvature does not affect the error rate and accuracy.

The QR-based localization process is shown in Figure 9. Figure 9(a) shows that the vehicle is at its initial position, and figure 9(b) shows that the vehicle is in the first sector of the road. We used a QR-based technique for localizing vehicles on a dedicated road. We used multiple QR codes and stored different types of information regarding the position of the

(a) Initial Location of the Vehicle

(b) Location of Vehicle at Sector A

FIGURE 9. Testing of Qr-based Localization module.

TABLE 4. Estimated positions of the vehicle.

Sectors	Position of vehicle	Distance (meters)
QR_Code_1	The first sector of road	5m from the initial position
QR_Code_2	The second sector of road	8m from initial and 3 meters from the previous position
QR_Code_3	The third sector of road	11m from initial and 3 meters from the previous position
QR_Code_4	The fourth sector of road	14m from initial and 3 meters from the previous position

vehicles. For example, when a QR code is read by the camera, our system outputs the current positions of the vehicles on the road and provides the distances from their previous positions. In Table 4, we show the positions of the vehicles on the road. We divided the road into different sectors, which represent different coordinates and areas. Moreover, the table also shows the distance of the vehicle from its previous position. When QR Code 1 is read by the vehicle, our system provides information that our vehicle is in the first sector of the road and its distance from its initial position is 5 m. Besides, the path trajectory exhibiting the position of the vehicle is provided in Fig. 10

V. COMPARISON

We qualitatively demonstrated the importance of our study by comparing it with existing approaches in the literature. In Table 5, we provide a comparison based on parameters

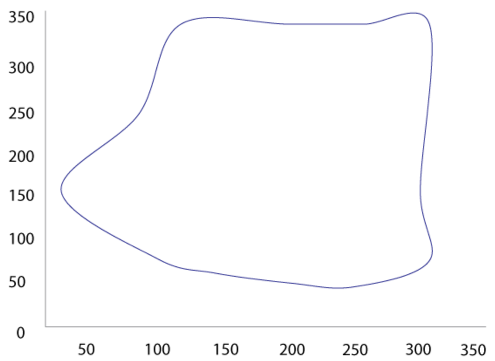


FIGURE 10. Trajectory of the vehicle.

TABLE 5. Qualitative comparison of our proposed approach with the existing studies.

Authors	Technique	Real-time conditions	Accuracy (meters)	Angle sensor less approach
Keisuke et al. [5]	Image-based localization	✓	0.11 m	X
Debaditya et al. [7]	DCNN based	✓	Within 2 meters	X
Ryan et al. [10]	Fast-multi-resolution scanner and LIDAR	X	NA	X
Rodolfo et al. [20]	CNN LSTM, and (FC) layer	X	NA	X
Seung-Hi et al. [24]	Multi-rate extended Kalman filter (EKF)	X	NA	X
Our proposed Method	Angle sensor less QR-based steering control, localization and motion planning of self-driving vehicles	✓	0 m	✓

such as the technique applied, real-time conditions, accuracy, and sensorless steering angle approach. The methods described in the literature use different tools and approaches for steering control and localization of self-driving vehicles. We found that the lack of availability of angle sensors for steering control and the high costs of different types of hardware, e.g., LiDAR applied for localization, make their use in academic research difficult to achieve. With our proposed approach, we used a sensorless steering angle approach that addresses the availability of angle sensors, which has been ignored in existing studies. Moreover, the accuracy of our localization module outperforms that of existing studies in the literature.

VI. CONCLUSION

In this study, we proposed a method based on the fusion of sensorless steering angle control and the localization of self-driving vehicles. This approach takes advantage of advanced lane detection techniques and QR code recognition to optimally determine the steering angle and localize the vehicle at the same time. For this purpose, we deployed QR codes on our test track and conducted advanced lane detection using PHT. We tested our solution in real time, and our experiments proved that our proposed solution is suitable for steering angle prediction of the vehicle. Furthermore, as our main contribution, we utilized a sensorless steering angle approach, which to the best of our knowledge has been ignored in previous studies. The proposed approach achieved a competitive accuracy of 0 m. In the future, we will focus on improving the accuracy of the proposed solution at different speeds and under curved road scenarios.

REFERENCES

[1] H. Zhang, C. Zhang, W. Yang, and C.-Y. Chen, "Localization and navigation using QR code for mobile robot in indoor environment," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2015, pp. 2501–2506.

[2] S.-J. Lee, G. Tewolde, J. Lim, and J. Kwon, "QR-code based localization for indoor mobile robot with validation using a 3D optical tracking instrument," in *Proc. IEEE Int. Conf. Adv. Intell. Mechatronics (AIM)*, Jul. 2015, pp. 965–970.

