The Role Of Control System/Algorithm Subsystems In Mechatronics Systems Design

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Abstract— **This paper focuses on control systems and control algorithms subsystems selection, evaluation, design and synergistic integration stage in Mechatronics systems design and development methodology, main concepts, classifications, role, description of main features and selection criteria are presented and discussed. The paper intended to support engineering educators and help students in solving Mechatronics design and development tasks.**

Keywords— Mechatronics design, Control system, Control algorithm, Synergy, Integration.

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. 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[1-2], 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 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], this methodology is developed, based on VDI 2206 guideline and different industrial, scientific and educational resources listed and some discussed in [1], 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.

Mechatronics systems are supposed to be 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, one of important decisions in Mechatronics system design process are, two directly related to each other subsystems; the control unit (physical control-unit) and control algorithm subsystems selection, design and synergistic integration. This paper focuses on control system and control algorithm selection, design and synergistic integration stage in Mechatronics systems design and development methodology. Concepts, classifications, role, description of main features and selection criteria are to be presented and discussed. 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 control system selection, design and integration stage in Mechatronics is presented.

II. MECHATRONICS SYSTEMS DESIGN APPROACH-CONCEPTS AND TERMINOLOGIES.

There are many definitions of Mechatronics, it can be defined as multidisciplinary concept, it is 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. The Mechatronic system design process addresses these challenges, it is a modern interdisciplinary design procedure, it is the concurrent selection, evaluation, synergetic integration, and optimization of the whole 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, through the integration of components (hardware integration) and through the integration by information processing (software integration). 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 [1]. synergy can be generated by the right combination of parameters.

1.3 MECHATRONIC – BASIC APPROACH

Regardless of the type of Mechatronic system, there is a need to understand the fundamental working principles of Mechatronic systems. The general scheme is shown in Figure 2. The basis of many Mechatronic systems is the mechanical subsystem which is a power-producing/generating machine (mechanical aspects/elements, including; mechanical structure, mechanisms, their mechanical properties and parameters, thermo-fluid and hydraulic aspects of a Mechatronics system), which converts or transmits the mechanical process (by actuators). Information on the state of the mechanical process and environment has to be obtained by (using sensor for) measuring generalized flows (e.g. speed, mass flow) or electrical current/potentials (e.g. temperature, speed). Together with the reference variables, the measured variables are the inputs for an information flow, which the digital electronics (Control unit compares them, and

according to control algorithm*)* convert into manipulated variables for the actuators (e.g. motors) to command, control and optimize the physical system ensuring desired excellent steady-state and dynamic performance*,* or for monitored variables to display. The addition and integration of feedback information flow to a feed

forward energy flow in the mechanical system (e.g. motor drive, drainage pump) is one of the characteristics of many Mechatronic systems. Interactions of man and machine have been profoundly enhanced by the development of electronics and IT technologies (e.g. SMS, voice control) and interactions have become more versatile and user-friendly [2-4]**.**

III.   CONTROL UNIT/ALGORITHM SELECTION, DESIGN AND INTEGRATION IN MECHATRONICS DESIGN

II.I Control stage components

During the concurrent 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 control system, 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), modeled and simulated to obtain unified model of both, that will simplify the analysis, prediction of whole system effects, performance, and generally to achieve a better performance, a more flexible system, or just reduce the cost of the system[2].One of most important decisions in Mechatronics design process are, two directly related to each other subsystems; the control unit (physical controller) and control algorithm subsystems selection, design and synergetic integration. As shown in Figure 3, three components can be identified at this level; the control system, control algorithm and the electronic unit subsystems. The physical-controller subsystem, can be structured, basically, around six basic forms (options) of programmable control system: Personal computer (PC), Microcomputer, Microcontroller (Mc), Digital signal processors (DSP), Application specific integrated circuits (ASICs) and Programmable logic controller (PLC)[1]. also, there are a variety of control algorithms exits, including: ON-OFF, PID modes, Feedforward, adaptive, intelligent (Fuzzy logic, Neural network , Expert Systems and Genetic) control algorithms. The key factors that might influence the decision on selecting certain control unit/algorithm include; *a)* Operation (how system will run and how

(vertical left margin text) simultaneous synergistic integration and optimization of the system and all its subsystems as a whole, no after-thought add-ons allowed – Iterate forward and backward to fulfill requirements

1 Pre-Study Process (*The problem statement*) :
(It is the process of understanding what the problem is, its goals and functions, and to state it in clear terms. Done by identification, gathering and analysis as much as possible information about) :

a Target **user**, **market** and **user interests/needs/requirements** identification and analysis; (build user requirements table)
System requirements/specifications identification, definition and analysis; functional, Performance and environmental and non-functional requirements.
Build requirements analysis table; fixed and soft requirements, description and types
Create detailed functional specifications.
Aesthetics: *if pleasing elegant design is required, color, shape, form and texture to be specified*

b The problem statement in clear terms : based on up steps, d*escription of* **what is the problem?** *the* **goal?** *the* **top-level functions**, *and/or state the problem in terms of the* **deficiency** *that must be ameliorated user and system requirements,*

2 Conceptual Design, functional specifications and their structure.
(Consider the system as a whole, building a description of it in terms of an interdisciplinary set of integrated general ideas and concepts, conceptual design is usually evolve from problem statement; user and system requirements)

a Identification, description and analysis of the required system ,what is the system?, it's overall function? , sub-functions?, behavior/performance?, how it looks like?.
Identify system's preliminary necessary structure (e.g. mechanical, electric, control….),
Break down the overall function/system into subfunction/subsystems; what are major subsystems/components? what are subsystem's/components' functions? how components interact ?and how they should be connected?
Built system functional model (function box, Sequence or Hierarchy), depicting the flow of (information, Energy or Material) between the system's components
Generate preliminary decisions about the dominant mechanical properties, (e.g. matrials, sizing, volume, DOF, joints types)

b Morphological analysis; Build Morphological table, suggest solutions for functions, evaluate the best solution.
A preliminary ideas about mechanical, electric problems and the necessary sensors, actuators, interfaces.

c Build preliminarysystem block diagram and layout of main components.

d A preliminary economic analysis;feasibility study , cost-benefit evaluation

3 Parallel (concurrent) selection, evaluation, synergetic integration and optimization of the system and all its sub-systems 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.
Designing system as a whole, serve as methodological basis for Mechatronic Systems development

a Divided the system into realizable modules (subsystems).

b Parallel (concurrent) optimal selection, evaluation, synergetic integration and optimization of the system and all its modules-sub-systems and all components as a whole and concurrently throughout the design and development process, with respect to the realization of the design specifications and requirements

Mechanical sub-system; the design of all mechanical aspects in full details to meet the requirements; *structure Eements, Mechanisms, Dimensions, Materials, Properties, Parameters …(CAD/CAM tools ….)*

Control unit sub-system | Control algorithm and design | Sensors subsystem | Actuators subsystem

Human—machine interaction field | Electric & Electronics; Interconnections, signal conditioning, interfacing.

