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ESP32-Based Workbench for Digital Control Systems of Duty-Cycle Modulation Buck Choppers

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Abstract— This research work presents an *automated workbench for* digital control systems of DCM (*Duty-cycle modulation*) *Buck choppers*. The prototyping control system used as practical case study consists of: a power Buck chopper associated with a simple DCM driver, an UTD2052CL digital storage oscilloscope, a PS150 power supply with ±15 V outputs, a Laptop computer with installed Arduino IDE/C++ 1.8.13, analog signal conditioning circuits, an ESP32 system-on-chip device, and a standard testing board. The overall ESP32-based workbench has been implemented, built and well tested. Then, experimental conditions and results for all automated operating modes are presented and discussed.

Keywords— Digital control system, DCM Buck choppers, analog signal conditioning circuits, ESP32 system-on-chip, Arduino C++ application, automated operating modes.

I. INTRODUCTION

The modern DCM (duty-cycle modulation) technique with associated building circuits developed in the pioneering paper [1], falls into a wide class of switching signal transform techniques, involving high frequency ON/OFF modulated waves. Since 2005, it has increasingly become a versatile signal processing policy with increasing applications in industrial electronics [2]. The first realistic applications of DCM principles were novel analog-to-digital converters) architectures [3, 4, 5]. Then, new DCM digital-to-analog conversion structures were implemented in [6, 7]. Furthermore, pioneering DCM transmission systems were successfully developed and published in the literature [8, 9].

Compared to PWM and SDM schemes with open loop hardware structures, the DCM topology owes its greater challenge to numerous merits, e.g., dual feedback architecture, embedded clock, minimum building components, low realization cost, and more. Given such numerous advantages, finding new DCM application fields, remain an active research area. As an implication, DCM-based drivers for Boost choppers have been developed and well tested in [10, 11]. In addition, a few DCM drivers for power inverters have been designed and well tested in [12] [13, 14]. On the other hand, many research works on DCM drivers for Buck converters have been published [15, 16].

However, in existing control systems for DCM Buck choppers, the great emphasis is more on the analog synthesis problem [15]. The resulting block diagram is presented in Fig. 1, where descriptive variables are chosen as in [17]. These variables are defined as follows: *Uc* (control signal), Ucm (DCM output wave), Ton (H-Pulse time), Tof (L-Pulse time), Uy (DC output signal), Tm(DCM period), $f_m(Uc)$ (DCM frequency), Rm (duty-cycle).

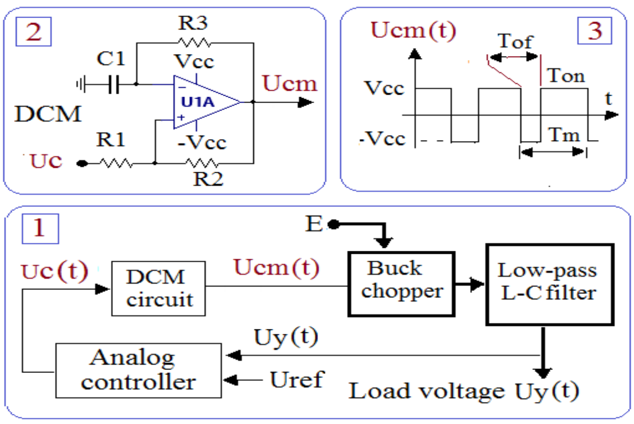


Figure 1. Analog control systems for DCM Buck choppers

Using these notations, let us recall under linear modulating range, expressions (1) and (2) below according to [1, 5], where α1=R1/(R1+R2) and α2= 1-α1 are design parameters. It is important also to recall that $f_m(Uc = 0)$ in (2), is the upper bound of $f_m(Uc)$ since it is convex in Uc.

$$R_m(Uc) = p_m \; Uc + \frac{1}{2} \quad \text{with} \quad p_m = \frac{\dfrac{\alpha_1 \alpha_2}{E(1-\alpha_1^2)}}{\log\left(\dfrac{1+\alpha_1}{1-\alpha_1}\right)} \tag{1}$$

$$T_m\,(Uc=0)=\frac{1}{fm(Uc=0)}=2\;R3\;C1\;\log\left(1+\frac{R1}{R2}\right)\quad(2)$$

