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The Role Of Modeling, Simulation And Analysis Stage In Mechatronics Systems Design Education

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Abstract—Mechatronics systems are designed with synergy and integration toward constrains like higher performance, speed, precision, efficiency, lower costs and functionality and operate with exceptional high levels of accuracy and speed despite adverse effects of system nonlinearities, uncertainties and disturbances, therefore, such constrains must be tested, verified, refined, ensured and met. In order to evaluate such concepts and others generated during the design process, without building and testing each one and take corresponding design decisions, Modeling, simulation and evaluation, play a critical role and considered as highly important during the design stages of a Mechatronic system. The primary challenge in modelling and simulation of Mechatronic systems lies in their multidisciplinary and crosses domain boundaries nature. This paper focuses on modelling, simulation, analysis and evaluation stage in Mechatronics design and development education oriented methodology, concepts, description, role, classification and applications are presented and discussed, and by means of examples-projects. The paper is intended to support engineering educators and help students in solving Mechatronics design and development tasks. A short review of scientific resources on modelling and simulation in Mechatronics are also presented.

Keywords—Mechatronics education, Design methodology, Modeling, Simulation, Analysis.

I. INTRODUCTION

The modern advances in information technology and decision making, as well as the synergetic integration of different fundamental engineering domains caused the engineering problems to get harder, broader and deeper. Problems are multidisciplinary and to solve them require a multidisciplinary engineering systems approach, such modern multidisciplinary systems are called Mechatronics systems[1-2].Mechatronics engineer is expected to design products with synergy and integration toward constrains like higher performance, speed, precision, efficiency, lower costs and functionality, also in order to evaluate such concepts and others generated during the design process, without building and testing each one, Mechatronics engineer must be skilled in the modeling, simulation, analysis and control of dynamic systems and understand the key issues in hardware implementation[3]. due to different disciplines involved, the Mechatronics design process may become very complex, and correspondingly, engineering educators face daunting challenges.

The key element in success of a Mechatronics engineering program, and correspondingly Mechatronics engineering graduates, is directly related to the applied structural design methodology. A guidelines for structural design methodology and tools for the development process of Mechatronic products, that can support educators and help students in solving Mechatronics design integrated tasks with their specific properties and can be applied in educational process is highly required, such guidelines for structural design methodology are proposed in [1-2], this methodology is developed, based on VDI 2206 guideline [5] and different industrial, scientific and educational resources including [4-20], and is proposed to fulfill Mechatronics optimal program requirements. The proposed methodology consists of a systematic specific simple and clear steps (depicted in diagram 1) that are easy to memorize, follow and aims to support engineering educators and help non experienced student or group of students to integrate gained multidisciplinary abilities and knowledge, in various stages in solving Mechatronics design integrated tasks.

This paper extends writer's work [1-2] and focuses on Modeling, simulation, analysis and evaluation stage and corresponding concepts in Mechatronics design and development methodology, concepts, description, role, classification and applications are to be presented, explained and discussed, and by means of examples-projects. The papers is intended to support engineering educators and help students in solving Mechatronics design and development tasks, also, a review of scientific resources on modelling and simulation in Mechatronics are presented.

I.I MECHATRONICS SYSTEMS DESIGN APPROACH.

There are many definitions of ***Mechatronics***, it can be defined as multidisciplinary concept, it is the synergistic integration of mechanical engineering, electric engineering, electronic systems, information technology, intelligent control system, and computer hardware and software to manage complexity, uncertainty, and communication through the design and manufacture of products and processes from the very start of the design process, thus enabling complex decision making. Modern products are considered Mechatronics products, since, it is comprehensive mechanical systems with fully integrated electronics, intelligent control system and information technology. Such multidisciplinary and complex products, considering the top two drivers in industry today for improving development processes, that are shorter product-development schedules and increased customer demand for better performing products, demand another approach for efficient development. ***Mechatronic system design*** process addresses these challenges, it is a modern interdisciplinary design procedure, it is the concurrent selection, evaluation, integration, and optimization of the system and all its sub-systems and components as a whole and concurrently, *all* the design disciplines work *in parallel and collaboratively* throughout the design and development process to produce an overall *optimal* design– no after-thought add-ons allowed, this approach offers less constrains and shortened development, also allows the design engineers to provide feedback to each other about how their part of design is effect by others. ***Integration*** refers to combining disparate data or systems so they work as *one* system. The integration within a Mechatronics system can be performed in two kinds, *a)* through the integration of components (hardware integration) and *b)* through the integration by information processing (software integration) based on advanced control function. The integration of components results from *designing* the Mechatronics system as *an overall system*, and *embedding* the sensor, actuators, and microcomputers into the mechanical process, the microcomputers can be integrated with actuators, the process, or sensor or be arranged at several places. Integrated sensors and microcomputers lead to smart sensors, and integrated actuators and microcomputers developed into smart actuators. For large systems bus connections will replace the many cable. Hence, there are several possibilities to build up an integrated overall system by proper integration of the hardware**.** ***Synergy*** from the Greek word *synergeia* meaning "working together“ and refers to the creation of a whole final products that is better than the simple sum of its parts, an integrated and concurrent design should result in a better product than one obtained through an uncoupled or sequential design [2][21]. synergy can be generated by the right combination of parameters.

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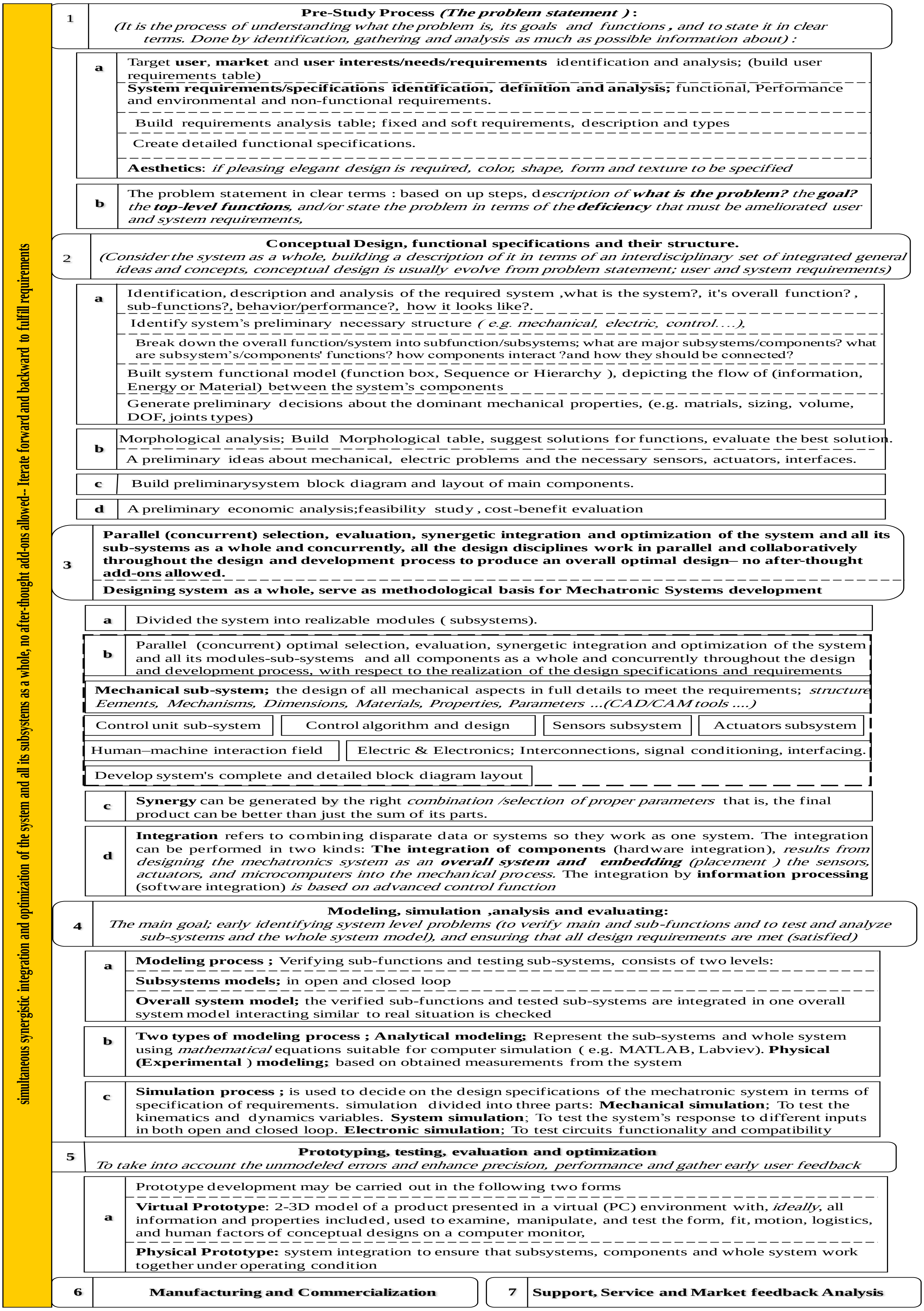

