Towards Safe Cooperative Autonomous Platoon systems using COTS Equipment

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Abstract

The domain of Intelligent Transportation Systems (ITS) is becoming a key candidate to enable safer and efficient mobility in IoT enabled smart cities. Several recent research in cooperative autonomous systems are conducted over simulation frameworks as real experiments are still too costly. In this paper, we present a platooning robotic test-bed platform with a 1/10 scale robotic vehicles that functions based on the input front commercially off the shelf technologies (COTS) such as Lidars and cameras. We also present an in-depth analysis of the functionalities and architecture of the proposed system. We also compare the performance of the aforementioned sensors in some real-life emulated scenarios. From our results, we were able to concur that the camera based platooning is able to perform well at partially observable scenarios than its counterpart.

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***Abstract*—The domain of Intelligent Transportation Systems (ITS) is becoming a key candidate to enable safer and efficient mobility in IoT enabled smart cities. Several recent research in cooperative autonomous systems are conducted over simulation frameworks as real experiments are still too costly. In this paper, we present a platooning robotic test-bed platform with a 1/10 scale robotic vehicles that functions based on the input front commercially off the shelf technologies (COTS) such as Lidars and cameras. We also present an in-depth analysis of the functionalities and architecture of the proposed system. We also compare the performance of the aforementioned sensors in some real-life emulated scenarios. From our results, we were able to concur that the camera based platooning is able to perform well at partially observable scenarios than its counterpart.**

***Index Terms*—Intelligent transportation systems, Platooning, IoT**

I. INTRODUCTION

The possibility of featuring the connectivity and cooperation between vehicles in an intelligent transportation system (ITS) has led to the emergence of platooning where multiple vehicles follow each other as shown in Figure 1. A vehicular platoon consists of a leader vehicle and a number of following autonomous vehicles, where each vehicle maintains a safety distance (S_{opt}) to its preceding vehicle [1].

With the emergence of technologies such as smart vehicles that can autonomously decide the controls on road, artificial intelligence can possibly help in taking complex take decisions like newer vehicles joining and leaving platoons [2]. Adding to the paradigm of being safer and efficient, these secure platoons [3] also aim at improving being environmentally-friendly by reducing CO2 emissions [4]. In parallel, by improving the traffic flow, this technology is more efficient in the passenger or freight transport.

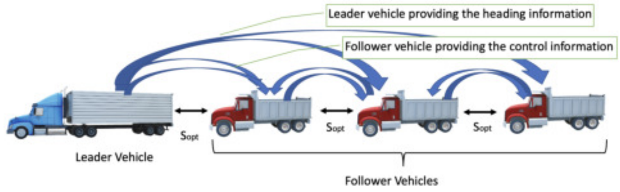

Fig. 1. Example of a platoon travelling with a safety distance between them and communicating wirelessly their respective headings and control information

Wireless communication amongst the vehicles in platoon that enable control decisions has resulted in the domain called cooperative platooning. In cooperative platooning, every following vehicle uses information from its own in-vehicle sensors, and the data received wirelessly from the precedent vehicle for cooperatively adjusting the position, based on several factors such as the speed, acceleration and the heading (direction of the movement of the precedent vehicle).

Cooperative platooning presents several challenges, notably regarding the reliability of communications [5]. There is a dire need for monitoring tools or mechanisms in cooperative platooning for assuring if the right trajectory has been taken in accordance with a certain target. Any error in such a real-life system can be catastrophic in nature. Hence to validate such system, there is a need of a physical cooperative robotic testbed capable of emulating the real-life environment and testing. Robotic testbeds are a low-cost solution that can emulate a real vehicle's functionality and physics [6].

In this paper, we present the implementation of a platooning test-bed that utilizes commercial off-the-shelf technologies (COTS), such as Lidars and zed cameras, to enable safe cooperative platooning and compare their performances in real-life platooning scenarios.

The contributions of this paper are as follows:

- We present a real-time precise decision measuring system between vehicles using image processing (Zed Cameras) and Lidars.
- We present the architecture and the functionalities of a COTS enabled cooperative platooning test bed
- We present the performance comparison of the aforementioned technologies in some real-life platooning scenarios

The rest of the paper is structured as follows. In Section II, we present the state of the art about platooning enabled by image processing and Lidars. In Section IV, we present the underlying system model of our cooperative platooning test bed. Then in Section V, we provide some detailed analyis of the performance of our test bed.