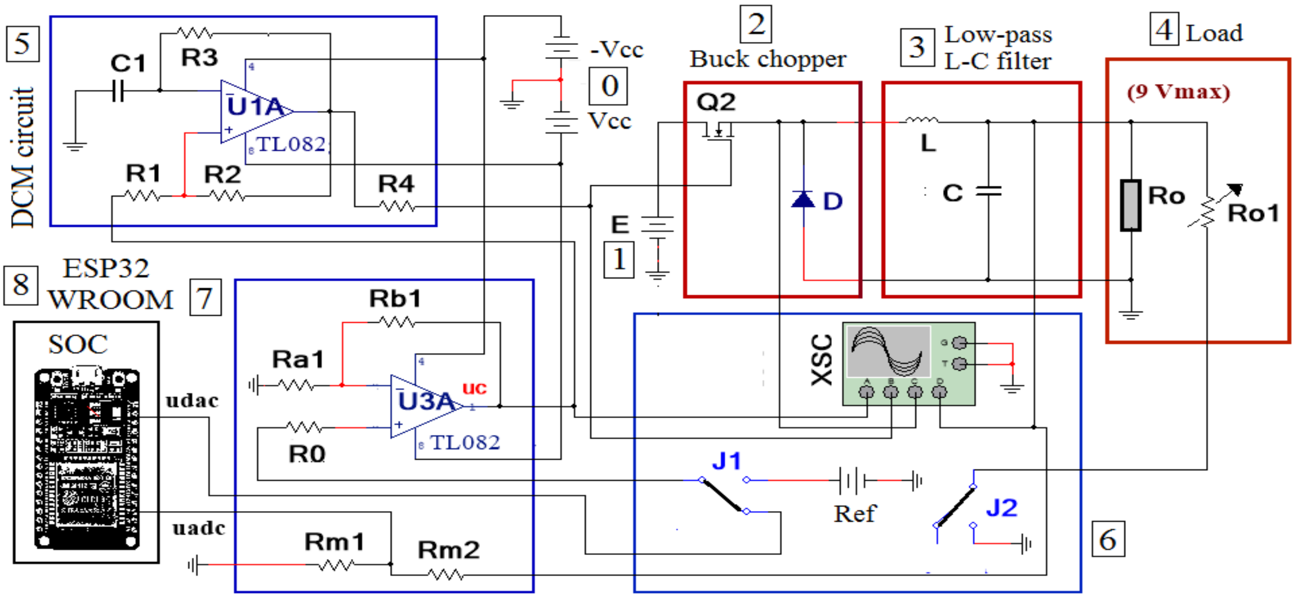


Figure 2. Schematic diagram of the automated workbench for DCM Buck choppers

Table 1. Summary of ESP32 resources

ESP32 (SOC device)	
	
PINS FOR THE FRAMEWORK	
NAME	ROLE
GPIO 23	0V/3V Uref selector
GPIO 22	6V/9V Uref selector
GPIO 25	DAC1 for Uc DAC
GPIO34	ADC for Uy ADC
Vcc	Vcc = 3.3 V supply
GND	Ground

