Enhancing the educational process related to autonomous driving

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Abstract— **Autonomous driving is one of the major areas of interest for the automotive industry. This constantly evolving field requires the involvement of a wide range of engineers with complementary skills. The education of these engineers is a key issue for the further development of the field. Currently in the engineering curriculums, there is a lack of related platforms that can assist the engineers to train in and further develop the required dexterities. The current practice is using either small robotic devices or full scale prototypes in order to understand and experimentate in autonomous driving principals. Each approach has disadvantages ranging from the lack of realistic conditions to the cost of the devices that are used. In this paper we present a low cost modular platform which can be used for experimentation and research in the area of autonomous cars and driving. The functionality of the suggested system is verified by extensive experimentation in - very close to- real traffic conditions.**

I. INTRODUCTION

In recent years, autonomous driving has emerged as a major innovation in the automotive industry. Currently the technology has matured and commercialisation is expected in the following years. Autonomous driving, refers to the ability of a vehicle to perceive its surroundings with various attached sensors, evaluate the conditions and navigate to an exact location safely without the interference of a human driver, taking into consideration the ever-changing and unpredictable environment. Due to the broadness of the term autonomy, SAE International has explicitly defined the levels of automation to characterize the extent to which a vehicle can drive autonomously [1], [2]. Explaining autonomy further, like every robotic system, autonomous vehicles utilize the "sense-plan-act" design. They use a combination of sensors to perceive the environment including but not limited to lidar (light detection and ranging), radar, cameras, ultrasonic and infrared. The information gathered is fused and used for decision making. As far as it concerns localization a combination of the Global Positioning System (GPS) and Inertia Measurment Units (IMU) is currently used [3].

Autonomous driving has significant internal (user) and external (external actors) impact. It provides a stressful environment for the driver and increases its productivity during the time spend inside the car, as well as it provides the option to non-drivers (or incapable to drive people) to commute. On the external side, increased safety (reducing crash risks and high-risk driving), increased road capacity and reduced costs, increased fuel efficiency and reduced pollution are equally important [4].

Even though the related technology has made significant advances on the domain, the cost of developing and experimenting with autonomous cars still remains high. Apart from the standard platform cost, there is a significant cost related with the actual sensors and processing unit which are essential for autonomous capabilities.

The aforementioned cost makes it difficult for a platform to be adopted in the educational and research activities of higher education institutes. There is always the option of small autonomous robotic vehicles [5], [6], [7], [8], [9] which are adequate for understanding the basic concepts of autonomous driving, or even inexpensive RC-car based autonomous car testbeds but few attempts have been made to provide low cost realistic platforms for research and education. A detailed comparison between our approach and the other available vehicles is presented in Table I.

TABLE I
COMPARISON OF VARIOUS EDUCATIONAL PLATFORMS

Comparison of Educational Platforms						
Platform	Camera	LiDAR	Ultrasonic	GPS	IMU	Scale
Duckietown	✓	✗	✗	✗	✗	Radio Conrtrolled
Donkey Car	✓	✗	✗	✗	✗	Radio Controlled
BARC	✓	✗	✗	✗	✓	Radio Controlled
MIT Racecar	✓	✓	✗	✗	✓	Radio Controlled
F1/10	✓	✓	✗	✗	✓	Radio Controlled
Tucer	✓	✓	✓	✓	✓	Urban Mobility Vehicle

This paper proposes an approach that will allow the educational process on the domain of autonomous driving to become viable and inexpensive, providing students the ability to apply the principles related to autonomous driving in a realistic low cost platform using tools that will minimise the development time and maximise the efficiency, gaining important hands-on experience. The platform is based on a single seater, urban concept vehicle, that has previously competed in Shell Eco Marathon Europe competition [10], with TUCer Team [11] from Technical University of Crete (TUC). The aforementioned platform has been in constant development and has been used as the testbed for research in automotive engineering [12], [13], [14], [15]. It has been modified from a hydrogen fuel cell powered car to a battery powered autonomous vehicle. In order to achieve this goal a series of hardware and software solutions were adopted

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and several devices were installed. Stepper motors have been fitted for steering and braking control as well as various sensors for perception (Stereo Camera, Lidar, Ultrasonic) and localization (GPS, IMU) along with an embedded computer. All of the above sensors are off-the-shelf components, easy to acquire and use and suitable for entry-level approach on the autonomous vehicle domain. Our architecture is simple, yet efficient, and the combination of Nvidia's Jetson TX2 (main processing unit) along with a set of microcontrollers can support from plain digital and analog inputs to even CAN (automotive standard) connectivity. More details will be provided in Section II. The functionality of the proposed approach is highlighted through simple yet realistic experiments that highlight the efficiency of our approach.