[3] T. Bailey and H. Durrant-Whyte, "Simultaneous localization and mapping (SLAM): Part II," *IEEE Robot. Autom. Mag.*, vol. 13, no. 3, pp. 108–117, Sep. 2006.

[4] A. Buyval, A. Gabdullin, and M. Lyubimov, "Road sign detection and localization based on camera and lidar data," *Proc. SPIE*, vol. 11041, Mar. 2019, Art. no. 1104125.

[5] K. Yoneda, R. Yanase, M. Aldibaja, N. Suganuma, and K. Sato, "Mono-camera based vehicle localization using lidar intensity map for automated driving," *Artif. Life Robot.*, vol. 24, no. 2, pp. 147–154, Jun. 2019.

[6] M. Lundgren, E. Stenborg, L. Svensson, and L. Hammarstrand, "Vehicle self-localization using off-the-shelf sensors and a detailed map," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2014, pp. 522–528.

[7] D. Acharya, K. Khoshelham, and S. Winter, "BIM-PoseNet: Indoor camera localisation using a 3D indoor model and deep learning from synthetic images," *ISPRS J. Photogramm. Remote Sens.*, vol. 150, pp. 245–258, Apr. 2019.

[8] A. Y. Hata, F. S. Osorio, and D. F. Wolf, "Robust curb detection and vehicle localization in urban environments," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2014, pp. 1257–1262.

[9] B. Nagy and C. Benedek, "Real-time point cloud alignment for vehicle localization in a high resolution 3D map," in *Proc. Eur. Conf. Comput. Vis. (ECCV)*, 2018, pp. 226–239.

[10] R. W. Wolcott and R. M. Eustice, "Fast LIDAR localization using multiresolution Gaussian mixture maps," in *Proc. IEEE Int. Conf. Robot. Autom. (ICRA)*, May 2015, pp. 2814–2821.

[11] R. W. Wolcott and R. M. Eustice, "Visual localization within LIDAR maps for automated urban driving," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Sep. 2014, pp. 176–183.

[12] L. Lynch, T. Newe, J. Clifford, J. Coleman, J. Walsh, and D. Toal, "Automated ground vehicle (AGV) and sensor technologies–A review," in *Proc. 12th Int. Conf. Sens. Technol. (ICST)*, Dec. 2018, pp. 347–352.

[13] P. Nazemzadeh, D. Fontanelli, D. Macii, and L. Palopoli, "Indoor localization of mobile robots through QR code detection and dead reckoning data fusion," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 6, pp. 2588–2599, Dec. 2017.

[14] R. W. Wolcott and R. M. Eustice, "Robust LIDAR localization using multiresolution Gaussian mixture maps for autonomous driving," *Int. J. Robot. Res.*, vol. 36, no. 3, pp. 292–319, Mar. 2017.

[15] S. Thrun, Y. Liu, D. Koller, A. Y. Ng, Z. Ghahramani, and H. Durrant-Whyte, "Simultaneous localization and mapping with sparse extended information filters," *Int. J. Robot. Res.*, vol. 23, nos. 7–8, pp. 693–716, Aug. 2004.

[16] T. Senlet and A. Elgammal, "A framework for global vehicle localization using stereo images and satellite and road maps," in *Proc. IEEE Int. Conf. Comput. Vis. Workshops (ICCV Workshops)*, Nov. 2011, pp. 2034–2041.

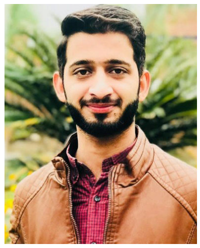
[17] E. Frazzoli, M. A. Dahleh, and E. Feron, "Real-time motion planning for agile autonomous vehicles," *J. Guid., Control, Dyn.*, vol. 25, no. 1, pp. 116–129, Jan. 2002.
[18] Y. Kuwata, S. Karaman, J. Teo, E. Frazzoli, J. P. How, and G. Fiore, "Real-time motion planning with applications to autonomous urban driving," *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 5, pp. 1105–1118, Sep. 2009.
[19] B. Li and Z. Shao, "A unified motion planning method for parking an autonomous vehicle in the presence of irregularly placed obstacles," *Knowl.-Based Syst.*, vol. 86, pp. 11–20, Sep. 2015.
[20] R. Valiente, M. Zaman, S. Ozer, and Y. P. Fallah, "Controlling steering angle for cooperative self-driving vehicles utilizing CNN and LSTM-based deep networks," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2019, pp. 2423–2428.
[21] P.-P. Du, H. Su, and G.-Y. Tang, "Active return-to-center control based on torque and angle sensors for electric power steering systems," *Sensors*, vol. 18, no. 3, p. 855, Mar. 2018.
[22] G. Yasuda and H. Takai, "Sensor-based path planning and intelligent steering control of nonholonomic mobile robots," in *Proc. 27th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov./Dec. 2001, pp. 317–322.
[23] M. Park, S. Lee, and W. Han, "Development of steering control system for autonomous vehicle using geometry-based path tracking algorithm," *ETRI J.*, vol. 37, no. 3, pp. 617–625, Jun. 2015.
[24] S.-H. Lee, Y. O. Lee, Y. Son, and C. C. Chung, "Multirate active steering control for autonomous vehicle lateral maneuvering," in *Proc. IEEE Intell. Vehicles Symp.*, Jun. 2012, pp. 772–777.