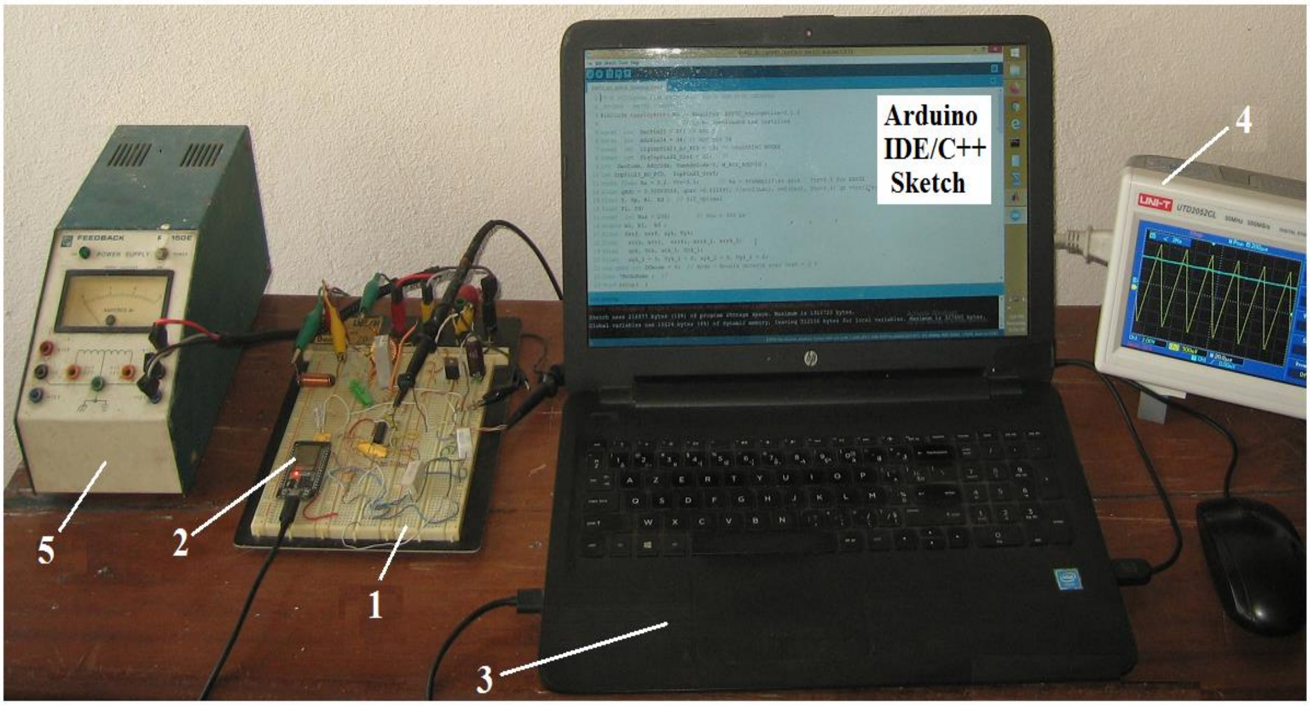
GENERAL CAPABILITIES	
BASIC RESOURCES	**CHARACTERISTICS**
Dual cores 0 and 1	Each core has 32 bits
Clock frequency	80 -240 MHz
SRAM	512 KB
ROM memory	448 KM
Supported flash memory	Up to 32 Megabyte
MAIN RESOURCES	**CHARACTERISTICS**
Build-in Wi-Fi module	Standard: 802.11, 2.2 -2.5 GHz
Build-in Bluetooth module	Version 4.2 (BLE)
23 general purpose pins (real time reconfigurable by user code)	DIOs, 18 ADC, 02 DAC, 16 PWM, 02 I^2C, 02 I^2S, Touch, etc.
Electrode capacitive touch	10
PCB antenna	01
Hall sensors	02
Low noise analog amplifier	01
Cristal oscillator - 32 KHz	01
USB connector	Version 2.0
03 operating modes	AP, Client, and Both
02 on-board buttons	Reset and enable
Red LED for power ON	01
ELECTRICAL AND THERMAL CHARATERISTICS	
Vcc supported	3.3 V
Active voltage range	2 V – 3.6 V
Operation temperature	-40°C to +125°C

However, most analog control schemes encountered in the literature of DCM Buck choppers provide numerous weaknesses [17]. A few examples are: greedy hardware size, significant noise level, lack of flexibility, dreadful reproduction and distribution cost. In a recent pioneering a PID/LQR digital control scheme for DCM Buck choppers has been successfully synthesized and simulated in [18]. However, its real time prototyping as well as experimental characterization, remain up to date an unsolved problem.

As a relevant contribution, the goal of this research paper, is to synthetize, develop, implement and test, a pioneering ESP32-based automated workbench for digital control systems of DCM Buck choppers. The digital control systems considered here, belong to the wide class of PID control policies. The next sections II, III, IV and V of this paper deal with methodology/tools, experimental setup, experimental results and general conclusion respectively.