Develop system's complete and detailed block diagram layout

c **Synergy** can be generated by the right *combination /selection of proper parameters* that is, the final product can be better than just the sum of its parts.

d **Integration** refers to combining disparate data or systems so they work as one system. The integration can be performed in two kinds: **The integration of components** (hardware integration), *results from designing the mechatronics system as an* **overall system and embedding** (placement) *the sensors, actuators, and microcomputers into the mechanical process.* The integration by **information processing** (software integration) *is based on advanced control function*

4 Modeling, simulation ,analysis and evaluating:
The main goal; early identifying system level problems (to verify main and sub-functions and to test and analyze sub-systems and the whole system model), and ensuring that all design requirements are met (satisfied)

a **Modeling process ;** Verifying sub-functions and testing sub-systems, consists of two levels:
Subsystems models; in open and closed loop
Overall system model; the verified sub-functions and tested sub-systems are integrated in one overall system model interacting similar to real situation is checked

b **Two types of modeling process ; Analytical modeling;** Represent the sub-systems and whole system using *mathematical* equations suitable for computer simulation (e.g. MATLAB, Labviev). **Physical (Experimental) modeling;** based on obtained measurements from the system

c **Simulation process ;** is used to decide on the design specifications of the mechatronic system in terms of specification of requirements. simulation divided into three parts: **Mechanical simulation**; To test the kinematics and dynamics variables. **System simulation**; To test the system's response to different inputs in both open and closed loop. **Electronic simulation**; To test circuits functionality and compatibility

5 Prototyping, testing, evaluation and optimization
To take into account the unmodeled errors and enhance precision, performance and gather early user feedback

a Prototype development may be carried out in the following two forms
Virtual Prototype: 2-3D model of a product presented in a virtual (PC) environment with, *ideally*, all information and properties included, used to examine, manipulate, and test the form, fit, motion, logistics, and human factors of conceptual designs on a computer monitor,
Physical Prototype: system integration to ensure that subsystems, components and whole system work together under operating condition

6 Manufacturing and Commercialization | **7 Support, Service and Market feedback Analysis**

Figure 1 Systematic guideline steps for Mechatronics systems design education-oriented methodology.
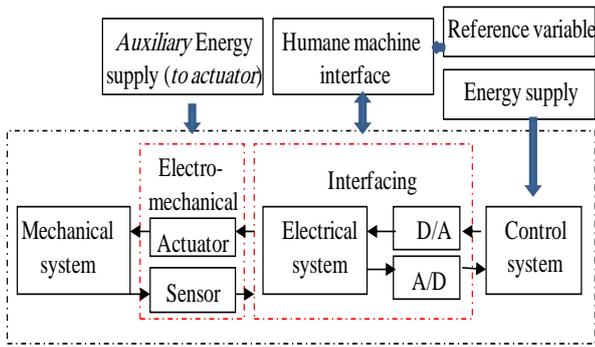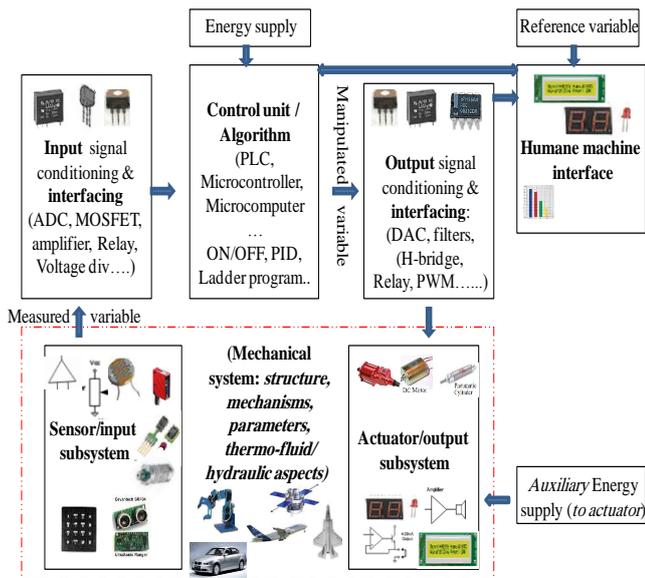
Figure 2(a)

Figure 2(b)

Figure 2(a)(b) Working principle and main subsystems of Mechatronic products

tasks/ instructions are processed), *b)* Robustness/environment (e.g. industrial, soft..), *c)* Serviceability (availability of replacement components and ease of repair/ replacement over controller life), *d)* Security (e.g. viruses), *e)* programming: Both programming environment (how control executes program) and language (e.g. C++) affect machine development time and operation *f)* unit cost, cost of final product, precision, required time to market*, g)* size-space saving, *h)* integration, *i)* processing power, also, safety criticality of the application, and number of products to be produced [1][6].

In Mechatronics system design, the selection of control unit, control algorithm, sensors and actuators is followed by selecting and integrating the electronic unit subsystem; in particular, Interconnection, signal conditioning, and interfacing e.g. power supplies, drives circuits, signal processing-conditioning circuits and data acquisition systems. As shown in Figure 4 these are selected to interface the whole system components and match components specifications and ratings in and to optimize the system performance. Since most measurement and control apparatus are of an analog nature, while control units are digital, to enable the control unit to communicate with the outside analog world, interface hardware

allows analog/digital interfacing, communication of sensor signal to control unit and communication of control signal from the control unit to the actuator.. The electronic unit has to adjust the control signals output by the control unit and by the sensor subsystem to the level required by the actuator subsystem, in order to be useful to the control unit. Sometimes, this unit can fulfill additional tasks: system protection, display and setting of some functional parameters etc. The electronic unit can contain: *a)* basic electronic components: resistors, potentiometers, condensers, rectifier diodes, stabilizers, transistors etc. *b)* linear integrated circuits based on operational amplifiers: ramp generators, step generators, adders, PID regulators, Dither generators, current generators, oscillators, demodulators etc. *c)* supply units; A/D and D/A convertors[7].
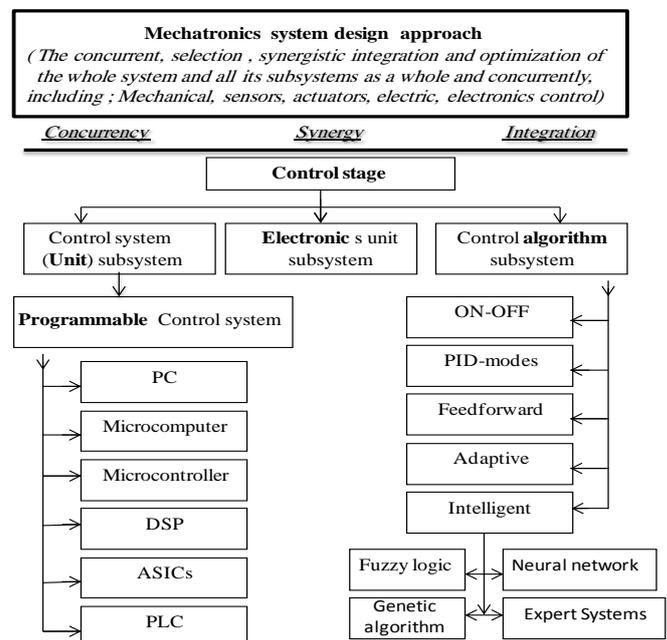

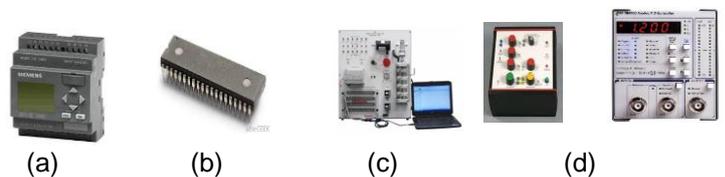Figure 3a components at control stage; Control system/ algorithm electronic unit subsystems.