Figure 1 Systematic guideline steps for Mechatronics systems design education-oriented methodology

II. Modeling, simulation, analysis and evaluation.

Modeling, simulation, analysis and evaluation, play a critical role during the design stages of a Mechatronic system, the primary challenge in modeling and simulation of Mechatronic systems lies in their multi-domain nature, consisting of many different interconnected, interdisciplinary, integrated subsystems (and components such as, sensors, actuators, interfaces and mechanical geometry), modeling and simulation are multidisciplinary and crosses domain boundaries.

In evaluating concepts, a modeling-simulation-and-analysis approach must replace any design-build-and-test approach, due to this, the key essential characteristics of a Mechatronics engineer and success in Mechatronics design, are a balance between two skills; Modeling/Analysis skills and Experimentation/Hardware implementation skills [1-3]. The main goal of Modeling, simulation and evaluation in Mechatronics design are; to support important design decisions by early identifying system level problems (to verify sub-functions and test sub-systems), and ensuring that all design requirements are met. Mechatronics design approach challenge conventional sequential design approach, by connecting machine design-test tools and creating a virtual machine prototype before designing the physical machine, to take all advantages that can result from an integrated design, this approach offers less constrains and shortened development, also allows the design engineers to provide feedback to each other about how their part of design is effect by others [1,2,9].

II.I Concepts, Description, Role, Classification and Applications

Referring to VDI 2206 design guidelines[5], four types of models are usually given for Mechatronic systems; namely topologic, physic, mathematic and numeric models [5]. A short introduction to these models and corresponding concepts in Mechatronics system design are followed next, later explained by examples. ***A model*** is a simplified representation of a system at some particular point in time or space intended to promote understanding of the real system. ***Modeling*** is the construction process of physical, conceptual or mathematical simulations of the real world. ***Mathematical Modeling***: A process of representing the behavior of a real system by a collection of mathematical equations and/or logic, any modeling task requires the formulation of mathematical models suitable for computer simulation or solution. ***Topological modeling*** (Figure 2(b)): a mathematical approach that allows to structure data based on the principles of feature adjacency and feature connectivity (describes and reflects interlinks, the function-performing elements, basically the relative position between each component, without considering the physics behind), Topology of mechanical elements could be presented in various ways (e.g. graphs, free-body diagrams, tree-structure) and essentially determines the kinematics of Mechatronic systems, Based on topology descriptions, a physical model is created and describes system properties in system adapted variables – e.g. masses and length for mechanical systems [4,23]. ***Physical model***; One that physically represents an object (figure 2(b)), may be applied to understand the type of forces being acting and applied*.* ***Simulation*** is the process of solving the model i.e. solving mathematical equations and/or logic equations**,** simulation generally refers to a computerized version of the model which is run over time to study the implications of the defined interactions. In order to simulate a Mechatronic system, a multi-domain simulation environment is required. Multi-domain simulation could be achieved in different ways: a more traditional way is to use a general-purpose solver to simulate each subsystem and the whole integrated system, other way, called co-simulation, [26]. ***Co-simulation*** is to use different communicating solvers, to simulate each subsystem and whole system. It is a test software tool, used in order to validate the design choices and to develop the model on gradually decreasing levels of abstraction. ***Hardware-in-the-Loop simulation (HILS)*** is a technique that is used in the development and test of complex process systems and real-time embedded systems. It differs from pure real-time simulation by the addition of a real component in the loop via their electrical interfaces to a simulator, which reproduces the behavior of the real time environment; this component may be an electronic control unit or a real engine. The hardware-in-the-loop simulation testing provides the designer with reassurance that any assumptions made on the plant model were correct, if any assumptions were incorrect, however, the designer has the opportunity to optimize the design [24]. Various kinds of HILS can be realized, simulation of electronics, mechanics, sensors and actuators. ***Optimization*** is to obtain maximum benefits, from the given resources under the given constraints, the achievement of optimal performance for the required system performance specifications. ***Unmodeled errors*****,** it is usually very difficult to build exact mathematical model for complex Mechatronics systems including all components. However, there is no single model which can ever flawlessly reproduce reality, there will always be errors called as unmodeled errors between behavior of a product model and the actual product. These unmodeled errors are the reason why there are so many model-based designs failed when deployed to the product. In order to take into account the unmodeled errors in the design process, the Mechatronics design approach includes virtual and physical prototyping phase**.** ***Prototyping*** is putting together a working model, serves to provide specifications for a real, working system rather than a theoretical one, it is believed to reduce project risks and cost.

Modeling, simulation, analysis and evaluation processes in Mechatronics design consists of two levels; ***subsystems models*** (e.g. mechanical, electrical and electronic components, plant-dynamics, inertias, energy flow, gears, interfaces, sensors, actuators, control) and ***overall system model*** with various sub-system models interacting similar to real situation, all engineering subsystems should be included in overall system model.

There are two types of modeling process*; **a) Analytical modeling***: **(**models can be obtained by either a theoretical approach based on physical laws**)**, It is the process of representing the system using *mathematical* equations, suitable for computer simulation and used to describe changes in a system, analytical models are used to assist in systems analysis; calculations and predictions and plays a critical role during the design stages of a Mechatronic system. For all but the simplest systems, the performance aspects of components (such as sensors, actuators, and mechanical geometry) and their effect on system performance can only be evaluated by simulation [6]. ***b) Physical (Experimental) modeling*****:** models can be obtained experimental approach based on obtained measurements from the system.

Once models are available, simulation is used to decide on the design specifications of the whole Mechatronic system, based on the specification of requirements, the performance aspects of subsystems (and components) and their effect on system performance and test circuits functionality and compatibility, can only be evaluated by simulation[24] .

The simulation can be divided into three parts: mechanical, electronic and system simulation; ***Mechanical simulation*****;** used to test the kinematics and dynamics variables. ***System simulation;*** to test the system's response to different inputs in both open and closed loop, where control system (laws) design involves formulation of reasonably accurate models of the plant to be controlled, designing control laws based on the derived models and simulating the designed control laws using available simulation tools e.g ProEngineer and Solid-Works, MATLAB/Simulink, Labview. The subsystem model parameters should be determined based on the designed mechanical components and the selected actuators and sensors. The designer has the freedom to modify these values, increase the number of inputs/outputs used and include non-linearities in the subsequent design iterations [26]. ***Electronic simulation*****;** To test circuits functionality and compatibility and evaluate the selection and design of interconnections, signal conditioning, and interfacing circuits, including; Drive-circuits (e.g. relays, MOSFETs, L93DIC, transistors,), signals (e.g. control signal, PWM signal), programming of control unit (e.g. Microcontroller), sensors, motor position-speed, the overall system or any such subsystem can be simulated using different computer software tools e.g. *Saber,* ISIS-Proteus and MATLAB. Commercial software tools available to design, model and simulate Mechatronic systems, that allow the stydy and analysis of components interaction and variation in design include MATLAB/Simulink, labview, Scilab/Scicos, Ptolemy, JMathLib [19] , ADAMS, CAE tools, 3D-CAD softwares Pro/Engineer, CATIA, *AMESim, ASCET-SD/CT, Saber*and SolidWorks for visualization and collision detection ,MATRIX-X, ACSL.