The rest of the paper is organised as follows, in section II the testbed is described in detail including the powertrain, the steering and braking system, the processing unit, the sensors used as long as the software sollutions adopted. In section III experimental test cases are presented that proves the functionality of the proposed approach. Finally in section IV concluding remarks and future directions for research and development are presented.

II. TESTBED

The testing platform is based on a single-seater custom vehicle, designed, developed and manufactured at the Technical University of Crete. The chassis of the car consists of aluminum tubing and the cover is made from carbon fiber. Its dimensions measure 2.5 x 1.25 x 1m (L x W x H) and its curb weight 108 kg. In Fig. 1 the prototype vehicle, and the position of all the major components is depicted, while in Fig. 2 we present all the major electronic components and the motor of the vehicle. In this section we will describe in detail the proposed testbed and its core components.

Fig. 1. The prototype autonomous vehicle

A. Powertrain

The vehicle is equipped with PGM132, a permanent magnet direct current brushed motor from Heinzmann. At 24V it outputs 1.8kW at 1100 rpm with rated torque of 15Nm (peak 38Nm) and 90A current. This motor is capable of inputs up to 60V, raising power to 5.1kW adding to our platform various performance profiles. The motor is controlled by an Alltrax AXE 4834 permanent magnet motor controller delivering 135Amps rated and 300Amps peak, more than enough for the motor paired with.

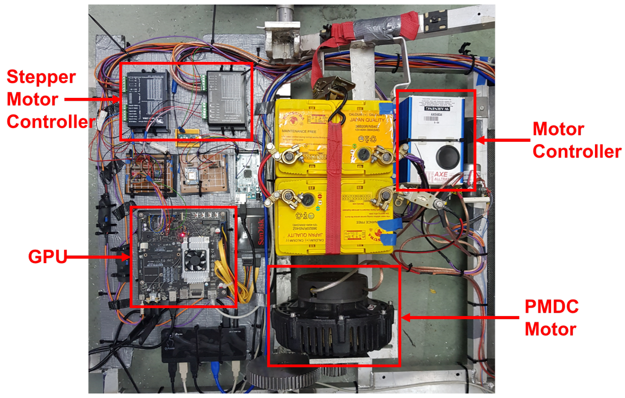

Fig. 2. The electronics and the motor of the testing platform

The propulsion system is supplied by two 12V-40Ah rechargeable lead-acid batteries, providing adequate power for propulsion to urban mobility speeds (~50km/h) with sufficient range (for testing purposes) before recharging. Additionally, a separate battery pack, consisting by 2 12V-7.2Ah rechargeable lead acid batteries supplies the various sensors and the on-board computer as described in II-C and II-D respectively. The reason for the separate supplies, even though the voltage is the same, lies to the fact that the common supply of motors and electronic devices, adds substantial electromagnetic noise to the circuit disrupting the integrity of sensor readings. Furthermore, motor's inrush current or sudden load changes (acceleration or hill climbing) could potentially cause voltage drops disrupting the constant power application needed by the electronic devices on board the vehicle. The power from the motor is transmitted to the wheels via a fixed gear ratio with one gear directly attached to the motor's rotating axle and the other to the wheel axle.

B. Steering and Braking System

Steering and braking control has been utilized with stepper motors, incorporated in the already existing steering mechanism and brake pedal, providing the ability to the driver to take control in a moments notice quiting the autonomous navigation if necessary or do not engage it at all and drive the vehicle manually. Both braking and steering stepper motors are powered by the propulsion batteries at 24V and controlled from Jetson TX2 GPIO ports.

The steering mechanism on this car is an implementation of the Ackerman steering geometry. A stepper motor is placed on the steering rack, using a pair of gears with fixed gear ratio rotating it directly to the desired direction. The hybrid stepper motor from Motech Motors with 1.26Nm of torque and step of 1.8^o is controlled by a Wantai Microstepping Driver. The driver is set up to further enhance the precision of the motor resulting in steps of just 0.225^o. In the end of the steering rack, a rotary magnetic modular encoder is attached providing information about steering's exact position.

The vehicle is equipped with Shimano hydraulic bike pistons and disk brakes on the wheels. The braking control utilizes a similar design. A stepper motor with 4Nm of torque and 1.8^o steps actuate the brake pedal. A microstepping driver is set to the same level of precision for ease of programming and coherence between braking and steering steps. Braking stepper motor packs higher torque due to the needs of the lever pulling design for brake actuating.