II. STATE OF THE ART

This method of following cars with communication between them and complex controls require a lot of testing. One of the best and safest ways to do it is by using a testbed. There are many test beds for vehicular cloud robots (VC-bots) such as the [7] which allowed to ensure an open platform for researchers and students on VANET (Vehicular Area Networks). This testbed enabled testing domains such as vehicular cloud computing infrastructure, and future smart vehicles applications. Similar to the WiFi used in [7] for communication, in our platooning testbed, we enable communication through GPS in accordance with the highly reliable European Telecommunications Standards Institute (ETSI) ITS-G5. Our testbed offers a wider sensory input analysis because of the use of GPS [8] [9]. It also has more flexibility for testing with several WiFi routers acting as Road side Unit (RSU) and simulating a better real life scenario.

Providing sensing in platooning is done through two major ways, either utilizing computer vision and image processing or utilizing sensors like radars and lidars. One of the major goal of this work is to incorporate our testbed with both of these methods and learn their respective advantages and drawbacks.

A. Platooning with image processing

Researchers in [10] present a camera-based perception system for truck platooning to overcome the lane detection occlusion problem. A camera-based object detector is used in detecting a precise region of interest. They evaluate their proposed solution a highway driving scenario with prototype trucks. Their evaluation results show that their perception system obtains better results in the target platooning scenarios.

One of the complexities in sensing for platooning using image processing is that the real time images such scenarios are prone to noise. Provided that these images involve moving objects, precise detection of the region of interest is much difficult to achieve. Researchers in [11], train a robust model merging both YOLO network and traditional image processing methods. Their results show that their proposed method copes up with more complex real world scenarios. In one of our approaches in this paper, we utilize the YOLO network for detecting the objects in front of the vehicle to aid the control of the platoon.

B. Platooning with sensors

Commercially available sensors are a good alternative to vision based sensing in platooning. Researchers in [12] have developed a platooning system in which the lateral control is based on lane detection and the longitudinal control is based on radar and lidar. Their proposed system was safe and was able to reduce the overall fuel consumption by 14%.

Recent developments in this domain includes the usage of lean sensor packages such as factory-ready standard Adaptive Cruise Control (ACC) system utilizing a dual-beam radar, precision Global Positioning System (GPS), and a Vehicle-to-Vehicle (V2V) communication system for enabling platooning [13]. Researchers in [14] have used fusion of multiple sensors such as radars and lidars to enable (ACC). They propose a Linear Quadratic Integral Regulator with double integrator to improve the stability of the underlying platoon.

C. Novelty of this work

In this paper, we present an experimental test bed of a platoon that utilizes both image processing and commercially off the shelf sensor capabilities. On one hand, with image processing, we utilize a zed camera on the car for line detection and obstacle detection using YOLO. YOLO helps in learning the distance between the vehicles and the line detection provides us with coordinates. Their respective output is used in defining the velocity of the vehicle and the cruise control. On the other hand, LIDARs were used to determine the distance from the leader car and establishing cruise control in accordance with it. We do an in depth performance analysis emulating some real-life platooning scenarios and compare the performances of these sensors.

III. SAFETY DISTANCE AND DRIVING VELOCITY

In accordance with the the intelligent driver car-following model (IDM) [15] for a vehicle V_i with a preceding vehicle in the platoon, with a driving velocity of $\Upsilon_{V_i}(t)$, maximum acceleration a and a comfortable deceleration b with a maximum velocity of Υ_{max} and a safety distance of $S_0(t)$, The acceleration $a_i(t)$ of the vehicle V_i can be given by:

$$a_i(t) = \left[1 - \left(\frac{\Upsilon_{V_i}(t)}{\Upsilon_{max}})\right)^4 - \left(\frac{S_{V_i}(t)}{S_0(t)}\right)^2\right] \quad (1)$$

The desired safety distance $S_0(t)$ between the vehicle V_i with its preceding vehicle with a time headway of T_0 can be defined as:

$$S_0(t) = S_{min} + \Upsilon_{V_i}(t)T_0 + \frac{\Upsilon_{V_i} + \Upsilon^*_{V_i}}{2\sqrt{ab}} \quad (2)$$