A flow of modeling, simulation analysis and evaluation for Mechatronics systems design and integration procedure could be as follows (diagram 2(a) [23]: *a)* Problem statement: establish the goals to achieve; based on the specification of requirements and design (as well as, constrains, assumptions, performance predictions). *b)* System representation: *1)* Since Mechatronic system consists of many different interconnected subsystems (components and elements), divided the system into realizable *modules* (sub-systems/sub-functions), and develop physical model; represent the integrated physical system using physical model. *2)* Develop the functional block diagram and show interconnections of sub-systems and components, *3)* Develop mathematical model: represent system by correct dynamic equations (differential equations), this is done by first by modeling the component, then the subsystem, and finally integrated all subsystems to develop whole system model. In this stage, the component, plant and subsystems models parameters should be determined based on the specification/ requirements, designed mechanical components and the selected actuators and sensors. Mechatronic design requires that a mechanical system and its control system be designed as an integrated system. Modeling should be considered as the most important because the quality of the final product and its performance depend on the model developed and used. The designer has the freedom to modify these values, increase the number of inputs/outputs used and include non-linearities in the subsequent design iterations [18]. *c)* Simulation: Solve the mathematical model (differential equations). *d)* Analyze and evaluate the design analytically, that is to early identify system level problems (to verify sub-functions and test sub-systems) and to ensure that all design requirements and specifications are met, if the specification are not met, modifications-refinements can be made, if the specifications are met, the model can be optimized. *e)* System optimization; the achievement of optimal performance for the required system performance specifications, this can be is divided as follow: First each component are optimized, This operation can be done in parallel. Second components are combined together into subsystems and each subsystem is optimized. Finally subsystems are combined together into whole system is optimized. *h)* prototyping (virtual and physical) a prototype is built to take into account the unmodeled errors in the design process and tested, if the prototype behaves as required (meets optimal performance), the design need not advance any further. *i)* Iterate this procedure.

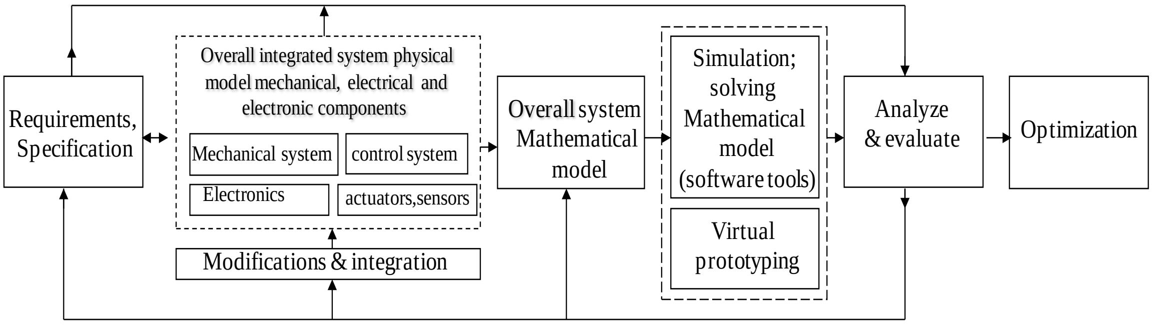

Figure 2(a) flow of modeling, simulation analysis and evaluation for Mechatronics systems design [23]

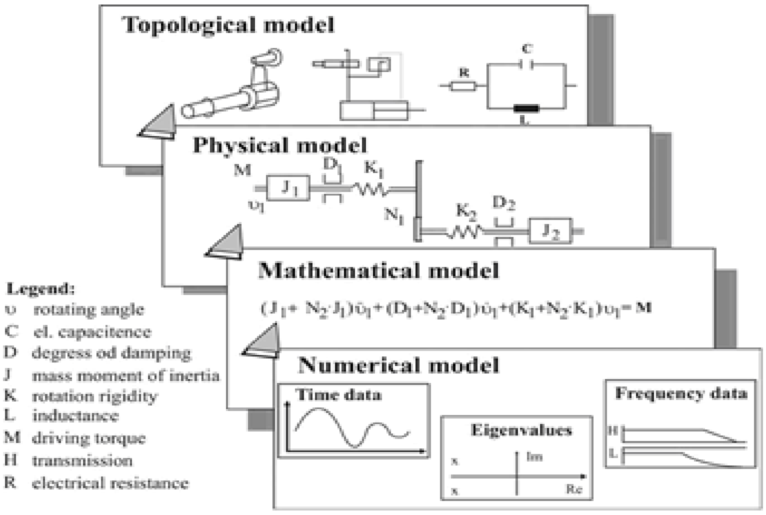

Figure 2(b) The modeling process of Mechatronic product [23]

III. EXAMPLES -CASE STUDIES.

Considering that industrial projects are quite different from academic projects. Industrial project require a quick and dynamic interaction oriented to reduce the project time and get the final results [25]. In this part, are to be introduced and discussed Mechatronics system education oriented design example-projects with emphasize on modeling, simulation analysis and evaluation concepts, also, for engineering educators and students for getting more and detailed information on application of Mechatronics design approach concepts applied in products design and deployment, the following industrial, scientific, educational and research recourse, are proposed: [1-2][26-43]. A detailed explained example-projects on Mechatronics system design and mathematical modeling, as a stage of design process, can be found in [2,26,44-52]. In [52], an overview of the state-of-the art in modeling and simulation, and studies to which extent current simulation technologies can effectively support the design process is presented, that focuses on modeling for design of multi-disciplinary engineering systems that combine continuous time and discrete time phenomena.

III.I MODELING , SIMULATION AND ANALYSIS OF SOLAR ELECTRIC VEHICLE (SEV)

In [44], a refined model for Mechatronics design of pure solar electric vehicles (SEV) and some considerations regarding design, modeling and control solutions are proposed. SEV system consists of eight main subsystems, shown in Figure 3(a)(b), in particular: PhotoVoltaic panel, DC/DC converter, PWM generator, battery bank, DC machine (one or more electric or traction motors) for propulsion drive system, sensing devices, control units (one or more controllers) and vehicle platform with its kinematic and dynamic. Evaluating concepts, and supporting important design decisions can by done by early identifying system level problems (to verify sub-functions and test sub-systems), and ensuring that all design requirements are met, therefore, each subsystem, is ***mathematically*** described and corresponding ***Mechanical or System*** simulation sub-model in Simulink is developed, then an integrated of all subsystems, overall SEV system model is developed, tested and evaluated. simulation (sub-)models of overall SEV system, are developed to allow designer to have the maximum output data to to design, tested, analyze and evaluate overall SEV system and/or each subsystem outputs characteristics and response, for desired overall and/or either subsystem's specific outputs, under various PV subsystem input operating conditions, to meet particular SEV system requirements and performance. Each of these subsystems modeling, simulation and synergetic integration is summarized/discussed next.

III.I.I PV PANEL SUBSYSTEM MODELING AND SIMULATION

SEV uses the PV panel as electricity generator to convert the irradiance from sunlight into electricity to generate its own power, The circuit diagram of PV cell is shown as sub-circuit in Figure 3 (a). A mathematical description of a PV cell/panel in terms of output voltage, current, power and I-V and P-V characteristics are given by Eq.(1), based on these equation, PV Panel ***System*** simulation (in MATLAB) sub-model shown in Figure 3(c) is developed.

III.I.II DC/DC BUCK CONVERTER SUBSYSTEM MODELING AND SIMULATION

The circuit diagram is shown as sub-circuit in Figure 3(a). The exact control of output voltage is accomplished by using a Pulse-Width-Modulation (PWM) signal to drive the buck converter *MOSFET*-switch ON or OFF, by controlling the switch-duty cycle D, based on this, if the principle of conservation of energy is applied then the ratio of output voltage to input voltage is given by Eq.(2). DC/DC Buck converter subsystem Simulink ***system simulation*** sub-model shown in Figure 3(d) is developed.

During the design of Mechatronic systems, it is important that changes in the mechanical structure and other subsystems be evaluated simultaneously; a badly designed mechanical system will never be able to give a good performance by adding a sophisticated controller, therefore, Mechatronic systems design requires that a mechanical system, dynamics and its control system structure be designed as an integrated system (this desired that (sub-)models be reusable), and correspondingly modeled and simulated to obtain unified model of both, that will simplify the analysis and prediction of whole system effects and performance. This unified model is to be developed after modeling each subsystem separately.