C. Processing Unit

The central processing unit installed on the vehicle is an NVIDIA Jetson TX2 Developer Kit. It is an embedded ARM architecture equipped with a Quad ARM A57 processor plus a Dual Denver processor, 8GB of LPDDR4 memory and 256 CUDA cores of NVIDIA's Pascal Architecture, able to deal with the most computational intensive processes. It supports CAN, UART, SPI, I2C, I2S protocols as well as plain GPIO. For higher level communication WLAN, Gigabit Ethernet and Bluetooth is supported together with USB 3.0 and USB 2.0 ports. Internal memory is 32GB eMMC, but SATA connectivity and SD Card port are available too. In our setup the a 240 GB Sandisk Extreme II Solid State Disk is used for speed and extended storage capabilities. Additionally, a TP-Link 7-port powered USB 3.0 hub is attached to the USB 3.0 port, for easier multiple peripherals connectivity and uninterrupted power supply, since built-in ports are able to deliver 900mA of current, not enough for the attached USB devices. The Jetson TX2 was selected for two main reasons: (i) the extended capabilities that provides for a reasonably low cost and (ii) the ability to rapidly prototype solutions and test them in a the real testbed using standard tools which are widely used in the education process (i.e. Maltab, libraries provided by NVIDIA or other open resources etc.).

D. Sensors

A wide range of sensors for perception and localization have been used. The overall set-up is presented in Fig. 1. As far as it concerns the perception sensors, a ZED stereo camera from Stereolabs is mounted at the center of the vehicle. It consists of two 4 Megapixels cameras, with wide-angle dual lenses, field of view at 90^ox60^ox110^o (HxVxD) and f/2.0 aperture. Sensors are 1/3" with backside illumination capable of high low-light sensitivity and have a native 16:9 format for a greater horizontal field of view. USB 3.0 connectivity allows for high resolutions (up to 2.2K@15 FPS). Equally important are the depth recognition capabilities of the ZED camera, achieving the same resolution as the video with range from $0.5m$ to $20m$ and the motion sensing with 6-axis Pose Accuracy (Position:+/- $1mm$ and orientation: 0.1^o) using real-time depth-based visual odometry and SLAM (Simultaneous Localization and Mapping). Our choice was further backed by the fact that Sterolabs provide an SDK for the Jetson TX2, our main processing unit.

The second sensor responsible for perceiving the environment is a Scanse Sweep lidar. It consists of a LIDAR-lite v3 sensor from Garmin, in a rotating head, thus providing 360^o scans of the surroundings. It has a range of $40m$ and a sample rate of 1000 samples per second. It scans on a single plain (2 dimension lidar scanning) and is suitable for Robotics and UAVs. The counterclockwise rotating head emits a beam with $12.7mm$ diameter which expands by approximately 0.5^o. Scanse Sweep pairs it with and SDK for easy implementation to projects, as well as a visualizer app for graphical representation of the measurements.

Apart from the aforementioned sensors there are also forward mounted, two Maxbotix MB1010 Lv-MaxSonar-EZ1 ultrasonic sensors. With a range from $15cm$ to $645cm$ and a refresh rate of $20Hz$, they are capable of accurately detect and measure the distance from objects in front of the vehicle. They have multiple connectivity protocols such as analog, pulse width and serial output for easier sensor integration to different platforms. Due to cross-talk issues between the two sensors, a chaining between them is required, triggering sensors one after another eliminating the interference on the measurements of each individual sensor.

Both the Stereo Camera and the Lidar are connected to the USB hub and then directly to Jetson TX2. For the ultrasonic sensors, the analog output is selected to be used. Since Jetson TX2 has no analog inputs, a microcontroller is used as middleware between the sensors and the processing unit improving input-output capabilities of the system.

For localization purposes an Adafruit Ultimate GPS Version 3 is used. Capable of using up to 66 channels and having -165dBm sensitivity, the achieved accuracy is adequate to position our vehicle in the real world with pinpoint accuracy. For more robustness and better satellite reception, an external GPS antenna is used (instead of the built-in) with the u.FL connector provided in this board. The serial output of the GPS sensor, similarly to the ultrasonic sensors, uses a microcontroller as a middleware between the device and the processing unit. Complementing the GPS an IMU module is also used. The Sparkfun Razor IMU is a 9 Degrees-of-Freedom sensor, able to measure the absolute orientation, angular and linear acceleration, gravity vector and magnetic field strength. The Razor IMU, connects directly to the Jetson TX2 via USB with the help of an FDTI breakout board. Apart from the aforementioned configuration several other smaller electronic systems are used to support the functionalities of the custom vehicle.