(a)   (b)   (c)   (d)

Figure 3(b) (Physical) controller options; *a)* PLC, *b)*Microcontroller, *c)* Computer control, *d)* Analog controllers.
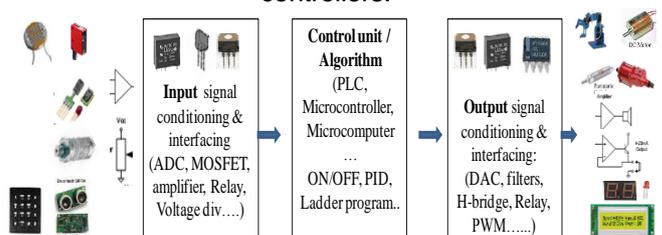

Figure 4 Interconnection, signal conditioning, and interfacing.

II.II Control system strategies/algorithms selection and design

There are many control strategies that may be more or less appropriate to a specific type of application, each has its advantages and disadvantages; the designer must select the best one for specific application [8-10]. Engineering practice usually dictates that one chooses the simplest controller that meets all the design specifications. In most cases, the more complex a controller is, the more it costs, the less reliable it is, and the more difficult it is to design. Choosing a specific controller for a specific application is often based on the designer's past experience and sometimes intuition, and it entails as much *art* as it does science [10] the choice of the controller type is an integral part of the overall controller design, taking into account selection factors, and in particular, with final aim to obtain the best *cost/benefit ratio* and therefore the simplest controller capable to obtain a satisfactory performance should be preferred [11]. Based on up mentioned, and on particular Mechatronics system purpose, destination, desired performance, precision, efficiency, costs, functionality and complexity, the control unit and algorithm are selected and designed.

The terms control system design can be referred to any of the following three forms; *a)* writing corresponding control program/algorithm (e.g. for PLC, CNC or Microcontroller) to control the process, or *b) Developing* a knowledge base, Inference mechanisms and communication interfaces for intellegent control or, *c)* The process of selecting feedback gains (poles and zeros) that meet design specifications in a closed-loop control system. Most design methods are iterative, combining parameter selection with analysis, simulation, and insight into the dynamics of the plant [11-12]. Different control system design approaches are available and can be applied to design and test the selected control algorithm [1]. In [13-14] is presented simple and user friendly controllers and design guide that illustrates the basics of controllers and control algorithms, their elements, effects, selection and design procedures.

III. Control system-units classification and description of main features

Automatic control applications are particularly well suited to take advantage of microcontroller/ microprocessor technology. Microprocessor-based control systems are rapidly replacing many older control systems based on analog circuits or electromechanical relays. One of the first microprocessor-based controllers made specifically for control applications was the programmable logic controller (PLC) [15]. As noted, the physical-controller subsystem, can be structured, basically, around six basic forms of programmable control system, those basically are computers which have four basic operational parts depicted in Figure 5(a); Central processing unit (CPU), Programmable memory, and

I/O peripherals. All computers have a means of getting input, a means of generating output, a means of controlling the *flow* of signals and operations, memory for data storage, and an arithmetic logic unit (ALU) which executes the instructions. The ALU and control elements are often called the central processing unit (CPU). Small computers, which just contain a CPU, are often called *microprocessors* (Figure 5(b)). Memory for these computers is often attached to the microprocessor but in distinct electronic packages. Input and output to the microprocessor is often handled by electronics called peripherals. If the memory is included in the same package, the computer is called either a *microcomputer or computer* depending on its physical size. CPU and memory on a single electronics chip is often called a *microcomputer* [16].
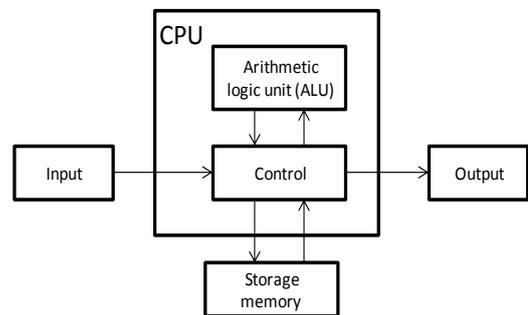

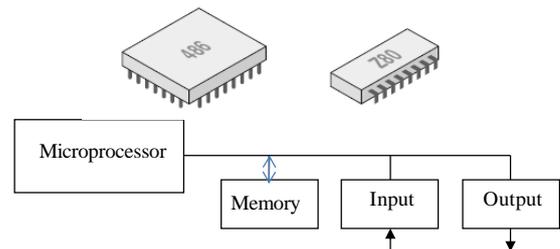Figure 5(a) Main elements of a computer.

Figure 5(b) Microprocessor and Microcontroller [15]

III.I Variables, Processes and Controls.

There are two basic types of variables (and parameters) that characterize (*production*) operations; continuous and discrete variables. Corresponding to these two types, there are two basic types of *production* processes; continuous and discrete, corresponding to this, there are two basic types of industrial control; continuous and discrete control systems. Continuous control is used to control the continuous variables in continues processes in processes industries (e.g. an oven temperature). Continuous controllers automatically and continuously measure and compare the value of controlled variables to the reference set-point to determine if an error exists, and take corresponding actions to alter the processes. Discrete control is used widely in both discrete manufacturing, as well as, in the process industries. Consequently many industrial controllers are designed with the capability to receive, operate on, and transmit both types of signals and data (continuous and discrete). The mentioned

categorization is depicted in Figure 12(a). Discrete control system executes their actions to change and alter the processes in the following two cases: *a)* When *discrete-state* of the controlled process has changed, or *b)* when a certain a mount of *time* has elapsed. According to these changes, we can distinguish two types of processes: *a)* Discrete event – driven processes, and *b)* Time-driven-process. Also, we can distinguish two types, executed by controller, changes to alter the process : *a)* Discrete event–driven executed changes: the controller execute the next step in the program to act on the processes , in response to the *occurrence* of some discrete processes *event,* that change the state of the system, and *b)* Time-driven executed changes: The execution of control changes occur, when a certain a mount of *time* has elapsed or at a specific point in time. Corresponding to this, we can distinguish two types of discrete control: *a)* Combinational logic control (*or logic control*)*,* and *b)* Sequential control. Logic control and sequencing are referred as switching systems in the sense that they switch their output vales *ON* and *OFF* in response in changes in *events or time*, whose output values at any time are, exclusively, determined from the *present* combination of inputs. The basic elements of combinational logic control are the logic gates (e.g. AND, OR, NOT , NOR, NAND) and the use of ladder logic and Boolean algebra. Meanwhile, sequential control, controls a process that is defined as a series-sequence of *time/event-driven* operations of tasks to be performed, one after the other and the controller execute the next step in the program to act on the processes , in response to the *occurrence* of some discrete processes *event, th*at change the state of the system. Examples of discrete processes: Manufacturing lines, elevators, traffic systems, Conveyors and other material transport system, automated storage system, stand-alone production machines, all these processes operate by following a defined sequence of performed operations (start and stop actions, on and off) [15].