III.I.III MODELING AND SIMULATION OF ELECTRIC VEHICLE SUB-SYSTEM DYNAMICS

The electromechanical structure of EV is shown in Figure 3(e). The modeling of an EV sub-system dynamics involves the balance among the several acting on a running EV forces (Figure 3(f)), these acting forces are categorized into road-load and attractive force. The disturbance torque to EV is the total resultant torque generated by all acting forces, given by Eq.(3), main of acting on running vehicle forces to be mathematically described including: *Rolling resistance force* and torque are given by Eq.(4). *Aerodynamic Drag force* and torque given by Eq.(5). *The force of wind* given by Eq.(6). *The hill-climbing resistance force* and torque given by Eq.(7). Based on all derived forces-torques models, expressions given by Eq.(8) (9) can be proposed for total force, such that can be used to develop Simulink SEV dynamics *Mechanical* simulation sub-model.

III.I.IV MODELING AND SIMULATION OF ELECTRIC MACHINE SUBSYSTEM

PMSM motor used as actuator subsystem, it is equivalent PMDC motor transfer function model given by Eq.(10), to develop Simulink *Mechanical* simulation sub-model, with SEV dynamics sub-model, all as one integrated model, is shown in figure 3(g) .the total equivalent inertia, J_{equiv} and total equivalent damping, b_{equiv} at the armature of the motor with gears attaches, are given by Eq.(11). ***Gears modeling****: Gear* ensures the transmission of the motor torque to the driving wheels. The gear is modeled by the gear ratio n , **rechargeable Energy source (battery) modeling** is given by Eq.(12).

III.I.V MODELING AND SIMULATION OF SENSING DEVICES SUBSYSTEM

When the pedal is pushed, the controller delivers electrical currents from the battery to the motor; this gives the car acceleration to accelerate to the desired output speed, the sensors sense the actual output speed and fed it back to controller. Tachometer is a sensor used to measure the actual output angular speed, ω_L. Dynamics of tachometer can be represented using Eq.(13).

III.I.VI MODELING CONTROL ALGORITHM SUBSYSTEMS

PI controller is widely used in variable *speed* applications and *current* regulation. separate PI controller configurations will be applied for achieving desired outputs characteristics of PVPC subsystem and meeting desired output speed of whole EV system. The *PI* controller mathematical model-transfer function is given by Eq.(14). Mechatronic systems design requires that a mechanical system, dynamics and its control system structure be designed as an integrated system and correspondingly modeled and simulated to obtain unified model of both, that will simply the analysis and prediction of whole system effects and performance.

The unified model of mechanical/actuator/dynamics and control/algorithm subsystems is shown in Figure 3(h,i). These subsystem to be designed, tested and evaluated as one unified model . Integrating all subsystem simulation sub-models, in one model, will result in one integrated whole SEV system simulation model shown in Figure 3(g), this simulation model is to be used to Evaluate concepts, and support important design decisions, by testing, verifying and ensuring the whole SEV system, and each subsystem functions and performance.

III.I.VII TESTING, ANALYSIS AND EVALUATION OF WHOLE SEV SYSTEM.

With reference to testing a maximum speed of 23 m/s, (that is 82.8 km/h) in maximum of 10 seconds, for generated converter's output voltage of 38 DC V and for all subsystems parameters defined in[44]. Each subsystem and component sub-model is to be test, evaluated and optimized, then whole system model is tested and evaluated. Running whole SEV

Simulink model, will result in response curves shown in Figure 4, where in Figure 4(a) are shown linear speed, acceleration, current and motor torque response curves. Meanwhile in Figure 4(b)(c) are shown generated PV panel's output voltage and converter's output voltage. in Figure 4(d)(e), PV panel V-I and P-V characteristics for defined operating condition are shown. Analyzing these response curves for each subsystem and/or whole SEV system, we can verify sub-functions and test sub-systems and ensure that all design requirements are met, The obtained response curves show that most of design (and performance) requirements are met, The PV panel-converter generates output constant voltage of 38 DC V, and the SEV reaches desired speed of 23 m/s in less that 10 s, without overshoot and oscillation). In case, if the specification are not met, modifications-refinements can be made, if the specifications are met, the model can be optimized, for optimal performance for the required system performance specifications,

$$I = I_{ph} - I_d - I_{RSH}$$

$$I = \left[\left(I_{sc} + K_i\left(T - T_{ref}\right)\right)\frac{\beta}{1000}\right] - \left[I_s\left(e^{\frac{q(V+IR_S)}{NKT}} - 1\right)\right] - \left[\frac{V + R_S I}{R_{sh}}\right] \quad (1)$$

$$I_S(T) = I_S\left[\frac{T}{T_{ref}}\right]^3 e^{\left[\left(\frac{T}{T_{ref}}-1\right)\frac{qE_g}{NKT}\right]} \Leftrightarrow I_S(T) = I_S\left[\frac{T}{T_{ref}}\right]^3 e^{\left[\left(\frac{1}{T_{ref}}-\frac{1}{T}\right)\frac{qE_g}{NKT}\right]}$$

$$\frac{V_{out}}{V_{in}} = D = \frac{I_{in}}{I_{out}} \Rightarrow V_{out} = D * V_{in} \Leftrightarrow D = \frac{T_{on}}{T_{on} + T_{off}} \quad (2)$$

$$F_{Total} = F_{aerod} + F_{rolling} + F_{climb} + F_{angl\_acc} + F_{lin\_acc} + F_{w\,ind} \quad (3)$$

$$F_{Rolling} = F_{normal\_force} * C_r = M * g * C_r * \cos(\alpha)$$

$$F_{Rolling} = M * g * C_r, on\ a\ level\ surface, \alpha = 0,\ \cos(\alpha) = 1 \quad (4)$$

$$T_{Rolling} = \left(M * g * C_r * \cos(\alpha)\right) * r$$

$$F_{aerod} = 0.5 * \rho * A * C_d * \left(\upsilon_{vehicl} + \upsilon_{wind}\right)^2$$

$$T_{aerod} = \left(\frac{1}{2} * \rho * A * C_d * \upsilon_{vehicl}{}^2\right) * r \quad (5)$$

$$F_{wind} = 0.5 * \rho * A * C_d * \left(\upsilon_{vehicl} + \upsilon_{wind}\right)^2 \quad (6)$$

$$F_{climb} = M * g * \sin(\alpha)$$

$$T_{climb} = F_{slope} = \left(M * g * \sin(\alpha)\right) * r \quad (7)$$

$$F_{Total} = M\dot{\upsilon} + M\upsilon g\sin(\alpha) + sign(\upsilon)Mg\cos(\alpha)C_r + sign(\upsilon + \upsilon_{wind})0.5\rho C_d A(\upsilon + \upsilon_{wind})^2 \quad (8)$$

Or

$$F_{Total} = 0.5 * \rho * A * C_d * \upsilon_{vehicl}^2 + M * g * C_r * \cos(\alpha) + M * g * \sin(\alpha) + J\frac{n^2}{r^2}a + \left(M + \frac{J_{wheel}}{r^2}\right)\frac{d\upsilon}{dt} + $$
$$+ 0.5 * \rho * C_L * B * \upsilon^2 + F_{aerod}\left(K_{wind}\left[0.98\left(\frac{\omega_{wind}}{\upsilon}\right)^2 + 0.63\left(\frac{\omega_{wind}}{\upsilon}\right)\right] - 0.4\left(\frac{\omega_{wind}}{\upsilon}\right)\right) \quad (9)$$

$$G_{open}(s) = \frac{\omega_{platform}(s)}{V_{in}(s)} = \frac{K_t / n}{\left(L_a s + R_a\right)\left(J_{equiv}s^2 + b_{equiv}s\right) + \left(L_a s + R_a\right)\left(T\right) + K_b K_t} \quad (10)$$

$$b_{equiv} = b_m + b_{Load}\left(\frac{N_1}{N_2}\right)^2 \Leftrightarrow J_{equiv} = J_m + J_{Load}\left(\frac{N_1}{N_2}\right)^2 \quad (11)$$