S_{min} represents the minimal intra platoon spacing and $\Upsilon^*_{V_i}$ represents the difference in velocities between the vehicle under observation and the precedent vehicle,

$$\Upsilon^*_{V_i} = \Upsilon_{V_i} - \Upsilon_{V_{i-1}} \tag{3}$$

In order to achieve this the difference between the reference speed limit and momentary speed must be minimized such that, the vehicle follows each other at a safe distance. The reference speed can be defined as a predefined speed at a point in the trajectory. For a point i in the trajectory the reference speed is Υ_{i,V_i}, which is the maximum speed limit at that reference point. The momentary value of speed (initial speed at the beginning of observation maintaining the safety distance) can be formulated as Υ_{0,V_i}. A weight ω is added on to the momentary speed and weights $\chi_1, \chi_2, ...\chi_n$ are applied to all the reference speeds. Summation of all the weights is unity, ie. $\omega + \chi_1 + \chi_2 + ... + \chi_n = 1$.

The weights added to the reference speeds include road conditions, channel conditions, resources available and so on. The weights added to the momentary speed determines its tracking requirement. Optimal selection of these weights help in striking a balance between speed and quality of service. Based on the formulation from [16], the speed of the vehicle with respect to the reference speed and the prediction weights can be calculated as follows :

$$\Upsilon_{0,V_i} = \sqrt{\Lambda - 2l_1(1-\omega)(\Upsilon^l_{0,V_i} + g\sin\theta_{in})} \tag{4}$$

where, l_1 length of the road, Υ^l_{0,V_i} represents the actual longitudinal acceleration, g is gravity and θ_{in} is road inclination angle of the upcoming section of the road. Λ is a reference value that depends upon road slopes, the reference speeds and the weights added on to the aforementioned speeds

$$\Lambda = \omega\Upsilon_{0,V_i} + \sum_{i=1}^{n}\chi_i\Upsilon_{i,V_i} + 2(1-\omega)/n\sum_{i=1}^{n}l_i\Xi_i\sum_{j=1}^{n}\chi_j \tag{5}$$

Ξ_i represents the force resistance from road inclination at the section of the road i, as the car moves towards the section j newer weights χ_j are added on to the reference speeds. The velocity of the vehicle can only be considered optimal when the acceleration of the vehicle reaches an equilibrium point at a time instant t. At this equilibrium the difference in the velocities $\Upsilon^*_{V_i}$ will be zero. Also, there will be no acceleration ($a_i(t)$) as the vehicles move at a constant speed. At an optimal velocity of Υ_{opt} is obtained at a specific intra-platoon spacing distance S_{opt} which is :

$$S_{opt} = \frac{S_{min} + \Upsilon_{opt}T_0}{\sqrt{1 - (\frac{\Upsilon_{opt}}{\Upsilon_{max}})^4}} \tag{6}$$

There is a need in tuning the weights for optimizing the speed of the cruise. For an optimal solution the vehicles will have to travel at a predefined speed in order to satisfy the safety distance and not move astray from the rest of the vehicles in the platoon. However, this is not feasible in a real-life scenario. In our testbed, we consider several such scenarios to validate its functionality.

$$\textbf{P1:} \min|\Upsilon_{i,V_i} - \Upsilon_{0,V_i}| \tag{7}$$

The problem P1 must stay true to the constraint that the vehicles maintain a safety distance of 10 m between them in a real life scenario. Optimization here can be achieved when the reference weight respective to the momentary speed (ω) is set to one and the other other weights (χ_i) to zero. In our platooning testbed, we provide a constraint to maintain a safety distance of 1 m between the vehicles.

IV. ROBOTIC SCALE TESTBED DESCRIPTION

Our platooning testbed [17] is a combination of software and hardware architectures to emulate the real world platooning. The vehicle on the ground is powered by a 12V Power Bank connected to the Jetson TX2, a central processing unit of the platooning system. As shown in Figure 2 the Teensy is the interface between the Jetson and the motor and servo. By sending Pulse Width Modulation (PWM) signals, it is possible to control speed and steering of the vehicle.

