Development of a ROS controlled chassis dynamometer for lightweight, single seater EVs

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***Abstract*— TUCer team developed a prototype, portable chassis dynamometer capable of carrying out experimentation with alternate scenarios of acceleration, constant speed and deceleration, in a fully automated way. A controller scheme based on Robot Operating System was programmed, using open source tools. The testing scenarios are implemented using a motor/generator and an electronically controlled load, embedded on the dynamometer. Extensive testing during TUCer systems' development and real race conditions proved the dynamometer's reliability and functionality.**

***Index Terms*— Chassis dynamometer, Robot Operating System, ROS, electric vehicle, hybrid power system, energy harvesting, regenerative braking, finite state machine.**

I. INTRODUCTION

Electric Vehicles (EVs) are undoubtedly the future of automobiles. Worldwide environmental issues, technology advances, policy incentives and growing popularization contribute to the acceleration of the transition from internal combustion engine cars to EVs. Last decade the global car market is experiencing a significant activity, not only in presenting new commercially available, electric passenger cars [1], [2], but also trucks and buses [3]. Following the above global trends, EV's technology is a popular contemporary research and development target at the academic community of engineers. Moreover, a growing number of low consumption and/or zero-emission competitions, challenges, marathons and formula-student events for EVs are taking place around the world [4]–[6]. Technical University of Crete Eco Racing (TUCer) team [7] participates at such kind of competitions since 2007. This work refers to the development of a prototype chassis dynamometer for the hydrogen powered EVs of the TUCer team, Fig. 1.

Automotive manufacturers, universities, research centers and racing teams participating at the above mentioned competitions need specialized testing equipment to develop their prototypes. At the category of academic, low consumption competitions for EVs, several teams worldwide share the need to develop and test prototype single seater, ultra lightweight, low power, efficient EVs with the ability to perform energy regeneration. It is extremely useful to experiment and test the prototype during the several phases of the competition, away from the team's university or research base and so the portability of the testing equipment is a very important and desired specification. The academic teams taking part in such competitions usually have limited budget, compared to the automotive industry. Consequently, the development, experimentation and maintenance cost of their prototypes is a critical parameter, as its value should be kept as low as possible. Indoors testing is, also, a crucial factor when the experimentation cost is considered.

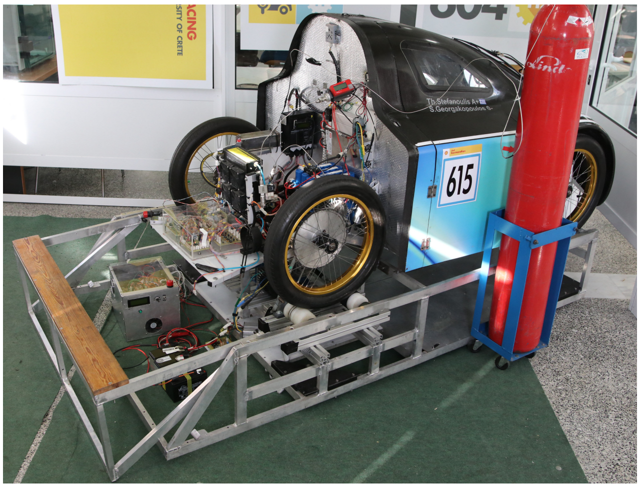

Fig. 1. TUCer team's prototype urban concept vehicle Spyros Louis onto the prototype ChD.

The industrial standard for testing vehicles indoors is the Chassis Dynamometer (ChD) as it monitors, among other parameters, the performance by emulating vehicle's load under different road conditions and experimentation scenarios. The testing procedure on a ChD may be repeated, under the same conditions, to provide much more precise results than a road test. The experimentation remains unaffected from the weather conditions and does not require the transportation to a motor racing circuit or other safe, testing facility. It is, also, less time consuming, comparing to real road tests. Safety is another great advantage as ChDs are operating under fully controllable conditions.

A. Related works

ChDs are available as commercial products in the global market [8]–[19]. While [10], [14], [16]–[18] are able to oper-

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ate in regenerative mode, no one is designed for lightweight, low power EVs. The only one that is portable [12], has no regenerative mode operation.