E. Software

A key issue for the adaption of the proposed system in the education and research process, apart from the actual capabilities of the vehicle, is the ease of use and the time needed to develop and test new approaches for autonomous driving. Based on that, we have developed a modular approach which minimizes the development time and allows the user to speed up the development process.

A series of software modules responsible for the control of the devices onboard the vehicle have been developed using

C++ . These modules are implemented onboard the NVIDIA Jetson TX2 and there are also responsible for data logging for post processing analysis.

The devices on board the vehicle have to communicate with the main computer. Some of them, such as the LiDAR have their own SDK that handles connectivity via a serial library and have predefined functions for use. Regarding GPS, IMU and Ultrasonic Sensors, similar architecture modules have been developed using a C++ serial library (LibSerial) for sending command and receiving data. For easy of wiring the serial communication has been established via the USB interface. Respectively software libraries for handling the GPIOs of the Jetson have been used responsible for selecting direction (in/out) and logic level(0/1) of the pins for controlling the stepper drivers.

The external code development is performed using Matlab and by adopting the GPU Coder we have the ability to generate optimized CUDA code from MATLAB code for deep learning, embedded vision, and autonomous navigation. The generated code is portable across NVIDIA GPUs and can be compiled and executed on an NVIDIA Jetson platform. This approach is user friendly, and most of the students attending a related engineering curriculum are familiar with using it, therefore make the platform easily adaptable for educational purposes. The data acquired from experimentation can be easily extracted and used for post processing analysis and further development. The proposed approach is depicted in Fig. 3.

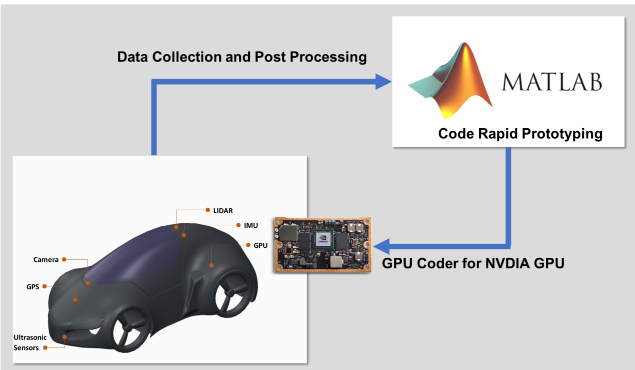

Fig. 3. Software development circle

III. Results - Proof of Concept

To validate our approach several tests have been conducted. In this section we will present two test cases that highlight the functionality of the proposed system. Initially we will demonstrate the ability of the vehicle to move in a predefined path based on the readings from the GPS sensor. This test case emulates, the operation of a real autonomous vehicle in a urban environment which has to operate and navigate in an unknown area using the GPS coordinates. The second test case will demonstrate the ability of the proposed platform to perceive the environment, using the available sensors, identify an obstacle (in our case a pedestrian) and safely avoid it.

To assure that our vehicle is capable of following the desired waypoints we have used a simplification of an ackerman steered vehicle commonly known as the bicycle model. For path tracking we have used the pure pursuit method as it is described in detail in [16]. This approach although simplified provides reliable results that have been verified with extensive experimentation.

It has to be emphasised, that the following experiments have a dual goal. To prove the functionality of the proposed approach and also highlight its robustness which is essential for using it as an educational tool. Therefore our goal wasn't to demonstrate novel approaches in autonomous driving, but adopt well established techniques to prove its functionality.

A. Test Case 1

In the first test case we present the ability of the vehicle to follow a predefined path autonomously without human intervention. Initially we prerecorded a path taking GPS readings and we used this measurements so that we can validate the autonomous operation based on pure pursuit method. Sample trajectories that the vehicle has followed inside the Technical University of Crete's Campus are depicted in Fig. 4 and Fig. 5.