$$J_{load} = \frac{bh^3}{12} \Leftrightarrow J_{equiv} = J_{motor} + J_{gear} + J_{veh} + (J_{wheel} + mr^2)\left(\frac{N_1}{N_2}\right)^2$$

$$I_{Battery} = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4(R_{in} + R_t)P_b}}{2(R_{in} + R_t)} \quad (12)$$

$$V_{out}(t) = K_{tach}\frac{d\theta(t)}{dt} \Rightarrow V_{out}(t) = K_{tach}\omega \Rightarrow K_{tach} = \frac{V_{out}(s)}{\omega(s)} \quad (13)$$

$$G_{PI}(s) = K_P + \frac{K_I}{s} = \frac{(K_P s + K_I)}{s} = \frac{K_P\left(s + \frac{K_I}{K_P}\right)}{s} = \frac{K_P(s + Z_o)}{s} = \quad (14)$$

$$G_{PI}(s) = K_{PI} * \frac{(T_I s + 1)}{T_I s} = K_{PI} * \left(1 + \frac{1}{T_I s}\right)$$

$$G_{open}(s) = \frac{2K_{tach} * K_t}{2b_{equiv}L_a s^2 + r^2 M L_a s + 2b_{equiv}R_a s + r^2 M R_a s + C_r L_a s + 2J_{equiv}L_a s + 2K_b K_t + C_r R_a + 2J_{equiv}R_a} \quad (15)$$

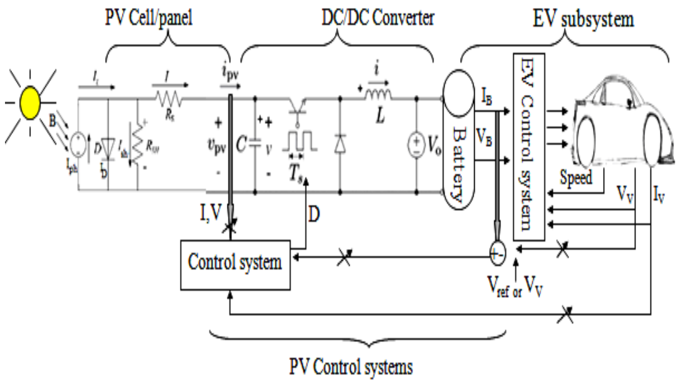

Figure 3 (a) SEV system circuit diagram, main subsystems

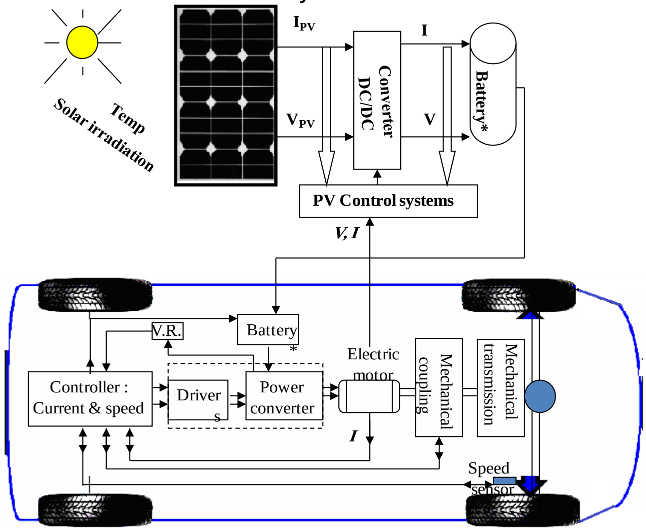

Figure 3 (b) SEV system diagram, main subsystems

Figure 3(a)(b) SEV system diagram and main subsystems, including; PV panel, DC/DC converter, battery bank, DC machine, control units and platform, [44] .

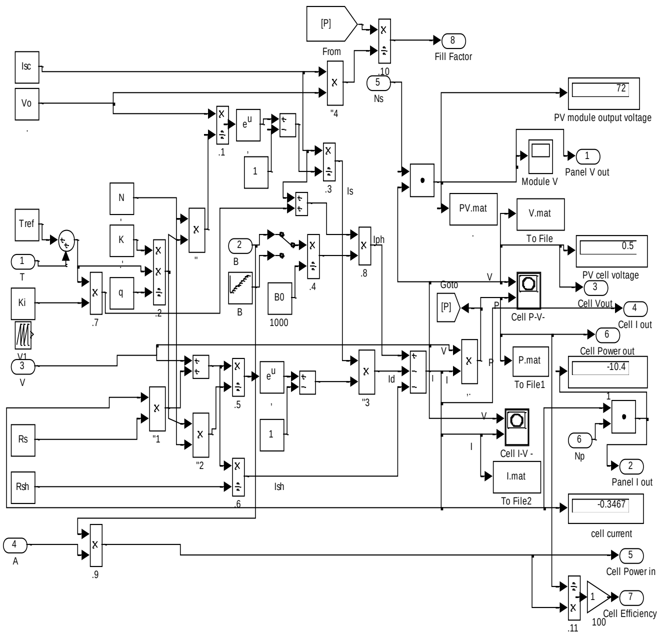

Figure 3(c) PV Panel system simulation sub-model[44]

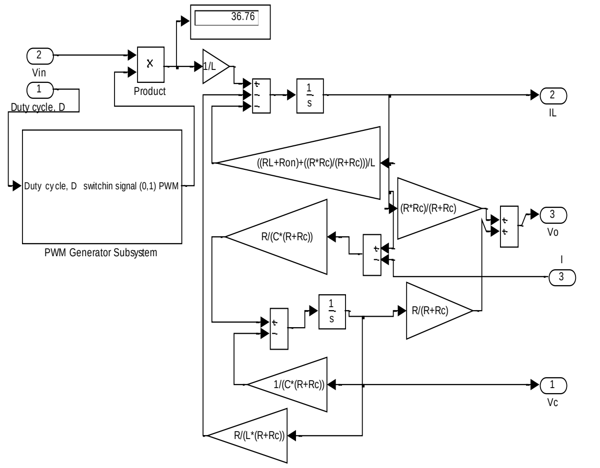

Figure 3(d) Buck converter system simulation sub-model[44]

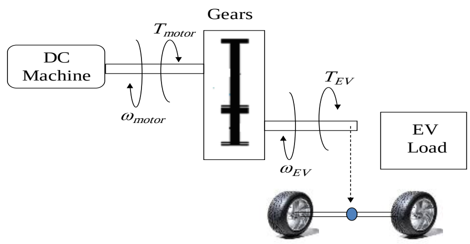

Figure 3(e) EV's Electromechanical structure[44]

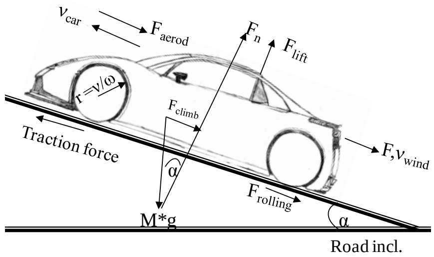

Figure 3(f) Forces acting on a running vehicle[44]

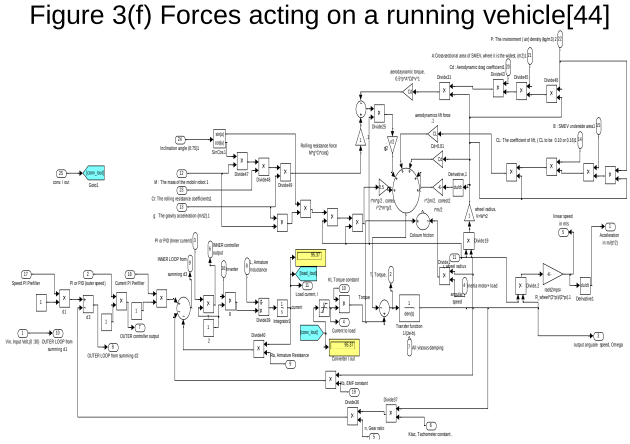

Figure 3(g) integrated DC machine system - dynamic simulation sub-model [44].