Published works related to the subject of the ChD include reviews, case studies of prototypes' development, simulation tests, reports and designs. A review of the different types of the ChD systems is available at [20] while [21] describes a low cost, portable prototype ChD with compact dimensions. The last is suitable only for two wheelers and can not undertake any regenerative braking mode testing. There is no regenerative mode analysis neither prototype development in [22], that is a preliminary study about the parameters governing the ChD's operation. A prototype ChD, that requires the powertrain of the EV to be disassembled from the vehicle and assembled onto the dynamometer is presented in [23]. An integrated hybrid ChD system, comprising of a powertrain, disassembled from an EV, the dSPACE real-time control system and a commercially available ChD is presented in [24]. The development of a prototype system consisting of a prototype EV and a commercially available eddy current ChD, able to collect data as the vehicle speed, driving pedals positions, motor power output, battery energy consumption in traction, regenerative braking energy recaptured and total battery energy is described in [25]. The prototype CD comprising of two electric motors connected via a common shaft is described in [26] and [27], where the first motor is the motor to be studied and the second acts as a generator and absorbs power, trying to emulate the road conditions and vehicle's load. The simulation of bidirectional power flow on a ChD, in [28], is used as a testing method for regenerative braking mode. Finally, [29] describes the design and analysis of a hydraulic ChD used by a university team for participating at low consumption competitions: a hydraulic system is utilized to absorb energy and brake the ChDs rollers. There is no prototype development neither the option for regenerative mode experimentation and monitoring in [29].

As the reader may noticed, there is no work among the above ones aiming at the development procedure of a prototype ChD that

- is suitable for low power, ultra light prototype EVs,
- has the ability to collect real testing data under fully automated operation using alternate scenarios,
- has the ability of regenerative mode experimentation,
- is adjustable and portable featuring compact dimensions.

The prototype ChD described in the following sections was developed by TUCer team to combine all the above specifications. Moreover, its automation system integrates a controller scheme powered by the Robot Operating System (ROS). ROS is an open-source, meta-operating system [30]. Apart from being a popular tool in the academic community, it tends to become an industrial standard. Although it is specifically designed for robotic applications, it was proved to be an effective, reliable and efficient solution, easy to program and use.

II. SYSTEM DESIGN

The prototype ChD is designed to undertake experimentation tasks, in a fully automated way, aiming at the development of the electrical - mechanical systems of the EV. These tasks may include, for example, either a simple maximum power-velocity test or a complicated scenario simulating a track lap. To accomplish these experimentation tasks, two modes of operation may be alternatively engaged: *normal* and *regenerative*. For safety reasons the Vehicle Under Test (VUT) is tightly secured onto the ChD during both operation modes, Fig. 1.

In normal mode operation, the VUT is either accelerating its driving wheels or rotates them at a constant speed. During this mode the ChD applies braking force in the VUT's driving wheels, according to the testing scenario.

On real road conditions, when the driver releases the acceleration pedal the vehicle does not stop instantaneously, due to vehicle's inertia, but decelerates. During deceleration the wheels of the vehicle are urged, by the friction between them and the road, to a decelerating rotation. This state is called regenerative mode, when referring to EVs. The prototype ChD simulates the regenerative mode by rotating the rollers attached to the driving wheels of the VUT.

The total cost of the prototype ChD is approximately 1000€, excluding labor costs. It practically does not require any maintenance, apart from periodically lubricating some of its moving parts.

A. *Mechanical Design*

The mechanical structure of the ChD was designed taking into consideration the features of portability, adjustability and ergonomics. ChD's frame, as illustrated in Fig. 2, was constructed by a complex of welded rectangular tubes with total dimensions $2.3 \times 1.3 \times 0.375m$ and weights $16.6kg$. Aluminum alloy 6063 T4 tubes were chosen, as this material offers a stiff, rigid and lightweight structure, sufficient enough to accept the loads and vibrations created by the VUT during testing.