II. METHODOLOGY AND TOOLS

The schematic diagram of the automated workbench for Buck choppers, is presented in Fig. 2. The ESP32 capabilities summarized in table I show its enormous embedded resources, compared to the popular ESP8266 device encountered in many projects [19, 20]. It is worth noting here that, the ESP32 device is the latest and optimal system-on-chip for rapid and low cost development of ambitious projects. The overall digital control system is designed for many automated operating modes. Therefore, it is more flexible than existing analog control platforms for DCM Buck choppers.



1 - Test board DCM Buck converter; **2** - ESP32; **3** - Laptop/PC with installed Arduino IDE/C++; **4** - UNIT-T UTD2052C digital storage oscilloscope (50 MHz or 500 MS/s); **5** - PS150E ± 15 V power supply.
Figure 3. ESP32-Based workbench for digital control of DCM Power Buck choppers

Table 2. Operating modes

No	J1	J2	Set voltage	Mode
0	0	0	Uref = 0 V	OLDC-0V
1	0	1	Uref = 2 V	OLDC-2V
2	1	0	Uref = 6 V	OLDC-6V
3	1	1	Uref = 6 V	CLDC-6V

Table 2 shows the *true table* of the aforementioned automated operating modes. J1 and J2 switches are available to the user for preselecting any desired operating mode before its activation by pressing an *onboard reset button* of the ESP32 device, for the sake of better flexibility. They are numbered in the first column from 0 to 3. The acronyms used in the last column stand for:

- OLDC (Open Loop Digital Control)
- CLDC (Closed Loop Digital Control).

III. EXPERIMENTAL SETUP

A. *Prototyping system*

Table III shows the technical information and data required for building components of the prototyping ESP32-based Framework for DCM power Buck choppers, as earlier schematized on Fig. 2 in Section II.

Table 3. Digital control data

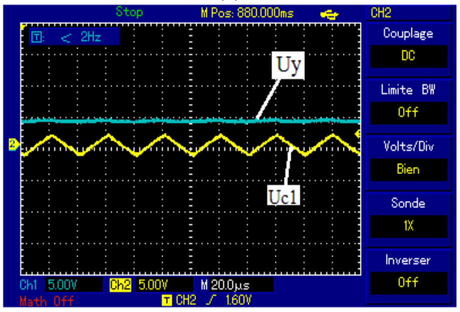
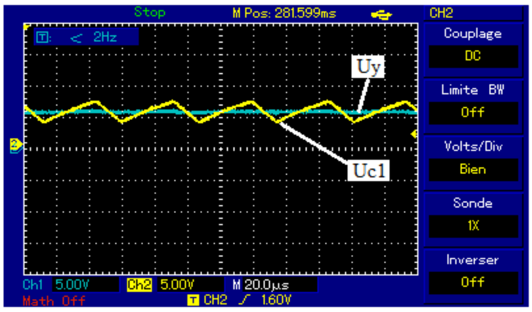
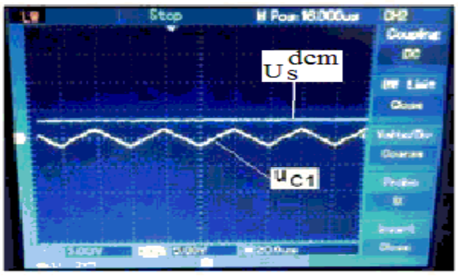
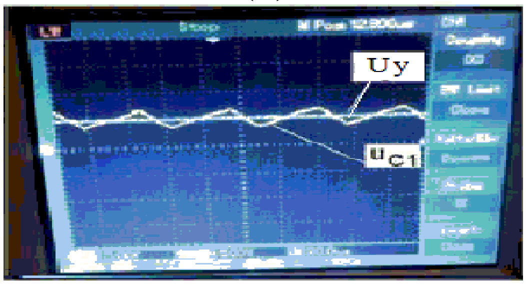
	Type	Name	Valeurs
Power Buck chopper	Main power	E	15 V
	Power suply	± Vcc	±15 V
	Load	Zo	3.3 to 10 Ω
	MOSFET	Q	IRLZ14
	Diode	D	HFAD04TB60
	Capacitance	L	1 mH
	Capacitance	C	220 uF
DCM circuit	Integrated CI	U1A	TL084 (1/4)
	Resistance	R1	1.2 kΩ
	Resistance	R2	10 kΩ
	Resistance	R3	2.32 kΩ
	Resistance	R4	1.2 kΩ
	Capacitance	C1	33 nF
Output and input circuits	Integrated	U3A	TL084 (1/4)
	Resistance	R0	1 kΩ
	Resistance	Ra1	1 kΩ
	Resistance	Rb1	2.2 kΩ
	Resistance	Rm1	1 kΩ
	Resistance	Rm2	2.2 kΩ
SOC device	ESP32	ESP32	WROOM32

B. *Real view of the ESP32-Based framework*

The ESP32-based framework is presented in Fig. 3, where the building parts are numbered for the sake of rapid localization.