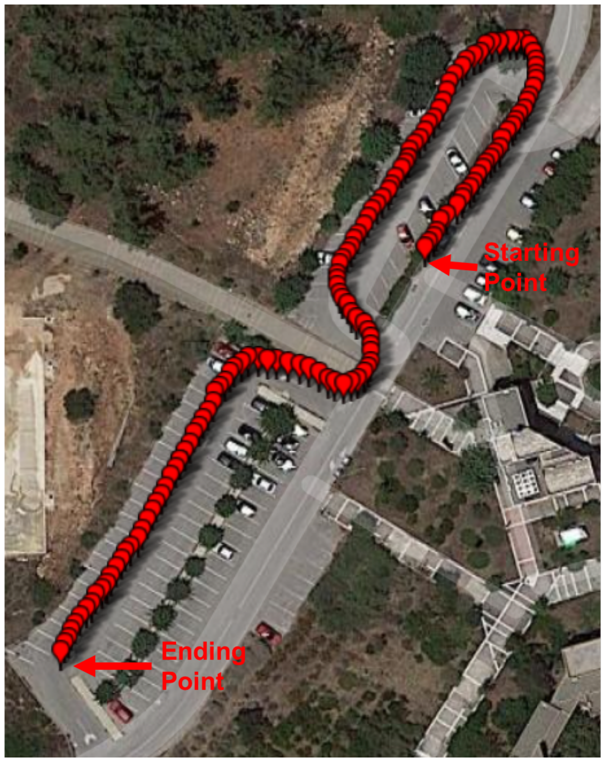

Fig. 4. Vehicle's trajectory inside the TUC campus (Test 1)

B. Test Case 2

In the second test case we present the ability of the vehicle to perceive the environment and avoid a moving obstacle,

Fig. 5. Vehicle's trajectory inside the TUC campus (Test 2)

Fig. 6. Pedestrian detection using stereo camera

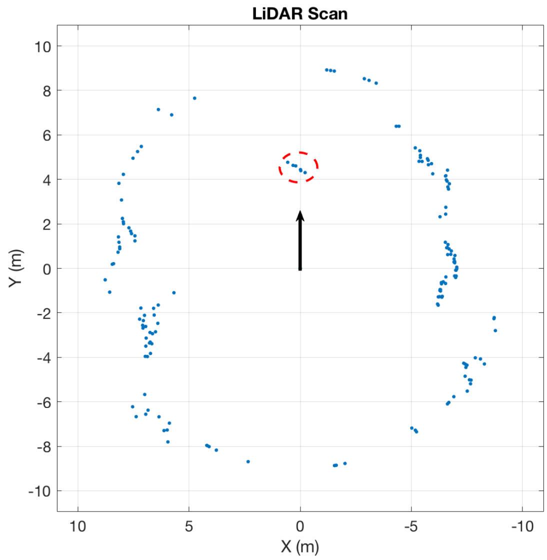

Fig. 7. Data acquired from the lidar sensor

in our case a pedestrian. For this process the vehicle is using the stereo camera and the lidar sensor. For pedestrian detection we have used the pedestrian detection network provided by Matlab. With the help of the GPUCoder, the above network is converted to CUDA code for direct and fast use in the embedded vehicle computer. The results of the identification process are presented in Fig. 6. These are combined heuristically with lidar measurements and as soon as the vehicle detects an obstacle (pedestrian) in a distance smaller that a certain threshold the vehicle stops its operation until the path is clear. A shapshot of the lidar readings is depicted in Fig. 7, where the arrow represents the actual heading of the vehicle, while the readings inside the red eclipse correspond to the pedestrian detected in Fig. 6. This approach also simplistic demonstrates the ability of the testing platform to handle unexpected events as they occur during the autonomous operation of the vehicle.

IV. Discussion and Conclusions

The proposed testbed aims to promote the educational procedure on the domain of autonomous vehicles. Having that in mind, we are planning to provide public access to the software in its final form. In addition, electronic schematics, mechanical blueprints and detailed bill of materials, to replicate the platform, will also be available. Our long term vision is to provide a robust open platform for education and research purposes to the community. We are also planning to fully integrate Robotics Operating System (ROS) in our platform, since currently it can be supported with slight modifications (Jetson TX2 is ROS enabled), and all the sensors selected are ROS compatible. The approach, which we currently followed, was not to install a middle-ware for simplicity and ease of prototyping.

An update version of the proposed system is under development, were we are also considering the need for additional computational power so that we can implement more complicated strategies. The Jetson TX2 has proven robust enough for our purposes. But, in order to keep up with the increasing demands of an autonomous vehicle navigating in a dense environment performing complex functions, other options can also be integrated. For that we have already considered the Drive PX2 which apart from the additional power can also accommodate the already developed CUDA code with minor tweaks and modifications. As far as it concerns perception we are planning on upgrading from the 2D lidar to a 3D capable of scanning at greater distances and providing a 3D representation of the real world.

Ultimately, we are planning to adopt the aforementioned platform in the educational process (as an experimental testbed in undergraduate and graduate courses) and asses its functionality and usability based on the students' feedback.

ACKNOWLEDGMENTS

This work was partially supported by the the SUNNY Project funded by the European Commission under the FP7 programme Grant Agreement number: 313243.

The authors would like to thank the members of the TUCer team of the Technical University of Crete for their continuous support during the development and experimentation with the autonomous platform.

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