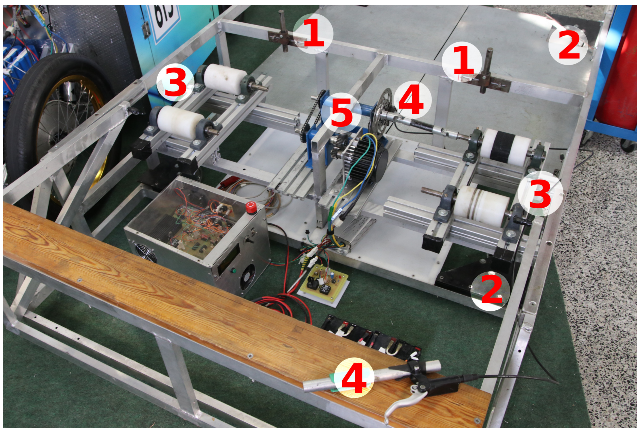

Fig. 2. The main components integrated at the prototype ChD's mechanical construction. (1) round bars, (2) caster wheels, (3) adjustable rollers, (4) brake and (5) transmission.

As shown in Fig. 2, the main components integrated in the ChD's construction, along with the rectangular tubes, are the following:

1) Two round bars securing the VUT's chassis with the ChD, offering safe testing and increased stability.
2) Four locking caster wheels are placed in the bottom of the ChD, to facilitate and simplify the transportation of the ChD.
3) Four rollers at the rear part of the ChD are used to support the rear part of VUT. The rollers are in contact with the rear wheels of the VUT during testing and transmit power from the VUT to the ChD and vice versa, enabling normal and regenerative mode operations respectively. They are attached to a rail system, that permits the adjustment of the rollers position. At the front part of the ChD, round tubes support the front wheels of the VUT. They, also, are able to move on a similar rail system. Thanks to the adjustable rear rollers and front round tubes, the ChD allows testing vehicles with different wheelbase and track.
4) A manual hydraulic disk brake attached to the rollers, to manually brake the driving wheels of the VUT. This feature is not only necessary for safety reasons, but it is also useful for testing manually, on the fly, the EV's powertrain.
5) A geared transmission system connects the rollers with the electric Motor/Generator (M/G) and transmits power between them during both modes of operation. As shown at Fig. 2, only the right rollers are connected to the transmission system, because Spyros Louis EV has only one driving wheel, at its right rear side.

B. Electrical Design

The proposed architecture of the electrical system is illustrated in Fig. 3. The system consists of:

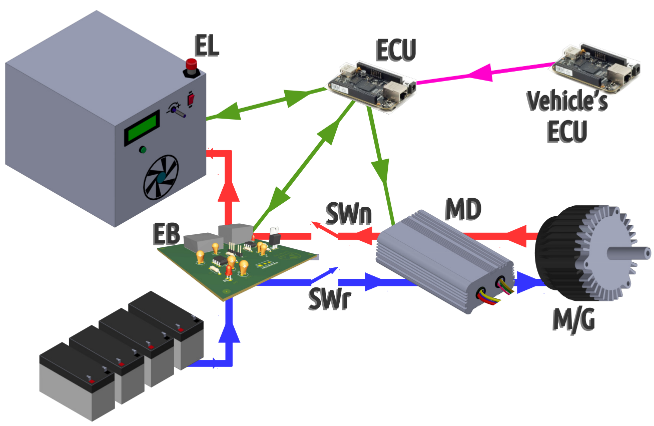

Fig. 3. Architecture of the electrical system. Red and blue lines represent the flow of energy in normal and regenerative mode respectively. Green lines denote the signals received and transferred from the system's ECU. Pink line denotes the communication channel between the ECUs of the ChD and the VUT.

- a $60V - 1.4kW$ prototype DC Electronic Load (EL),
- a prototype Electronic Board (EB),
- a BeagleBone Black [31] open source, ARM based, Linux-ROS powered Electronic Control Unit (ECU),
- a 12 FET Motor Driver (MD) [32],
- a $48V - 1kW$ electric Motor/Generator (M/G) [33] connected to the adjustable rollers at the rear part of the ChD,
- two electronically controlled power switches, SWn and SWr, to engage normal and regenerative mode operation respectively and
- four $12V - 7Ah$ Lead Acid batteries.

In normal and regenerative mode operation, kinetic energy from the VUT's wheels is converted to electrical energy and vice versa.