Control loops (Sensor-Controller-Actuator) can be divided into two categories: *a)* Single variable single-loop control, *b)* Multivariable multi-loop control. In practical control problems, there are a number of process variables which must be controlled and a number of variables which can be manipulated. Multivariable multi-loop control loop :are control loops in which a primary controller controls one process variable by sending signals to a controller of different loop that impacts the process variable of the primary loop. The common terms used for single loop control include: *a) feedback control* loop*, b) Feedforward control* loop. Meanwhile, *key* terms of multiple control loops include; *a)* Feedback plus Feedforward*, b)* Cascade control, *c)* Ratio control, *d)* override controls.

III.II (Embedded) Microcontroller based control subsystem

Microcontroller is inexpensive single chip computer designed using *all-in-one* technology (it is a computer with all its main components on a single chip; processor, programmable memory and I/O peripherals). Another term used for microcontrollers is *embedded* controller, since most of the microcontrollers are built into (embedded in) the devices they control.

Features of microcontroller are similar to those of a standard personal computer; it is capable of uploading, storing and running programs, programmed and re-programmed to perform/fulfill a wide range of complex tasks involving real-time data acquisition, monitoring and control. Because of their versatility, it adds a lot of power, control, and options at little cost. Microcontroller meets such selection requirements as; operation, serviceability, programming (both environment and language), small space-saving size result in easy to embed/integrate into larger electronic circuit designs, low processing power, low unit cost and cost of final product, therefore, Microcontroller is considered an optimal selection decision, for Mechatronics systems and an efficient low cost solution for the control of a Mechatronic system[17], and is used in a wide variety of applications including home appliances, medical equipment, telecommunication equipment, automobiles, trucks, airplanes, entertainment equipment, toys, and office equipment [18]. The advantages of microcontroller become obvious for certain Mechatronic applications with slow movement but requiring higher precision [19] at low cost. Microcontroller is programmed by first typing the program (control algorithm) into a suitable PC software environment (e.g. C+), fully checked for correct operation, compiled to machine code, loaded into program memory by programmer through the serial port.

III.III Digital Signal Processor (DSP),

Digital signal processors (DSP) are specialized form of embedded microprocessors for the purpose of *real-time digital signal computing*, with some on-chip peripherals but with external ADC/DAC, which represent the most important input/output channel. DSPs have advanced architectures; integrated multiplexer/accumulator, multiple buses, parallel computing/processing, fast sampling rate, a fixed point or floating point instruction set optimized for typical signal processing operations such as discrete transformations, filtering, convolution, and coding all for the purpose of real-time digital signal computing.

DSP is an optimal control selection decision and preferred over microcontrollers, for application requiring real-time DSP computing constrains (implement complex and iterative algorithms and perform computationally efficient and fast algorithms), like sound processing/generation, sensor (e.g., Vibration) signal analysis telecommunications (e.g., bandpass filter and digital modulation/demodulation in mobile phones, communication transceivers, modems), missile control and vector control of AC motors. [16] [20-22].

III.IV APPLICATION SPECIFIC INTEGRATED CIRCUITS (ASICs)

Are custom made devices to perform a specific application/operation such as a PID algorithm, run a cell phone, control the functions of the vehicle. ASICs can contain a CPU or memory or peripheral functions or even a MAC cell as part of its makeup [16].

ASIC is an optimal selection decision, for Mechatronics systems designer who wish to define the function of his own integrated circuit. The major incentive to design an ASIC for an application is its impact on the overall cost, size and performance of a system, many functions can be integrated into single devices, and therefore, the number of components and size circuit board can be reduced [23].

III.V COMPUTER BASED CONTROL SUBSYSTEM

In Mechatronic systems, computers play a variety of roles; they model, analyze, and simulate Mechatronic systems and components and are useful for control design. As part of measurement systems, they are used to measure the performance of Mechatronic systems, to determine the value of component parameters, and to validate models experimentally. Finally, they form the central component in digital control systems for Mechatronic designs. Because most Mechatronic systems are analog (the sensor and the final control element are analog devices), it must have both ADC and DAC converters, which serve as translators that let the computer communicate with the outside analog world[24]. Personal computer based control subsystem is not suitable for a large number of Mechatronics products and is limited by the high costs and size involved. Advantages include superior signals processing, graphical capabilities, and software flexibility.

Personal computer based control subsystem, are an optimal selection decision, for Mechatronics systems in the case of very complex applications, and when extensive signal processing and in-depth analysis is required, also in research activities, in laboratory conditions, e.g. when an experimental model has to be tested. PC can be made suitable for industrial environment (discussed in 3.6 PLC), some models of these computers are rack-mountable and contain their own battery-backup power supply.

There are two basic *requirements* that must be placed on the computer (and managed by controller) to achieve real-time control requirements: *a)* Process-initiated interrupts; to respond to incoming signals from the process, *b)* Timer-initiated actions: to executing certain actions at specific points in time. These two basic requirements correspond to the two types of changes in discrete control, *a)* Event-driven changes, *b)* Time-driven changes. In addition to these two basic requirements, the control computer must also deal with other types of *interruptions and events*, these include: *a)* Computer command to process actuators (able to send control signals to the process to accomplish a corrective action), *b)* System-and program-initiated events: such as the printing or display of reports on a printer or monitor, *c)* operator-initiated events: entering new programs, editing existing program, entering customer data, order or number, or startup instructions for the next production run, Emergency stop.

If the control system is configured around a PC, one of the following versions can be chosen: *a)* Computer-Aided Data Acquisition consisting of; PC , data acquisition board (DAC) and software. *b)* PC, I/O modules and software, an example temperature, computer based control system, of an eclectic furnace, is shown in Figure 6, the temperature in electric furnace is measured by analog thermometer, the analog temperature is converted to digital temperature by ADC converter, the digital temperature is fed to controller (Computer) through an interface, this digital temperature is compared with the programmed input temperature, and if there is an error, the controller, according to written control algorithm program, sends out control signal to control the actuator (Heater) , through an interface, amplifier, and relay, to bring the furnace temperature to desired value[25].

A *generation* refers to the state of improvement in the development of a product. This term is also used in the different advancements of computer technology, with each new generation, the circuitry has gotten smaller and more advanced than the previous generation before it. As a result of the miniaturization, speed, power and memory of computers. The development of the computer, and then the microcomputer, led to embedded computers/ Microcomputers. Microcomputers can be integrated with the actuator/sensors, this integration lead to smart sensors and smart actuators. Embedded microcomputers are hidden in products such as machines, vehicles, measuring instruments, telecommunication devices, home appliances, consumer electronic products (cameras, hi-fi systems, televisions, video recorders, mobile phones, music instruments, toys, air-conditioning). They are connected with sensors, user interfaces (buttons and displays), and actuators[1][26].
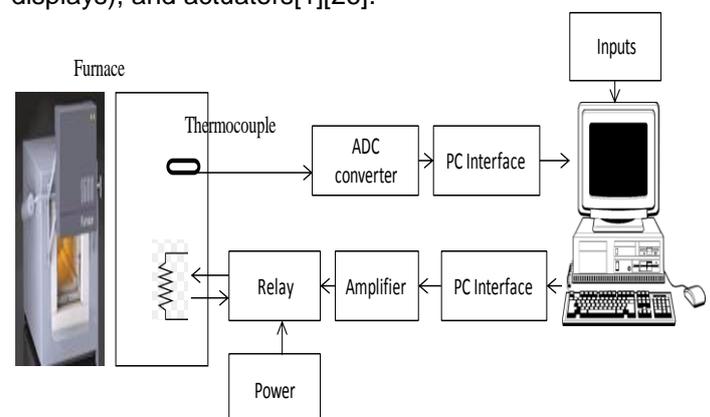

Figure 6 an example of temperature, computer based control system, of an eclectic furnace [25].