Note that the building electronic components (i.e. ESP32, analog interface, DCM driver, power diode and MOSFET, LC low pass filter and load), remain connected to the testing plate rather than to be mounted on a PCB (printed circuit board). The automated digital control application, has been developed as a C++ sketch, then compiled and uploaded ESP32 device, from Arduino IDE-C++ 1.8.13. The processing loop of the C++ source code is illustrated in the Appendix. It only requires 16 % of the maximum storage memory, and only 4% of dynamic memory for global variables. It is suitable for real time tasks, including data *acquisition, signal processing, and digital PID control* In addition, it is worth nothing that a fixed sampling period T= 0.1 ms has been used for the synthesis of z-transfer function of PID control according to Tustin's Technique.

Table 4. Obtained results compared to, those in [15]. Ucm (5 V/div), Uc1 (5 V/div) and time (20 us/div)

OLDC0V mode for the forroposed ESP32 control system	(a)  (a')	CLDC6V mode for the proposed ESP32 control system	(b)  (b')
OLDC0V mode m in [15]		CLDC6V (Reference [15])	

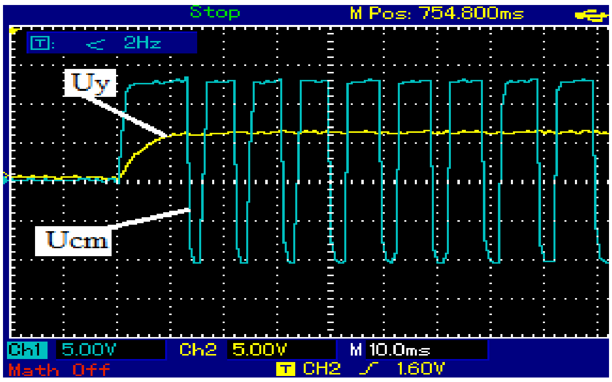


Figure 4. Transient step response under CLDC6V mode

IV. EXPERIMENTAL RESULTS

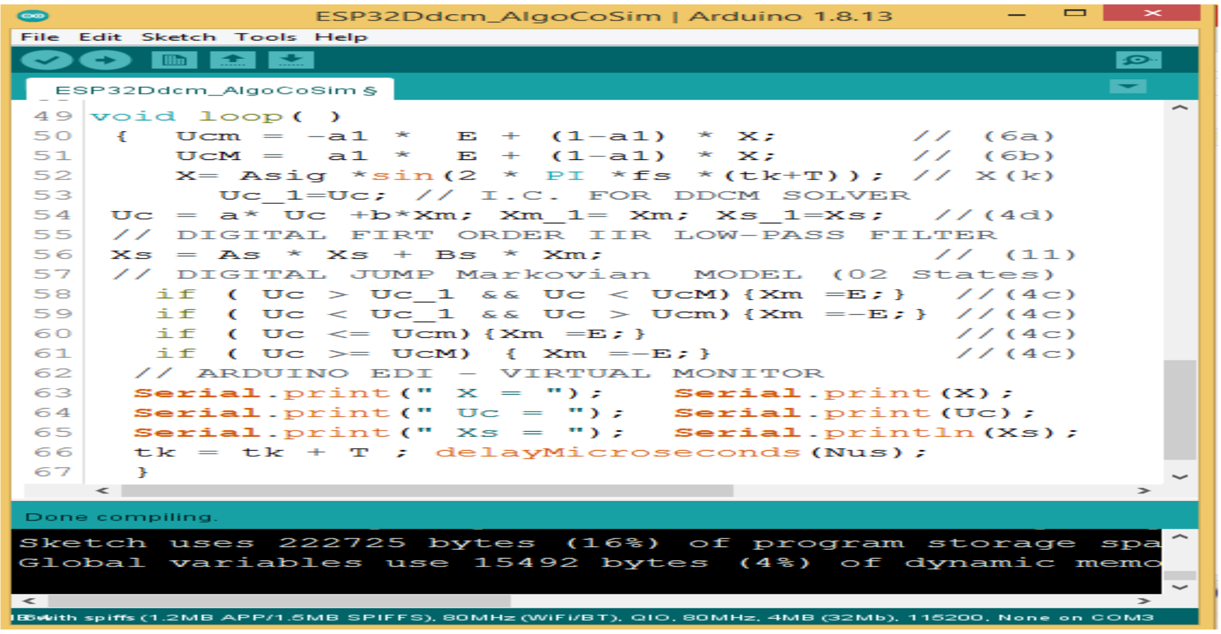
In Table 4, two types of experimental results (a, a') and (b, b') are displayed in steady regime using the same scale for the sake of better visual comparison. Note here that (a, b) results from ESP32-based workbench, and (a', b') being tests conducted under the same operation modes and conditions, from a pioneering analog PID control system [15]. In all cases, the state Uc and output Uy are identical for the same set voltage (0 V or 6V) and operating mode (OLDC0V or OLDC6V). In Fig. 4, a sample of transient step response obtained using the workbench in CLDC6V mode is presented. It is worth noting that duty-cycle of Ucm (modulated signal) and the amplitude of Uy (Load voltage) rapidly converge to constant values. As an effect, the transient time is limited to a few ms As a relevant finding, the digital PID application which has been embedded into the ESP32 system-on-chip, is a reliable and more flexible virtual reality, than greedy and tedious analog PID control circuits for DCM power Buck choppers as designed and built in [15].