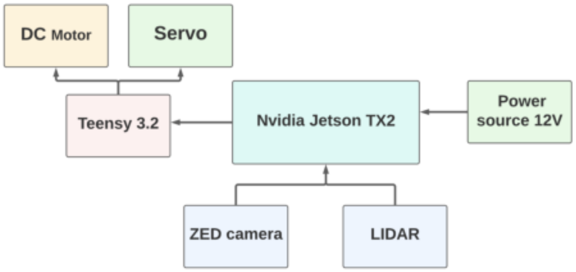

Fig. 2. System architecture showing the sensors (ZED and LIDAR) interfaced with the the CPU Nvidia Jetson that enables control decisions of the platoon

A. Robotic platform

For our platoon system emulation, we used the Traxxas Ford Fiesta St Rally as the vehicular model as shown in Figure 3. It is a 1/10 scale and has a four-Wheel Drive (4WD). The car comes with a 2.4 GHz radio system and also a Titan 12-turn 550 modified DC Motor up to 8.4V, a steering servo, a RC receiver.

B. Sensors

In line with image processing, we use ZED a Camera that is filled with a combination of sensors and Software that makes it very useful for spacial perception. This camera has

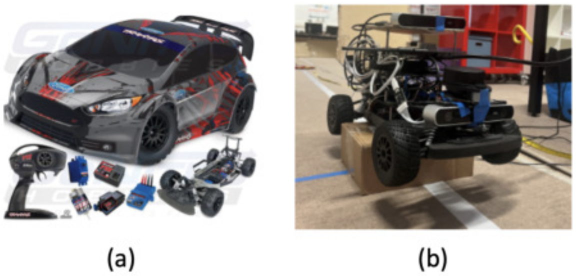

Fig. 3. Traxis Ford Fiesta car model 4(a) and the vehicle model of our test bed with Zed cameras and Lidar installed on it 4(b)

a built-in inertial measurement unit (IMU), a barometer and a magnetometer that can gather real-time inertial, elevation and magnetic field data together with image and depth. Line following and object recognition through YOLO are done simultaneously through the ZED camera that is connected on to the Jetson CPU. The LIDAR we use for this work can measure ranges up to 12 meters, it has a 360 Degree Omnidirectional Laser Range Scanning. The scanning repitions by the LIDAR is around 8000 times per second. Similar to the ZED, the LIDAR is also connected onto the Jeton CPU

C. Controllers

Jetson TX2 is a fast, power efficient embedded Artificial Intelligence (AI) computing device. It's built around a 256-core NVIDIA Pascal GPU, the CPU contains a Dual-Core NVIDIA Denver 2 64-Bit CPU and a Quad-Core ARM® Cortex®-A57 MPCore. Teensy is a complete Universal Serial Bus (USB) based micro-controller development system. You can use the teensy to program in many programming languages and we use it for it‘s Arduino capabilities that interface with ROS. The 32 bit processor allows to have multiple channels of Direct Memory Access, several high-resolution analog-to-digital converters (ADC).

D. Decision and control architecture

The key data needed for the platooning system are the distance to front car and its respective line coordinates. In case of the image processing strategy, we used a line following algorithm as shown in Figure 4 (a) to follow the road and we used a stop sign for the YOLO to detect as shown in Figure 4 (b). This corresponding distance to the stop sign is published as distance ROS topic. In the case of the LIDAR, the laser data providing the distance from the preceding vehicle was published as the distance ROS topic.

The data is then processed by decision algorithm and an output is published into a ROS topic. The decision script subscribes to ROS topics like the coordinates and the distance. The coordination ROS topic is used to control the steering of the car. Our decision algorithm helps the vehicle to stay within the optimal safety distance S_{opt} and provides a respective output speed which is published. The Teensy that is responsible for making the interface between the Jetson and the motor and servo provides the control algorithm that subscribes to subscribes to the output that is published and converts the speed and steering values in to numbers that will be interpreted as PWM signals, and are sent to the motor and servo of the vehicle