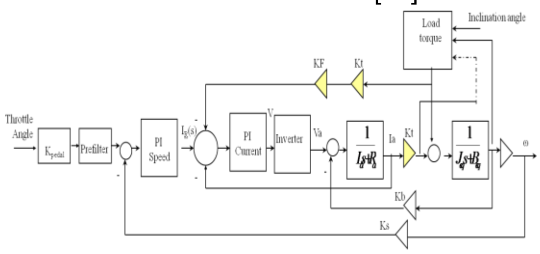

Figure 3(h) unified model of mechanical/actuator/dynamics and control/algorithm subsystems

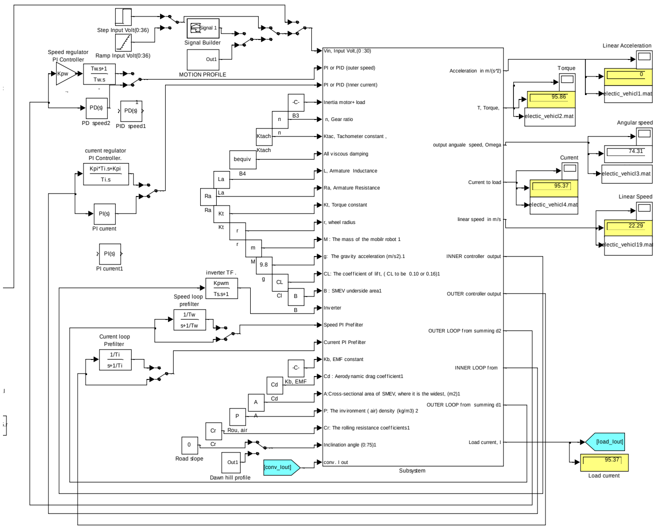

Figure 3(i) DC machine with dynamics and PI,PD controllers subsystems sub-models[44]

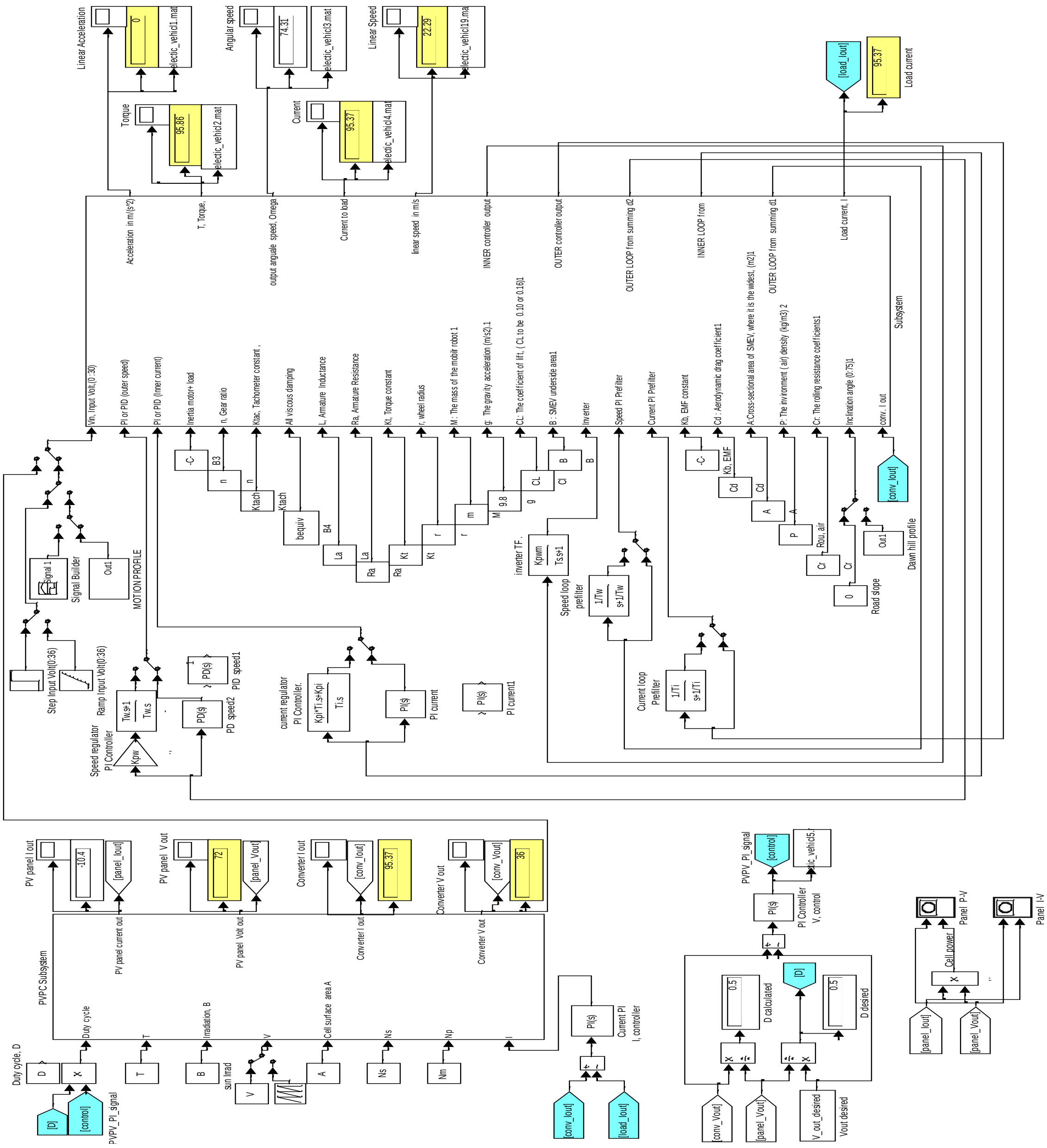

Figure 3(g) Whole SEV system Simulink model[44]

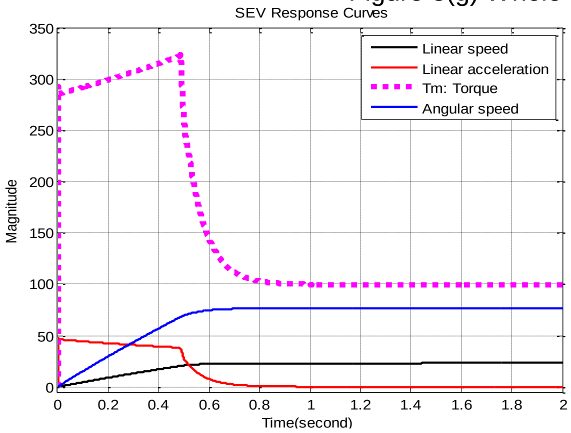

Figure 4(a) Linear speed, acceleration, current and motor torque Response curves of SEV

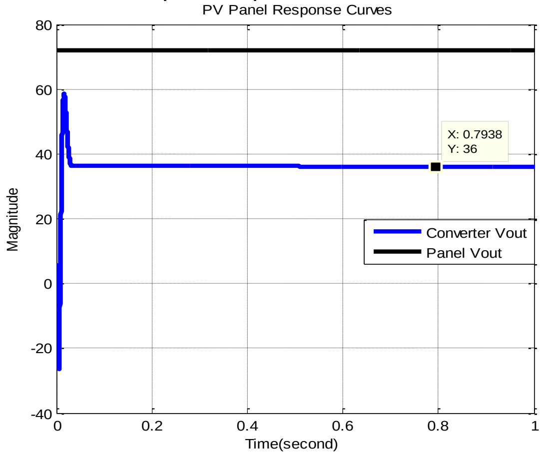

Figure 4(b)

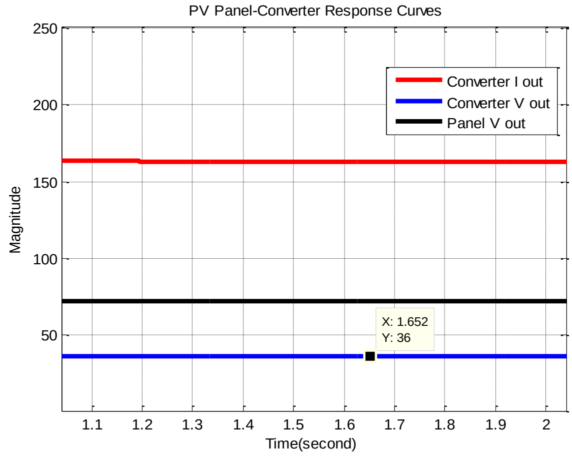

Figure 4(c)