V. CONCLUSION

The state of the art on control systems of DCM power Buck choppers, has been improved significantly in this research paper, by a pioneering ESP32-based workbench. The reliability and effectiveness of the proposed workbench have been proven using experimental tests, and their comparison with the behavior of an original analog PID control system. In addition to its relevant reliability and performance properties, the proposed automated workbench is equipped with a flexible Arduino IDE/C++ application, to be extended in future research works for handling more ambitious digital control systems involving other types of DCM power converters. While waiting these extensions, the proposed workbench is duplicable as a high level didactic tool for Master students in power electronic.

APPENDIX

Main C++ code in Arduino IDE/C++ framework of the proposed ESP32-Based workbench for DCM Buck power choppers



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AUTHORS PROFILE

Paul Owoundi Etouke is born in 1987 at Sobia (Cameroon). He obtained at ENSET of the University of Douala, a Master II degree for Electrical Engineering Education in 2012, a Master Research Degree in Automation engineering in 2015. In addition, Since 2017, he is a Ph.D student in Computer Science and Control Engineering. Furthermore, He is main author of 02 scientific papers published in indexed *International scientific Journals, e.g. Journal of Electrical Engineering, Electronics, Control and Computer Science (*2020)*, and International Journal of Computer Science, Engineering and Information Technology,* (2020). Hi is also main author of a scientific communication presented in the *International Conference of the 40th anniversary of ENSE*T of Douala from 04-07 December 2019. On the other hand, he is *Lecturer* since 2017 at ENSET of Douala, and has co-supervised 15 Master II thesis in Electrical and Computer Science Engineering. As an additional relevant fact, it is woty noting that since 2017, *Paul Owoundi Etouke* is *Head of the Scholar Service* of ENSET of Douala. His PhD thesis which is actually at final edition step, deals with *Theoretical and Experimental Studies of ESP32-based digital optimal PID/LQR control systems for low power DCM Buck choppers*.