III.VI PROGRAMMABLE LOGIC CONTROLLER (PLC), BASED CONTROL SUBSYSTEM.

PLC is form of programmable automation*, it* can be defined as a *micro*computer based controller that use control program instructions stored on its programmable memory to implement logic, sequencing, timing, counting and arithmetic functions through digital or analog input/output devices, it purpose to sense, activate and control industrial equipments, machine and process, and to operate in an unfriendly industrial environment. Therefore, PLC is an optimal efficient selection decision, for controlling industrial Mechatronics systems. *Advantages of PLC include:* designed for hursh industrial environment, programming is very user friendly (using ladder diagrams, instructions or function blocks), can be programmed to carry out arithmetic operations and control tasks e.g PID control algorithm, be re-programmed, can be connected to computer system-network, or with human interfaces, low price (PLC prices going down), size shrinking, and performance of PLCs improving over the years, have integrated diagnostics, can display process state, signal failures and override functions, applications can be immediately documented.

Differences between computer and PLC, include :*a)* PLC has the advantage of being designed for the harsh environment of factory, while PC was designed for office environment. *b)* PLC with its built-in input and output interface could be readily connected to external equipments, whereas the PC requires special input and output cards to enable such connections. *c)* In PLC, there is much more proprietarily software and architecture than in PC. *d)*Advances had mad PC speeds doubling every 18 months which is much more rapidly than PLC technology. PC can be made suitable for industrial environment, where numerous manufacturers are selling rugged PCs that can survive in harsh industrial environments: *a)* PC can be equipped with membrane-type key-boards for protection against factory moisture, oil, and dirt.. *b)* PC can be ordered (customised) to come with have sealed cases and filters covering the air vents, also, with input and output cards and related hardware, to provide the necessary devices to connect the industrial equipment's and processes[15].

III.VII DIGITAL COMMUNICATIONS

Intercommunication among Mechatronics subsystems plays a key role in their engagement of applications, both of fixed and flexible configurations. Digital communication depends on the designer's demands for the amount of transferred data, the distance between the systems, and the requirements on the degree of data reliability and security. The signal is represented by alterations of amplitude, frequency, or phase. This is accomplished by changes in voltage/current in metallic wires or by electromagnetic waves, both in radio-transmission and infrared optical transmission [16][22]

IV. CONTROL ALGORITHMS; ROLE AND DESCRIPTION OF MAIN FEATURES

Different types of control algorithms are available for Mechatronics system control, including; ON-OFF, PID modes, Feedforward, adaptive, intelligent (Fuzzy logic, Neural network , Expert Systems and Genetic) control algorithms [1].

IV.I ON-OFF CONTROL ALGORITHM

Also called Discrete (or bang-bang) controller, it is the simplest of all control algorithms and are ones that, in response to input error, have only two output modes (positions); fully OFF or fully ON (a third output may be; No change). It requires actuators (final control elements) that have two corresponding command positions: on/off (open-closed). The main purpose, of this algorithm, is to keep a given physical variable within certain limits or to change it according to a predetermined program. Home heating thermostat is an ideal example of mechanical on/off controller.

Advantages of ON-OFF control algorithm include; *a)* simple, requires basic types of instruments/components, *b)* easy to troubleshoot, *d)* low cost. Disadvantages include; *a)* no fixed operating, the controlled process oscillates, because control doesn't hold the variable at setpoint, but keeps the variable within proximity of setpoint, *b)* excessive wear of final control element, since it is always opening and closing.

ON-OFF control algorithm is optimal selection decision, for slow acting operations not requiring high accuracy; such as industrial automation applications, refrigeration unit, home water heater, and applications like smart home, microwave, washing machine.

IV.II PROPORTIONAL-INTEGRAL-DERIVATIVE (PID) CONTROL ALGORITHM MODES.

PID control algorithm is combinations of three control algorithms; Proportional (P), Integral (I), and Derivative (D) algorithms. The modes of PID control algorithm are combination of these thee algorithms: P-, PI- ,PD-, PID -, lag, lead or lag-lead algorithm, where the last three are soft approximation, PI,PD and PID modes respectively. The input to PID algorithms is the error between actual and setpoint values, if there is an error, the controller adjusts its output according to P-, I-, or D- parameters (gains) that have to be set in the algorithm, where, as noted, the term control system design refers to the process of selecting feedback algorithm parameters (gains) that meet desired design specifications in a closed-loop control system.

Role/effect of each tuning parameter (gain) on system's response, include: *a)* P-algorithm; is proportional to error, it is the simplest and determines how much correction should be made, speeds up response and reduces, but never eliminates steady state error. *b)* I-algorithm; integrates error and determines how long should the correction be applied, slows the response times and reduce/eliminates

steady-state error. *d)* D-algorithm; differentiates error and determines how fast should the correction be applied, acts only in the transient response, speeds up response and reduces overshoot. In [13-14] is presented simple and user friendly controllers and design guide that illustrates the basics of controllers and control algorithms, their elements, effects, selection and design procedures. the following simplified guide for PID control algorithm selection, can be suggested; *(1)* for processes that can operate with continuous cycling, the relatively inexpensive two position controller is adequate.*(2)* For processes that cannot tolerate continuous cycling, a P-controller is often employed. *(3)* For processes that can tolerate neither continuous cycling nor offset error, a PI controller can be used. *(4)* For processes that need improved stability and can tolerate an offset error, a PD-controller is employed. *(5)* However, there are some processes that cannot tolerate offset error, yet need good stability, the logical solution is to use a control mode that combines the advantages of the three controllers' action [13][27]

PID algorithms provides an optimal solution to both reference tracking and disturbances rejection, also, due to it's simplicity, ease of design, moderate cost, PID control algorithms are an essential part of the control loop of many applications in manufacturing industries and process industries.