During normal mode operation SWn is on and SWr is off. Kinetic energy is transferred from VUT's wheels to the rollers. The ChD's M/G, that is connected to the rollers via the transmission system, absorbs the power from the rollers, by converting kinetic energy to electrical energy, acting as a generator. Thus, the M/G applies braking force to the VUT's driving wheels. The generated electrical energy is guided through the EL and is dissipated as heat. The flow of energy is shown in Fig. 3 using red lines. The system is capable of simulating vehicle's inertia in real road conditions, by adjusting the amount of electrical energy that the EL sinks.

The regenerative mode requires an opposite transfer of energy, compared to normal mode, as shown in Fig. 3. In this mode the SWn is off and the SWr is on. The battery pack supplies power to M/G, which acts as an electric motor. Electrical energy is converted to kinetic energy as the M/G rotates the rollers that, in turn, rotate the VUT's driving wheels. The flow of energy for this mode is shown in Fig. 3 using blue lines.

III. ROS IMPLEMENTATION

ROS offers an anonymous, asynchronous, publish/subscribe message system that provides inter-process communication [30], [34]. Real time programming is an essential specification for the safe operation of the ChD where, for example, the utilization of its power switches demands precise synchronization. ROS messaging and communication system provides a soft real time solution for the scheduling of the power switches. Furthermore, the ROS message system implements the flow of sensors' data and control commands between the controller procedures, simplifying the programming task and increasing the robustness of the control scheme.

The ROS based scheme controlling the automated operation of the prototype ChD, as depicted in Fig. 4, is composed of five Python [35] programs, called nodes and two messages being broadcasted between them. The control task is distributed between the five nodes which are communicating, in soft real time, via the two messages.

A. Nodes

The following program nodes are all active during the execution of the control scheme and the several control tasks are distributed among them.

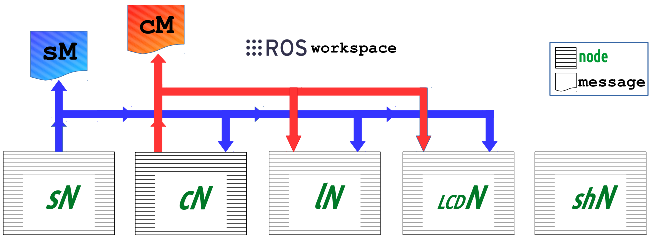

Fig. 4. Controller scheme of the ROS workspace.

1) *sensorsNode (sN)*: implements the data acquisition task by accessing the sensors and the communication channel connecting the VUT's and ChD's ECUs. It publishes data to the *sensorMessage* topic.
2) *controllerNode (cN)*: processes *sensorMessage*'s data, implements the control procedure by utilizing a Finite State Machine (FSM) and publishes some of the control commands as a broadcast at the *controllerMessage* topic. The *controllerNode* is a subscriber to the *sensorMessage* topic.
3) *loggerNode (lN)*: implements the data logging task. It is a subscriber to both *sensorMessage* and *controllerMessage* topics.
4) *LCDNode*: implements the task of printing data to the EL's LCD. It is a subscriber to both *sensorMessage* and *controllerMessage* topics.
5) *shutdownNode (shN)*: implements the task of system shutdown. It sends a power-off system call as soon the ChD's power switch is turned off.

B. Messages

Two message topics are broadcasted at the ROS workspace of the ChD controller's software, to implement the inter-node communication:

1) *sensorsMessage (sM)*: contains the sensors' measurements, sampled at a rate of $4Hz$. It, also, includes the actual velocity of the VUT's driving wheel, the ChD's braking power target value and the testing scenario's velocity target values, transmitted through the communication channel connecting the VUT's and the ChD's ECUs, transmitted at the same rate of $4Hz$.
2) *controllerMessage (cM)*: contains the values of two control parameters, the duty cycle used at the EL's switching method and the state of the EL's main input power switch.