Léandre Nneme Nneme is born in 1961 at Nsengou-Ma'an, in Cameroun. He is Associate Professor at ENSET on the University of Douala. He obtained a Master II degree in Electrical Engineering Education at ENSET of the University of Douala. Then, he also obtained a Master Science degree in electrical engineering in 1987 at ENSET of Tunis (Tunisia). In ddition, he further received a Master of Applied Science dedree in electrical and Automation engineering in 1992, and a PhD Degree in Automation and smart control systems in 1998, both degrees at "Ecole Polytechnique de Montreal", Quebec, Canada. On the orther hand, Pr Leandre nneme Nneme He has supervised 02 PhD Thesis in Engineering Science at ENSET. In addition, Pr Leandre Nneme Nneme is author/co-author of 32 indexed scientific papers publihed in indexed leading international journals including *International Journal of Computer Science, Engineering and* I*nformation Technology* (2020), *Journal of Electrical Engineering, Electronics, Control and Computer Science* (2020), *WSEAS Transactions on Circuits ans Systems* (2018), *International Journal of Engineering Research and Applications* (2014), *American Journal of Electrical and Electronic Engineering* (2014), *Asian Journal of Engineering, Sciences and Technoloy* (2013), *International Journal of Power Electronics* (2013), He is also author or co-author of 12 scientific communications presented in International Conferences. In 2013, he significantly brought a relevant reinforcement for stating and analytically proving of 04 new DCM fundamentals, i.e., 02 topological Lemmas and 02 structural Theorems. Futhermore, Pr Leandre Nneme Nneme is an active Member of clever Scientific Societies, e.g. RAIFFET, Education.Educ, Research Gate, etc. Head of the departemnent of Computer Science Engineering of ENSET of Douala since 2004, and Director of ENSET since 2017. His current research works deals with the study of smart robust control systems for mobile and humanoid robots.

Jean Mbihi is born in 1960 at Foreke-Dschang, Cameroon. He is *Full Professor* at ENSET of the University of Douala. He obtained a *Master II* Degree in electrical engineering education at ENSET of Douala, where he owned in May 25, 1989 a Patent No. PV 59580 "on "*Multisize Battery charger with automatic calibration and cutoff*", and is also obtained a *Master Science* degree in electrical engineering in 1987 at ENSET of Tusins (Tunisia). Then he obtained a *Master of Applied Science* degree in Electrical and Automation engineering in 1992, and a *PhD* Degree in Automation and stochastic flexible manufacturing systems in 1999, both degrees at "Ecole Polytechnique de Montreal", Quebec, Canada. He has supervised also 04 PhD Thesis in Engineering Science at ENSET. In addition, *Jean Mbihi* is author/co-author of 46 scientific research papers publihed in indexed leading international journals, e.g., *International Journal of Comuter Science, Engineering and Information Technology* (2020), *Journal of Electrical Engineering, Electronics, Control and Computer Science* (2020, 2018), *WSEAS Transactions on Circuits and Systems* (2018), *Transactions on Electrical Engineering* (2017), *Journal of computer Science and control systems* (2017, 2015), *WSEAS Transactions on Advances in Engineering Education* (2016, 2015), *IEEE Transactions of Circuits and Systems II* (2015), *International Journal of Engineering Research and Applications* (2014), *American Journal of Electrical and Electronic Engineering* (2014), and *International Journal of Power Electronics* (2013). Jean Mbihi is also author of 14 scientific communications presented in International Conferences. Since 2005, he has been the pioneering author of analytical developments of DCM theory, ,by formulatong and proving 03 *operational principles*, 05 *structural Lemmas* and *08 morphological Theorems*. On the other hand, he is author of 06 books on computer science Engineering and Automation, published over time as follows: 01 at Publibook Editions (Paris, 2005), 01 at Ellipses Editions (Paris, 2012), 02 at ISTD Ltd (UK, 2018), and 02 at Newy Jersy (USA, 2018). Furthermore, *Jean Mbihi* is an active Member of clever Scientific Societies, e.g., IAENG (International Association of Engineers), WASET (World Academic of Science, Engineering and Techology), RAIFFET, Academia.Educ, Research Gate, Google Scholar, etc. He has been Head of the departemnent of Textile and Clothing Industry at ENSET of Douala from 2004 to 2019, and Supervisor of the Research Laboratory of Computer Science Engineering and Automation since 2017. Since 2020, he is *Deputy Director* of ENSET of fthe University of Douala. His present research works deal with new application areas of DCM drivers, e.g., for robotic axis, ECG optical transmission systems, and Electronic-Textile instruments for smarth cloths Engineering.