IV.II.1 CONTROL SYSTEM CONFIGURATIONS SELECTION

Most of the conventional selection and design methods in control systems rely on the so-called *fixed-configuration design* in that the designer at the outset decides the basic configuration of the overall designed system and decides *where the controller is to be positioned relative to the controlled process?.* The five commonly used system configurations with controller compensation, are (see Figure 7) *(1)Series (cascade) compensation*; it is the most common control system topology, were the controller placed in series with the controlled process(plant)*,* with cascade compensation the error signal is found, and the control signal is developed entirely from the error signal. *(2)Feedback compensation,* the controller is placed in the minor inner feedback path in parallel with the controlled process. *(3) State-feedback compensation* the system generates the control signal by feeding back the state variables through constant real gains. *(4)Series-feedback compensation* a series controller and a feedback controller are used *(5) Feedforward compensation:* the controller is placed in series with the closed-loop system, which has a controller in the forward path the Feedforward controller is placed in parallel with the forward path[13]
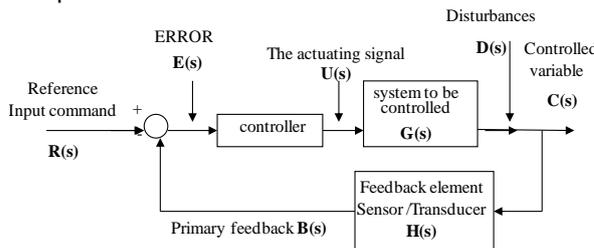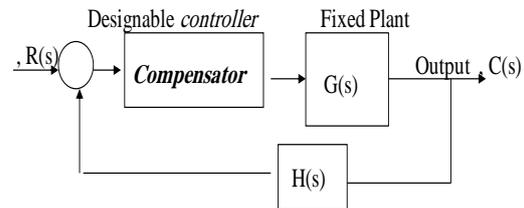

Figure 1 (a)

Figure 1 (b)
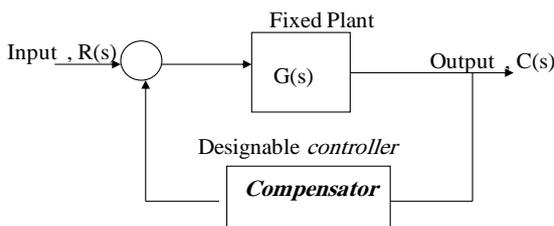
Figure 7(a) series or cascade compensation and Components
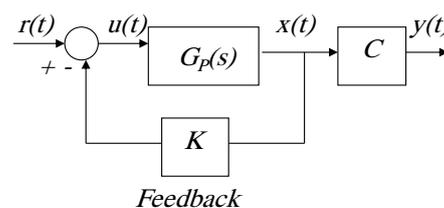

Figure7(c) Feedback compensation
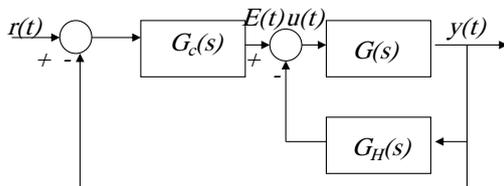

Figure 7(d) State feedback

Figure 7(e) Series-Feedback compensation (2DOF)
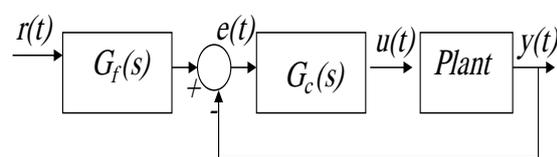

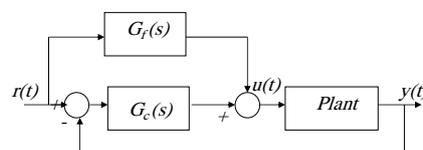Figure 7(f) forward with series compensations

Figure 7(f) Forward compensations

IV.III FEEDFORWARD (FEEDFORWARD/ FEEDBACK) CONTROL ALGORITHM.

The main disadvantage of feedback control loop, is that the controlled variable must leave setpoint, (an error must occur) for control action to be taken to return the controlled variable to desired setpoint, that is the disturbance must propagate through the entire process, before the feedback control can initiate action or compensation[28]. Feedforward control algorithm, addresses this weakness, it compensates for measured disturbances, it monitors (predicts and measures) all factors (important disturbance variables) influencing a process, as it enters the process, decides how to compensate for these factors and takes corrective action (how quickly and directly to cancel out the effect of a disturbance) a head of time before factors effect the controlled process. Therefore, the error is prevented, rather than correct.
Because of the difficulty of accounting (and anticipating) for every disturbance factor influencing a process and to decide how to compensate for each factor a head, Feedforward are often combined with feedback algorithm(shown in Figure 8), where a feedback algorithm is required to track setpoint changes and to reject the effect of unmeasured disturbances upon the controlled variables. Feedforward algorithm is optimal selection decision when the system stability and disturbance rejection are crucial, and only a small error is allowed.
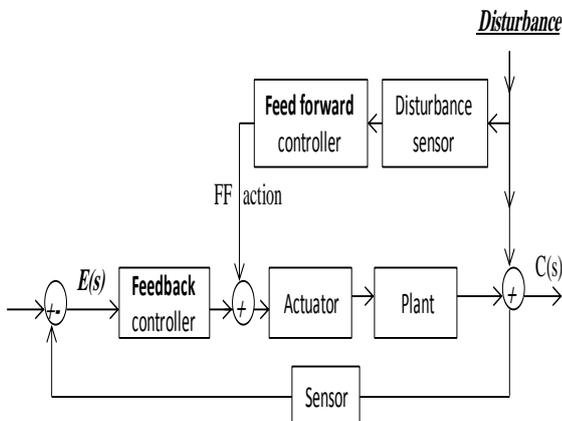

Figure 8 Block diagram of Feedforward-feedback control algorithm

IV.IV ADAPTIVE CONTROL ALGORITHM

To "adapt" means to change a behavior to conform to new circumstances[29]. An adaptive controller is a controller that can modify its behavior in response to changes in the dynamics of the process and the character of the disturbances. Adaptive control algorithm covers a set of techniques which provide a systematic approach for automatic adjustment of controllers in real time, in order to achieve or to maintain a desired level of control system performance when the parameters of the plant dynamic model are unknown and/or change in time.

As shown in Figure 9, Adaptive control systems consist of two loops; an ordinary feedback loop and a second loop which adjusts parameters of the feedback loop. The parameter adjustment loop comprises two main modular elements. One module performs operations to estimate the parameters of the model governing the plant process. Based on this knowledge, the second module computes the value of control parameters for the regulator. Both parameter estimation and control adaptation can be done in many different ways. Recursive least-squares estimation is one of the most commonly used estimation technique [6]. Different adaptive control algorithms exist, including feedback adaptive and Feedforward adaptive. Adaptive control algorithm is optimal selection decision for dynamic systems operating in unstable environments, ranging from aircraft to medical robots.
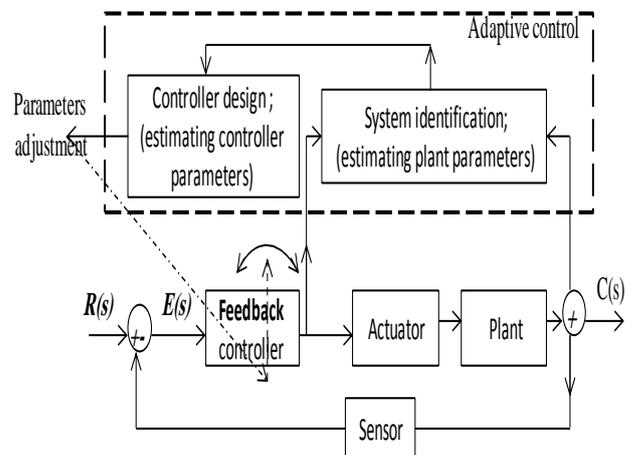

Figure 9 Adaptive control algorithm

IV.V INTELLIGENT CONTROL ALGORITHMS

The fact is that there are problems of control which cannot be formulated and studied in the conventional differential/difference equation mathematical framework. To address these problems in a systematic way, a number of methods have been developed that are collectively known as intelligent control methodologies [30]. Intelligent control algorithms include, but not limited to; Fuzzy logic, Neural network, Expert Systems, Genetic, Bayesian and Neuro- Fuzzy algorithms.
Various definitions of intelligent control systems do exist, can be found in [31-33]. Intelligent control algorithms can be defined as: a class of control algorithm techniques offer alternatives to conventional approaches, by the use of various artificial intelligent (AI) computing approaches to develop systems that display aspects of intelligent behavior and designed to imitate the human capabilities of thinking, sensing and decision-making. An intelligent system can be built up, with the ability "to model, reason and learn the process and its automatic functions within a given frame and to govern it towards a certain goal".
Intelligent control comprises: *a)* multi-control (executive) functions, *b)* a knowledge base ; contains

quantitative and qualitative knowledge, *c)* Inference mechanisms; draws conclusions either by quantitative reasoning (e.g., Boolean methods) or by qualitative reasoning (e.g., possibilistic methods) and takes decisions for the executive functions, *d)* and communication interfaces [34].