IV. FINITE STATE MACHINE

The ChD's controller program is based on an Finite State Machine (FSM), used as a computational model, consisting of a set of states and transitions. This is a dynamic approach that describes the evolution over time of a set of discrete and continuous state variables. Controller programs FSM can be described as the tuple $A = (Q, \Sigma, \delta, q_0, F)$ [36], where:

- $Q = q_0, q_1, ..., q_4$ is the finite set of states, described in Table I,

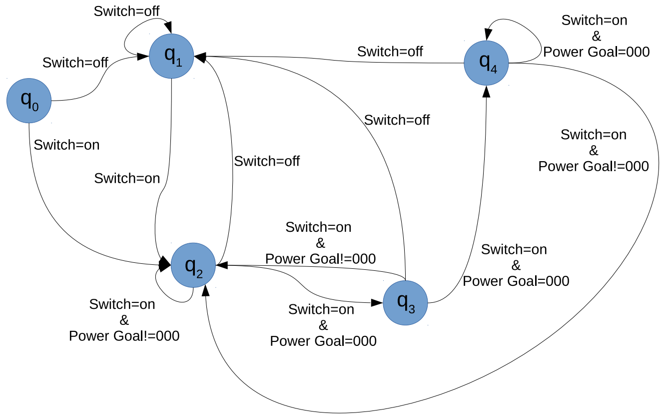

Fig. 5. Controller's Finite State Machine.

- Σ is the the alphabet, consisting of a finite set of symbols,
- $\delta : Q \times \Sigma \rightarrow Q$ is the state transition function and
- $q_0 \in Q$ is the initial state of the FSM.

The FSM technique was chosen as the control strategy representation, due to its advantages described in [37]. The alphabet Σ consists of two symbols:

- *Switch* that refers to a manual toggle switch on the EL. The switch selects whether the EL functions in Manual Status (MS) or Scenario Status (SS). In SS the EL is controlled by the ChD's ECU, fully automated.
- *Power Goal* value, that indicates the current power goal value during SS. When *Power Goal* is zero, so is the braking power, and the ChD changes its mode from normal to regenerative.

The initial FSM state, q_0, represents the initialization phase, where it awaits further signal to either enter MS or SS. When the *Switch* is turned off, the system transitions to q_1, where the EL can be manually operated by the user with no regenerative function. In the contrary case, in which the *Switch* is turned on, the system ignores any hand operated signals (apart from emergency switch) and begins to execute an automated behavior, SS, taking in consideration information sent by the VUT's ECU in every time cycle. The signal routing between the ECUs, through the communication channel, is shown in Fig. 3. Since it is not feasible to start in regenerative mode, the first FSM state of SS, q_2, uses the EL and sets its operational parameters' values according to the testing scenario. When regenerative mode is requested by the ongoing testing scenario, the system transitions to q_3. This state is referenced as an intermediate state, since it ensures that enough time is given to the SWn and SWr to be set properly before the change in the direction of energy transfer. Afterwards, it enters q_4, that corresponds to the regenerative mode state. As depicted in Fig. 5, the *Switch* can change its value at any time, to set the EL to MS and terminate the ongoing SS testing, at the next control step.

V. EXPERIMENTATION AND TESTING

Last year TUCer team used the prototype ChD to test the electrical and mechanical systems of Spyros Louis EV.

TABLE I

FSM'S STATES

State	State Description
q_0	Initialization
q_1	EL operates in MS
q_2	EL operates in SS-normal mode-SWn is on-SWr is off
q_3	EL operates in SS-intermediate step-SWn is off-SWr is off
q_4	EL operates in SS-regenerative mode-SWn is off-SWr is on

The ChD was utilized during almost all the steps of the hardware and software development of the vehicle's energy management system. Moreover, the mechanical construction of the transmission system of the EV was thoroughly tested on the ChD using several scenarios. The team's experience proved that, among others, the ChD is a valuable tool for:

- testing the electric motor's behavior in normal and regenerative modes of operation,
- test the EV's energy management systems in several operational modes,
- check the reliability of the transmission mechanical systems and
- conduct testing scenarios to tune the EV's performance.

A. SEM 2019 race scenario

Testing the vehicle according to a scenario is one of the ChDs most useful features. The test described in this subsection is a case study of a scenario testing procedure. TUCer team participated with Spyros Louis EV at the Shell Eco Marathon 2019 competition [5]. The team logged the velocity profile and the power consumption data of the races and used them as the base for editing a testing scenario. As this testing scenario can reproduce the race conditions on the ChD, the vehicle and its systems may be tested in a simulated race. The race log stored data from the vehicle's velocity, the voltage of the supercapacitors included in the vehicle's energy management system and the power consumption of the vehicle's electric motor. A one-race-lap scenario was edited and used to gather the experimental data shown in Fig. 6 and 7. The plots show the real values logged during the race, shown as *Race* values and the experimental data gathered during testing with the ChD, shown as *Scenario* values.