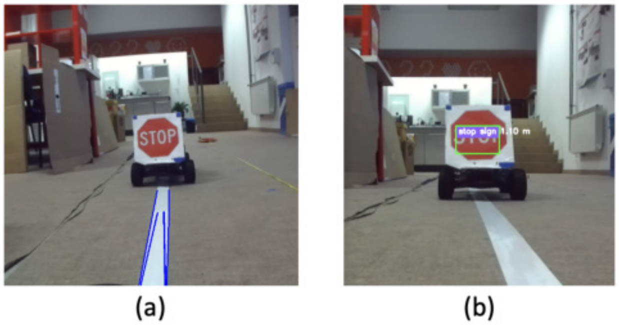

Fig. 4. Our platooning testbed following the blue line as line following robot (3a) at the same time also detecting the distance from the preceding vehicle by processing the image of the stop sign (3b)

V. PERFORMANCE ANALYSIS

In this section we provide the performance analysis and comparison of the COTS sensors in some real life platooning scenarios. In order to validate our system we study the influence of using these sensors and the impact they have on the underlying platooning scenario.

Scenario 1: Inter-Vehicles Distance Behaviour

It was noted that the vehicle enabled by the ZED camera enabled a gradual actuation by 30% when compared to the LIDAR. This is because the tests were conducted in a well lit room and the camera was able to detect the distance from the preceding vehicle easily, The LIDAR enabled vehicle also maintained the optimal safe distance but provided an immediate actuation and provided the deceleration much faster that one with the ZED camera.

Scenario 2: Cruising stability of the platoon

In any closed-loop adaptive cruise control system like the platooning there are several time delays and lags in the sensors like the LIDARs and the ZED cam and the actuators such as the servo. Impact on this delay has a severe impact on the stability of the platoon [18]. Unlike the previous experiment,

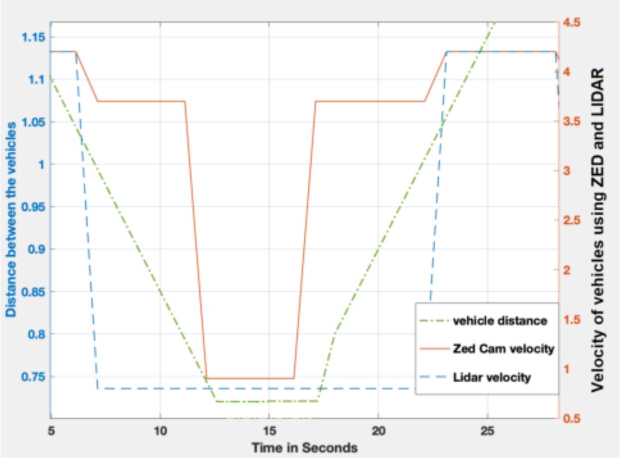

Fig. 5. Impact on the front vehicles acceleration and deceleration on the velocity of the follower vehicle enabled by the ZED camera and the LIDAR

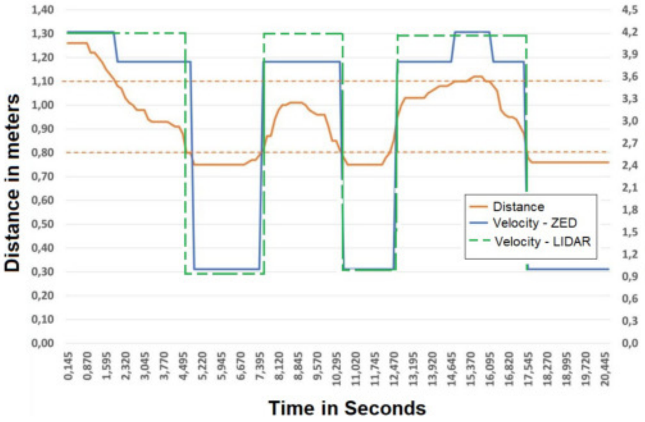

Fig. 6. Cruising stability of the platoon in accordance with the change in distance (orange line)

in this study we had the leader vehicle cruise steadily (not falling under the velocity of 2 m/s).

As seen in Figure 6, the ZED camera was able to capture the distance between the vehicles clearly, it provided frequent changes in the velocity, resulting in a stable cruise. The LIDAR on the other hand, provided changes in the velocity when the distance dipped under the safety threshold. But it was not a more stable cruise with more velocity variations like the ZED camera. When the distance fell between 1,40 - 1,30 meters, the vehicles enabled by the ZED cameras were able to decelerate accordingly. For maintaining a stable cruise, there is a need of low latency deterministic network protocols like [19] to provide the control information to the vehicles in the platoons to take fast decisions towards a stable platoon.