Intelligent control algorithm is optimal selection decision, when understanding of the plant or its internal dynamics are unknown, (no accurate plant's model or plant is too complex to be modeled) , also for plants with uncertain and varying operational conditions and environment, to result in improved efficiency, effectiveness and performance, disadvantages of intelligent control algorithms include; In some cases controller structures require the model of the plant, which may be is complex /uncertain and tedious to get., the design of controller requires understanding (experience) the system and to know the relationships between the input-output .

IV.VI FUZZY LOGIC CONTROL ALGORITHM

Fuzzy control is a practical alternative methodology to represent, manipulate and implement a smart human's heuristic knowledge about how to control a system [35]; it provides a convenient method for constructing nonlinear controllers via the use of a human's heuristic knowledge, where it integrates human's heuristic knowledge (thinking, understanding, sensing, decision-making and experience) of skilled operators and/or control engineer, then express it using a natural description language (descriptive model), as rules on how to control the process and achieve high-performance control, these rules are incorporated into a fuzzy controller that emulates the decision-making process of the human. Fuzzy control structure is shown in Figure 10,

The structure of the fuzzy controller largely depends on the input and output classifications. Fuzzy logic algorithm can be expanded to fuzzy-PD, fuzzy-PI, fuzzy-adaptive algorithms, where for example as shown in Figure 10(b), fuzzy algorithm is applied to assign the correct values of PID/PD/PI parameters based on the state of error and derivative/integral of error. Fuzzy control algorithm is optimal selection decision, when the internal dynamics of the plant are unknown, too complex real-world systems (no accurate plant model - difficult to model and simulate). Fuzzy control (as an intelligence control algorithm) is select for controlling complex system difficult to model, and is accomplished through system experienced based understanding. also, because of the simplicity of design and implementation, and thus significantly reduces the time required to develop the entire system[6]. Disadvantages of fuzzy control include that fuzzy controllers with fixed structures fail to stabilize the plant under wide variations of the operating condition.
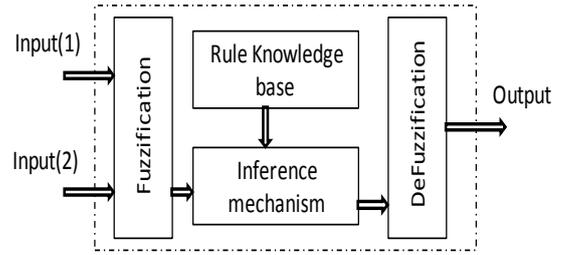

Figure 10(a)
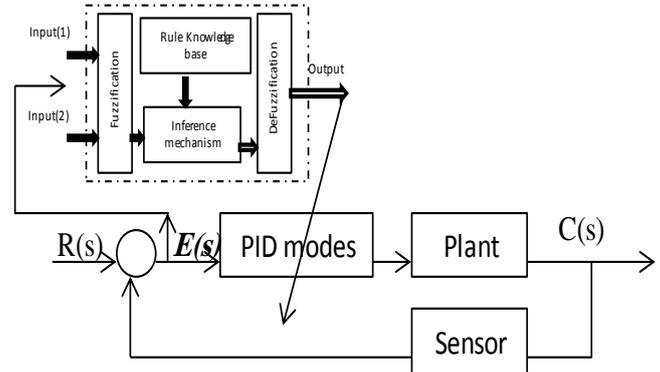
Fuzzy PID modes-gains scheduling

Figure 10(b) example of fuzzy logic algorithm expansion to fuzzy-PD, fuzzy-PI, fuzzy-adaptive algorithms

IV.VII EXPERT CONTROL ALGORITHM.

Also called *knowledge-based control system*, conceptually similar to fuzzy control algorithm, and can be defined as an artificial intelligence based system which can convert the knowledge and experience of an expert, to emulate the reasoning procedures of a human expert in order to generate the necessary control action. Expert systems can learn, gain new knowledge, and improve their performance through experience.

Expert systems are software programs, supplemented by man-machine interfaces, which use knowledge and symbolic reasoning to perform complex tasks at a performance level usually achieved by human experts. The Expert system is composed of ordinary estimation and control algorithms which are combined with a knowledge-based system that captures the heuristics concerning the design and operational practice [36].

IV.VIII NEURAL NETWORKS ALGORITHM

Also more appropriately called "Artificial Neural Network, ANN" , and are used to estimate or approximate, to capture and represent, functions that can depend on a large number of inputs and are generally *unknown*. Neural networks based control system performs a specific form of adaptive control. It is represented as a nonlinear map between the inputs and outputs which represent the dynamic behavior of the system; this map forms a network that can be trained to implement any kind of control strategy. The challenge in using ANN for feedback control purposes

is to select a suitable control system structure, and then to demonstrate using mathematically acceptable techniques how the ANN *weights* can be *tuned* so that closed-loop stability and performance are guaranteed [37].

ANN are modeled based on the structure of biological nervous systems, where the brain of all the advanced living creatures (Humans and other animals) process information with *neural networks*, which consists of *neurons* (a basic nerve cells). The sole purpose of a Neuron is to receive electrical signals, accumulate them and see further if they are strong enough to pass forward. Artificial Neural Network is shown in Figure 11. The circles in the image represents neurons. The network is called *multilayered* because it consists of more than two layers,(The neurons are arranged in a number of layers), generally three; *a)* input (is passive meaning they do not modify the data, they receive a numeric single value on their input, and duplicate/ pass the value to the next level), *b)* hidden/middle; is active meaning it modify the numeric input, does some calculations and forwards to the next layer, the number of neurons in this layer is crucial. There is no formula for calculating the number, the values entering a hidden node are multiplied by weights, a set of predetermined numbers stored in the program. The weight associated with a dendrites basically determines the importance of incoming value. A weight with larger value determines that the value from that particular neuron is of higher significance. The weighted inputs are then *added* to produce a single number. Before leaving the node, this number is passed through a nonlinear mathematical function called a *sigmoid*. This is an "s" shaped curve that limits the node's output. That is, the input to the sigmoid is a value between -∞ and +∞, while its output can only be between 0 and 1. *c)* output layers (active, consists of neurons which does calculations and gives the final result output). [38-39]
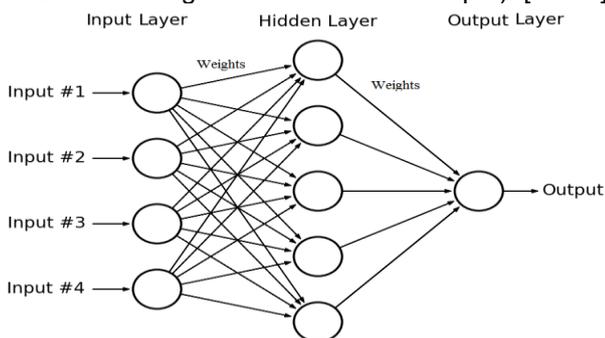