As shown in Fig. 6 and 7, although there are minor deviations, the ChD managed to simulate the race lap and test the vehicle systems under *near to real* conditions. The zero power values shown at Fig. 7 represent the regenerative phase of the log, where the M/G of the vehicle behaves as a generator and has no power consumption. The difference between the real and the simulated power consumption during the first 30 seconds of the test, Fig 7, is due to the inability of the M/G of the ChD to brake the rollers in low velocities. This happens because the M/G acts, at this phase, as generator that in low rotational speed values has no output power. Friction problems between the rollers and the driving wheel of the EV are the cause for the differences between the simulated and the logged motor power from the 30th until the 110th second, Fig 7.

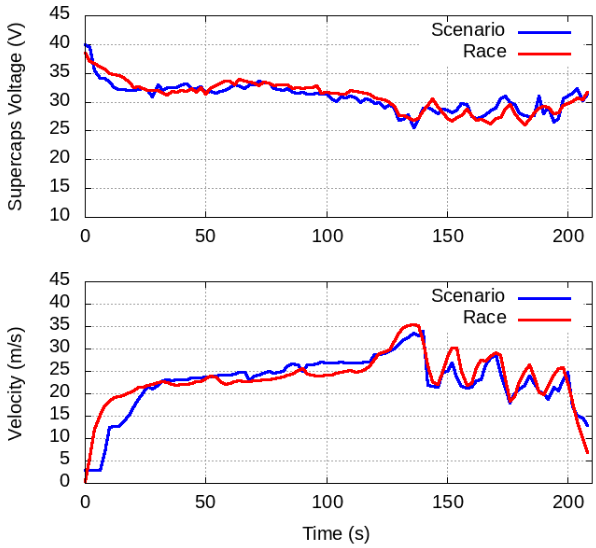

Fig. 6. Supercapacitors voltage and velocity values during a one race lap scenario. The supercapacitors voltage decreases during normal operation and increases during regenerative mode operation.

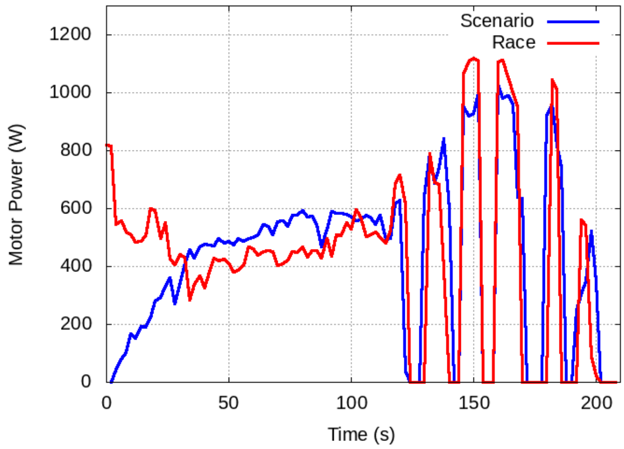

Fig. 7. Vehicle's electric motor power consumption values during a one race lap scenario.

VI. CONCLUSIONS AND FURTHER WORK

A prototype ChD, fully automated and portable, able to reproduce testing scenarios including regenerative mode phases, was developed by the TUCer team. The dynamometer proved its functionality throughout long periods of system development and tuning, at all the phases of the SEM 2019 competition and for demonstration and educational purposes at the university laboratories.

ROS was a prototype method applied for the control of the ChD and along with the deployment of the FSM, leaded to a simple, straightforward and intuitive control procedure. The racing activity of the TUCer team tested under harsh conditions the controller scheme that proved to be surprising stable, easy to program and debug.

Further work includes the ability to brake the driving wheel of the EV during acceleration scenarios starting from standstill. This may be accomplished by adding an automation mechanism to control the disk brake of the ChD, at low speeds. Finally a different choice for the material of the rollers or a proper treatment of their surface will be tested, as a solution to their friction problems.

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