Scenario 3: platoon taking a turn

One of the biggest challenges in autonomous platooning is when the leader vehicle has to take a quick turn. In both the cases of the LIDAR and the ZED camera, the following vehicle momentarily loses the ability to accurately sense the front vehicle. For our experiment the initial distance between the vehicles was set to 1,15m and the follower started at maximum following speed maintaining a safety distance. However, as it approached the turn, the distance oscillates some values because the stop sign is no longer centrally aligned with the car. This causes the reduction in the speed of the vehicle and the turn was performed in a steady pace. Again when the stop sign was much visible, the vehicle picked up its speed again.

In line with the ZED cameras, the stop sign was sensed minimally as it takes the turn at 3,5 seconds, along with the line following algorithm, the vehicle wen to a minimal velocity (a drop from 3,8 m/s to 0,8 m/s) in the two turns that were recorded and then sped up along with the leader vehicle when the stop sign came to full visibility.

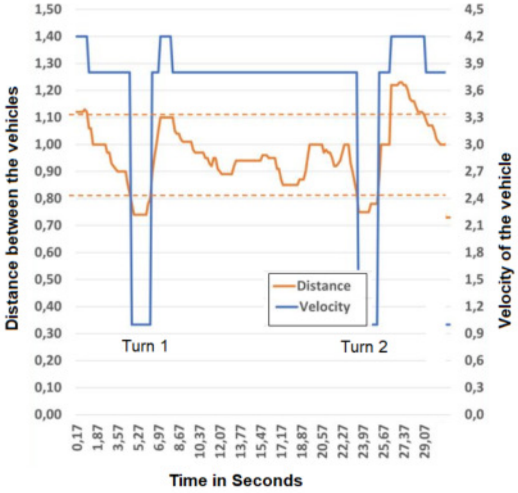

Fig. 7. Impact of the ZED camera sensing in the change of velocity in the event of taking a turn

In the case of the LIDAR, as it only operates on the scanning range in front of it, as the vehicle started to take the turn (around 5 seconds) the received scanning points from the LIDAR severely fluctuated resulting in minor faulty reads. Based on our control algorithm, the vehicle slowed down and picked its pace when it started steadily receiving the scanning points from its leader vehicle.

VI. CONCLUSION

This work presented the functioning of Robotic Testbed Platform that utilizes COTS such as Lidars and ZED cameras.

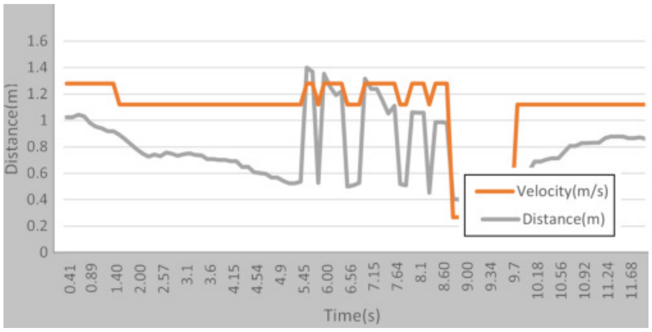

Fig. 8. Irregular detection from LIDAR resulting in a unsteady cruise in a curved path scenario

In this work, these two sensing technologies were used to emulate real world platooning and verify some of the common platooning scenarios. We were able to concur that under steady lighting conditions, the cameras help in providing a stable control to the platooning system. We identified the need of a low latency communication protocol between the the vehicles in order to alleviate communication latency and to provide trade-offs in the respective actuator delays and provide stable cruising. The platooning in this work is a successful implementation completely based on the local information. This can be still improved by the inclusion of artificial intelligence (AI) that can learn the pathway and aid in the control decisions. AI methods like the long short term memory (LSTM) that includes the partially observable states of the platoon like the turning of the vehicle can aid in taking more stable cruise decisions. AI coupled with the usage of these COTS sensors have the capability to be a candidate in the domain of smart efficient adaptive cruise control.

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