Figure 4(b)(c) generated PV panel's output voltage and Converter's output voltage

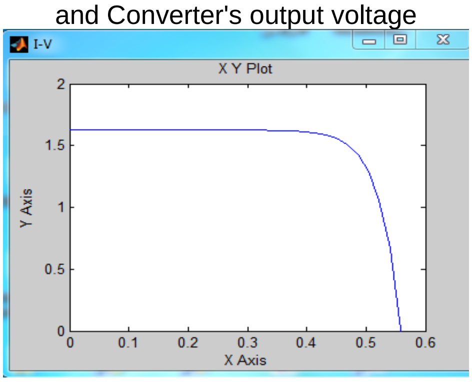

Figure 4(d) V-I Characteristics for β=200, and T=50

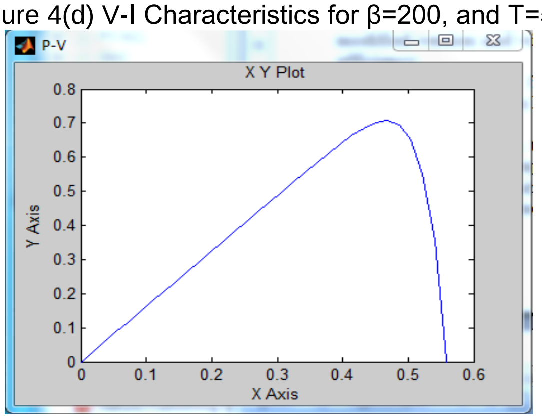

Figure 4(e) P-V Characteristics for β=200, and T=50

III.II Case study: Modeling, Simulation and Evaluation of Smart Guidance System.

In [53], the proposed Mechatronics design education oriented methodology developed in [2] was applied for Mechatronics design of smart guidance system in the form of smart Mechatronics wheelchair, shown in Figure 5(a), intended to help and support people with disabilities and special needs to perform specific predetermined tasks. The system is an application example of line-follower. This system is divided into the following sub-systems; Mechanical, Actuators, sensor, control unit, algorithm, electric and electronics; signals conditioning and interfaces subsystem and Human–machine interaction field, each of these subsystems is selected, modeled, simulated and integrated in whole system. The selected subsystems are control unit -microcontroller, actuator - PMDC motor, Sensors - Ultrasonic proximity sensor, Speed sensor (Tachometer) and LDR-LED based line sensor (Figure 5(b)) to track the predetermined path on ground. In Mechatronics proposed design methodology, selecting sensors and actuators is followed by selecting and integrating of power supplies, drive, and signal processing conditioning circuits, in order to interface the system components (sensor-controller-actuator). ***The drive*** is the link between the controller and actuator, the drive main job is to translate the low energy reference signals from the controller, (e.g. Microcontroller), into high energy power signals to the actuator (e.g. electric motor).

Two software tools (MATLAB/Simulink and ISIS-Professional Proteus) are used to simulate and analyze each subsystem, as well as, overall integrated robotic system. Proteus software is used, to develop ***electronic simulation***. The control program written in C, with the help of MikroC program is converted to Hex. File and downloaded on the simulated PIC-microcontroller and circuit, the *electronic* simulation of LDR-LED based line sensor, driver and whole system are shown in Figure 5(c)(d)(e), using this electronics simulation tool the circuits functionality and compatibility can be tested, also used to evaluate the selection and design of interconnections, signal conditioning, and interfacing circuits.

III.II.I Modeling and simulation of actuator subsystem and dynamics

The selected PMDC motor actuator, is described mathematically similarly as given by Eq.(10), the mobile platform dynamics can be described mathematically as given by Eq.(8), and can be further simplified, considering that, some of acting forces has less effect on overall system, due to the smaller size of mobile wheelchair, in comparison with SEV. **Mechanical simulation (**to test the kinematics and dynamics**)** ***and*** **System simulation** (to test the system's response to different inputs) are similar to those shown in Figure 5(e), as well as, inertias, sensor (tachometer) and controller modeling and simulation. The Overall system mathematical model of wheelchair system without control involved, is given by Eq.(15)

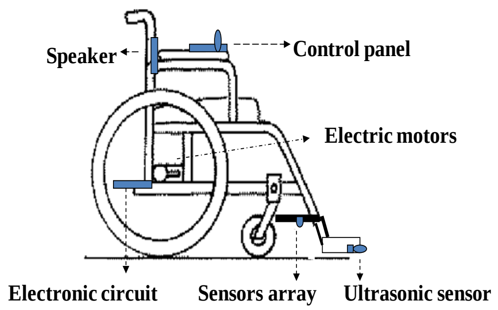

Figure 5(a) system layout side views: Sensors ,actuator and electronics integration-placement [53]

Figure 5(b) LDR- LED cell

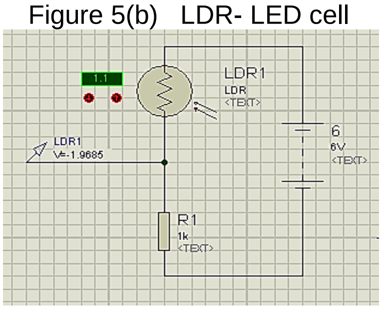

Figure 5(c) LDR-LED based line sensor electronic simulation[53]

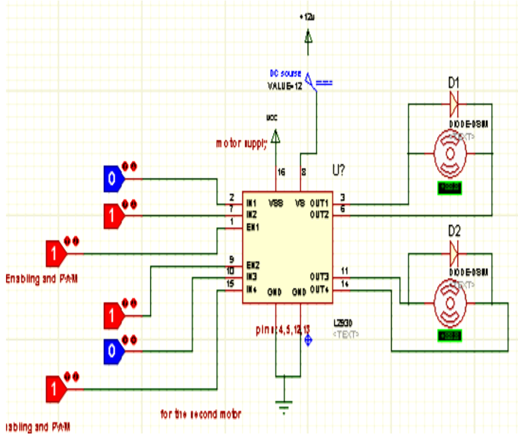

Figure 5(d) Electronic Simulation of controlling DC motor driver IC L293D

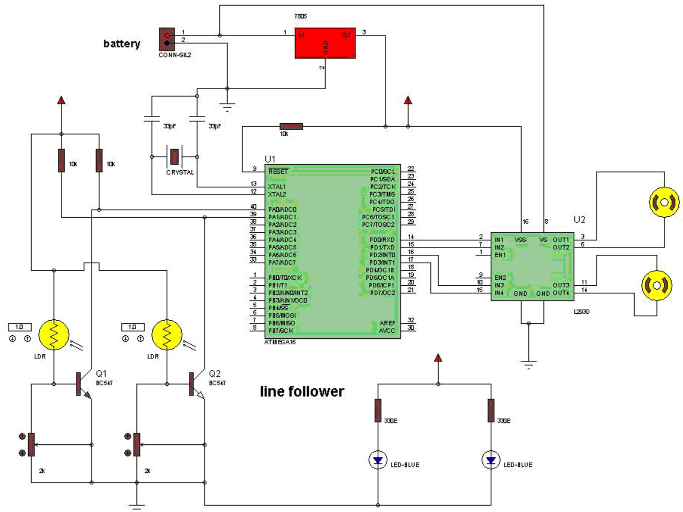

Figure 5(e)Overall system electronic simulations in Proteus

III.III Co-simulation

Co-simulation is to use different communicating solvers, to simulate each sub-system and whole system. One of the main advantages of the co-simulation is that each solver is optimized for its own specific domain. From the software point of view, co-simulation is not only a simulation performed in two or more different physical domains, but it is a simulation in which several softwares run in parallel and continuously exchange data to verify the behavior of each different component of the product under specific working conditions. the main disadvantage of the co-simulation approach is represented by the non trivial effort to synchronize the different solvers, though many simulators may be interfaced[26].