SAMIA ABID received the M.S. degree from COMSATS University Islamabad, Pakistan, in 2017, in the field of energy management of smart grids. She is currently working as a Research Associate with the Control, Automotive and Robotics (CAR) Lab, National Center of Robotics and Automation, Department of Computer Sciences, Mirpur University of Science and Technology (MUST), Pakistan. Her research interests include, but are not limited to, smart transportation, intelligent systems, energy management of smart grids, and optimization techniques.

BASHIR HAYAT received the M.S. degree in computer science from the Shaheed Zulfiqar Ali Bhutto Institute of Science and Technology (SZABIST), Islamabad, Pakistan, in 2010, and the Ph.D. degree in informatics from Gyeongsang National University, Jinju, South Korea, in 2020. He has been a Faculty Member of the Institute of Management Sciences, Peshawar, Pakistan, since 2011.

SARMAD SHAFIQUE received the B.S. degree in computer science from the Mirpur University of Science and Technology, Pakistan, in 2015, and the M.S. degree in computer science from Bahria University, Islamabad, Pakistan, in 2018. He is currently working as a Senior Research Fellow at the Control, Automotive and Robotics Lab, NCRA, Department of Computer Science and Information Technology, Mirpur University of Science and Technology, Pakistan. He has published multiple research studies in the fields of medical image analysis and deep learning. His current research interests include bioinformatics, machine learning, computer vision, and deep learning.

ZAIN ALI received the B.S. degree in electrical engineering from the Department of Electrical Engineering, HITEC University, Taxila, Pakistan, in 2019. He is passionate about smart grids, routing in underwater wireless sensor networks, the Internet of Things enabled WSNs, blockchain-based systems, data science-based WSNs, and intelligent edge empowered future generation networks.



BILAL AHMED received the B.S. degree from the Mirpur University of Science and Technology, Pakistan, in 2020, in the field of autonomous vehicles. He is currently working as a Junior Researcher with the Control, Automotive, and Robotics (CAR) Lab, National Centre of Robotics and Automation, Department of Computer Sciences, Mirpur University of Science and Technology (MUST), Pakistan.

FAISAL RIAZ received the Ph.D. degree from Iqra University, Pakistan, in 2018, in the field of cyber physical systems (CPS). He is currently serving as an Associate Professor with the Department of Computer Sciences, Mirpur University of Science and Technology. His research interests include vehicular cyber physical systems, cognitive radio, affective computing, and agent-based modeling. He has more than 34 research publications in various national/international research journals and conferences. He is also the author of the three books. Furthermore, he is the Head of the Control, Automotive and Robotics Lab, National Centre of Robotics, Department of Computer Sciences, Mirpur University of Science and Technology (MUST), Pakistan. Under the banner of CAR-Lab, he developed the world's first cognitive and emotional autonomous vehicle. He received the Hall of Fame Award, in 2018, in the recognition of his smart innovations. He is a reviewer of many well reputed journals and has served as a technical program committee member in many international IEEE conferences. His review profile can be viewed at https://publons.com/author/742771.

TAE-EUNG SUNG received the M.S. degree in electrical and computer engineering from The University of Texas at Austin, USA, and the Ph.D. degree in electrical and computer engineering from Cornell University, USA. He is currently an Associate Professor with the Department of Software, Yonsei University, Republic of Korea. His research interests include deep learning in data-driven information systems, including communications systems and wireless sensor networks.

KI-IL KIM received the M.S. and Ph.D. degrees in computer science from Chungnam National University, Daejeon, South Korea, in 2002 and 2005, respectively. He is currently with the Department of Computer Science and Engineering, Chungnam National University. Prior to joining, he was with the Department of Informatics, Gyeongsang National University, in 2006. His research interests include routing for network security, fog computing, MANET, QoS in wireless networks, multicast, and sensor networks.