Reference to [26]**,** a case study on Co-simulation is introduced, a mobile elevated working platform with an articulated arm The platform is provided with four driving and steering wheels. A great operational flexibility is guaranteed by four variable-length stabiliser legs. Every leg has 3 DOF, that allow multiple support configurations. The articulated arm, conceived to easily cover a large work volume, has 6 DOF. There are 22 actuators for the movements of the various parts and each of them has a sensor position for the feedback control. Thanks to the co-

simulation results, we were also able to implement a control-logic that allows the dynamic reconfiguration of the support stabilisers, making use of the balance of the whole structure on three of the four contact points with the ground. Interactive co-simulation with the controlled machine is realized by drawing the higher performances through the integration of the ADAMS and MATLAB/Simulink softwares (Figure 6).
The interface (link)between the MATLAB /Simulink environment and the Adams environment is the building block Adams-SubBlock , it is link between the control electronics developed in Simulink and the mechanical system of the machine modeled in Adams. From the Adams point of view, this block receives forces in input and gives the position of the actuators in output. From the MATLAB point of view, the Control Block receives positions in input and returns forces in output. During the co-simulation, all the parts that formed the 3D model are moved according to the simulation results.

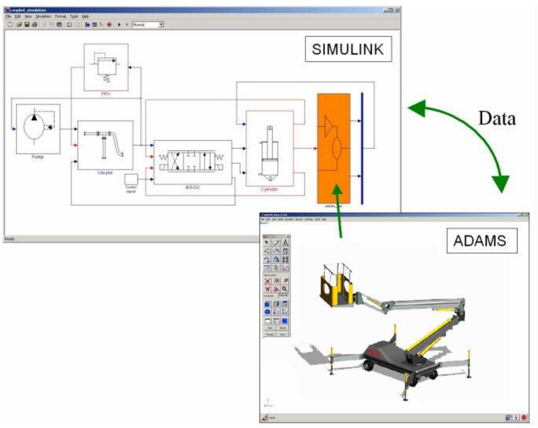

Figure 6 Software integration for co-simulation

III.IV HARDWARE-IN-THE-LOOP SIMULATION (HILS)

In [54], a method for building a *HILS of a hydraulic Antilock Braking System (ABS)* based on MATLAB/Simulink is presented. Figure 7(a) shows the *hardware* and *software* parts used in HIL experiments. The hardware comprises of a brake handle, brake pump, hydraulic servovalves and force sensor. The software comprises the vehicle dynamics, wheel dynamics, and tire model. As the model is used in the context of HIL system, it has to run in real-time on the target. The model is embedded as an S-function into a Simulink model by using Simulink interface block. By this way, the new set of parameters can be passed into the model in the form of an array of double values. The performance of the ABS HIL system signals such as; ABS input, the displacements of the spools, pressures of the master cylinder sides, and its displacement are recorded and illustrated in Figure 7(b). While Figure 7(c) shows the response of ABS and its master cylinder to foot brake push. application examples *on HILS* and discussions can be found in different resources including: [55-58]

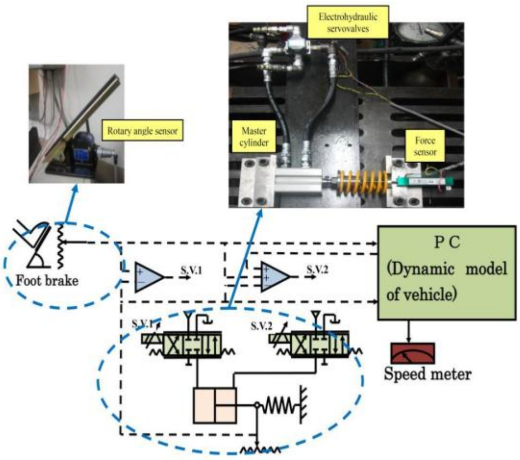

Figure 7(a) Main parts of HIL simulation for the ABS[54]

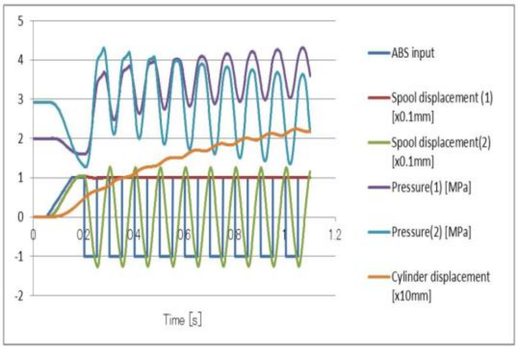

Figure 7(b) The performance of the ABS HIL system[54]

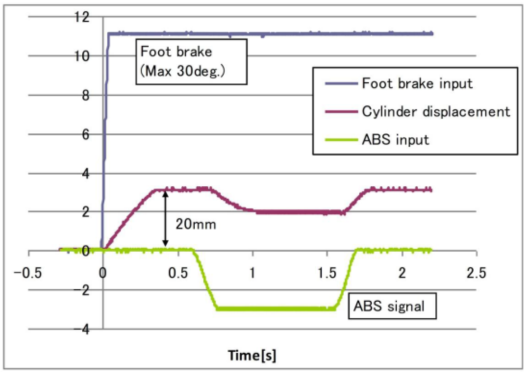

Figure 7(c) the response of ABS and its master cylinder to foot brake push[54]

IV.V TOPOLOGICAL AND PHYSICAL MODELING

In [59] is described the implementation of the VDI 2206 design guideline during the modeling of a mechanism for a medical device which is operated with an electric linear actuator. The topological, physical, mathematical and numerical models are obtained and proposed in order to improve an existing design.
Three topological models *(topological model, describes and reflects interlinks, the function-performing elements, basically the relative position between each component, without considering the physics behind)* were suggested as shown in Figure 8, The main difference among them was the node

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positioning of the linear actuator in reference to the nodes of the mechanic bars that resemble the leg folding mechanism.

After deciding upon a *good* topology (shaded subfigure from Figure 8) a physical model Figure 9, was created in order to understand the type of forces being applied on the main bar of the leg mechanism with the weight of a patient being applied.

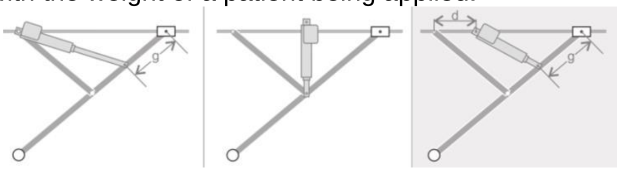

Figure 8: Leg folding mechanism topologies (Three topological models) [59]

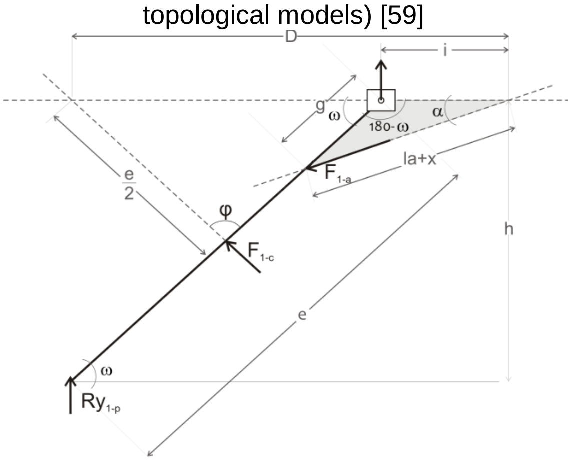

Figure 9 Physical model of leg folding mechanism [59]

3.6. In [60] as a case study, Mechatronics design approach is formulated and discussed in some detail, to design and develop a students' final year Robotic Parking Garage project. Robotic parking is a method of automatically parking and retrieving cars, using a computerized system. Models of Sub-systems and whole system are developed, integrated tested, evaluated and built. In [61] Mechatronics design approach is applied, where three student projects (*Clamp Robot Manipulator*, *Mechatronics Education Kit*, *CNC Machine*) are examined in detail, with descriptions of their goals, design, and implementation.

Conclusion

In order to evaluate such concepts as performance, speed, precision, efficiency, costs, functionality, effects of system nonlinearities, uncertainties and disturbances, without building and testing each one, Modeling, simulation and evaluation, play a critical role and considered highly important during the design stages of a Mechatronic system. In this paper, their main concepts, role, and description are presented and discussed, and by means of examples-projects. A short review of scientific resources on modelling and simulation in Mechatronics are also presented.

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