Figure 11 Artificial Neural Network

V CONTROL IN MECHATRONICS OF PRODUCTION SYSTEM (MECHATRONICS AUTOMATION TECHNOLOGY) [15][40-42]

V.I PRODUCTION, MANUFACTURING AND AUTOMATION

Industry can be defined as: any type of economic activity producing or supplying goods or services, it is part of a chain from raw materials to finished product, finished product to service sector, and service sector

to research and development. Industry varies over time and between different countries. As shown in Figure 12(a),industry can be classified into, four categories: Primary, Secondary, Tertiary and Quaternary industries.

Automation is derived from Greek word automatos: Auto *'self* 'and *Matos 'moving or acting'* means self dictated or self acting. automation can be applied in different fields resulting in such fields as Home automation, library automation, industrial automation. In the concepts of automation and production, If there is industry present, chances are good that there is automation present. **An automation system** is a precisely planned change in a physical or administrative task (e.g. *manufacturing or data-processing*) utilizing a new process, method, or machine that increases productivity, quality, and profit while providing methodological control and analysis. The value of system automation is in its ability to improve efficiency; reduce wasted resources associated with rejects or errors; increase consistency, quality, and customer satisfaction; and maximize profit. Manufacturing **Automation** can be defined as the process of having the machines follow a predetermined sequence of operations with little or no human labor using specialized equipment and devices that perform and control manufacturing process by applying advances in technology to all types of enterprise's (*factory*) production system operations. **Automated manufacturing systems** (AMSs), are combination of mechanical design/mechanics, automation, drive technology, sensors, safety technology and others. AMSs operate in the factory on the physical product, which perform operations such as: processing, assembly, inspection, Material handling. It is called automated because they perform operation with reduced human participation compared to manual process/system.

Production means all the stages and processes of producing a *product*, including market studying and analyzing, product designing, design for manufacturing, and manufacturing *processing* stages, packaging, distribution. *(information and processing stages)*. **Manufacturing** : the word *manufacturing* is derived from the Latin word *manu factus* (manu = hand, factus = made), which mean **mad by hand**, it is the process of converting (changing the shape, physical properties or appearance) of raw materials to create a final product. **Production system** is a dynamic network *(it is the collection)* of people, , principles, methods, procedures, tools , equipments (material handling, inspection and testing equipments), Production machines and workstations and computer system to coordinate and control, all these components are organized for planning, manufacturing and for continuous improvement of business processes. Production system can be clissified into, *a)* manufacturing system facilities(come in direct *physically contact* with the parts (*touch* the product) and/or assemblies the product being made, and include; people, machines, equipments, computer), *b)* The manufacturing support systems

include; Market analysis, Product design, Design for Manufacture and manufacturing planning, that *do not contact the produc*t, but they *plan* and *control* the product's progress through the factory and insuring that the products meets quality standards.

Automation of the production system corresponding to the production system classification, and classified into; , *a) Automation of manufacturing system* ; It is the process of automating the physical operations sequence on the product, such as processing using machine tools, assembly machines, inspection or material handling using specialized equipment and devices that perform and control manufacturing process, e.g. Computer numerically controlled machines (CNC), Automated Production Machines *using PLC*, Automation of Tool changing ,Automated Storage and Retrieval Systems and Automated Warehousing , all using PLC, *b) Computerization of manufacturing the support system*; Using the computer systems to accomplish the information processing activities that providing the data and knowledge required to successfully produce the product (CAD (computer systems that allow to sit and create the drawings on the computer screen instead of on a paper), CAM (linking of computer files directly from the CAD system to the shop floor) , CAD/CAM, and also CIM (Computer integrated manufacturing is the integration of the total manufacturing enterprise involves the integration of different manufacturing systems, and involves communication between robots, sensors, CNC machinery, and other types of devices that perform manufacturing operation) .

As shown in Figure 12(a), Automation system can be classified based on the flexibility and level of integration in manufacturing process operations into; *a)* Hard (or fixed) automation; It is an automation system in which sequence of processing (or assembly) operations is fixed by equipment configurations (production machines). Production machines are specialized and have a fixed set of operation and designed to be efficient for this set, and thus lack flexibility, examples include: automated assembly systems, Machining transfer lines, Distillation Process. *b)* Soft (or flexible) automation: also called Programmable automation; It is an automation system that has greater flexibility through the use of computer control of machine and its functions by various programs, The machine can be easily and readily reprogrammed to produce a part that has a shape or dimensions different than those produced just before it . Advances in soft automation, can allow dividing soft automation into two subcategories: *1)* Soft (or flexible) automation. *2)* Programmable automation system ; the production equipment is designed with the capability to change the sequence of operations to accommodate different product configurations, examples of Programmable automation include; (NC), industrial robots, and programmable logic controllers (PLC) .*the third class of automation: c)* Integrated Automation; it symbolizes full integration of process and management operations using information and communication

technologies. It denotes complete automation of a manufacturing plant, with all processes functioning under computer control and under coordination through digital information processing. It includes technologies such as computer-aided design and manufacturing, computer-aided process planning, computer numerical control machine tools, flexible machining systems, automated storage and retrieval systems, automated material handling systems such as robots and automated cranes and conveyors, computerized scheduling and production control, typical examples are seen in Advanced Process Automation Systems and Computer Integrated Manufacturing (CIM)[15][40-42].

V.II LEVELS OF AUTOMATION IN A MANUFACTURING ENTERPRISE

The levels of automation in a manufacturing enterprise, are: *a) Device* level: control system components as sensors, actuators and other hardware components that comprise the machine level, *b) Machine* level: Hardware at the device level is assembled into individual machines; examples include industrial robots, powered conveyers, Control function at this level include performing the sequence of steps in the program of instructions in the correct order and making sure that each step is properly executed, *c) Cell or system level:* A manufacturing cell or system is group of machines or workstations connected and supported by a material handling system, computer and other equipment appropriate to the manufacturing process, Functions at this level include part dispatching and machine loading, coordination among machines and material handling system, and collecting and evaluating inspection data, d) *Plant* level: This is the factory or production system level, it receives instructions from the corporate information system and translates them into operational plans for production, Functions at this level include: order processing, process planning, inventory control, purchasing, material requirements, shop floor control, and quality control, f) *Enterprise* level .This is the highest level, consisting of the corporate information system, it is concerned with all of the function necessary to manage the company: marketing and sales, accounting, design, research, aggregate planning, and master production scheduling. these levels are shown in Figure 12(b)

V.III LEVELS OF INDUSTRIAL PROCESS CONTROL

The levels of industrial process control in manufacturing enterprise are :*a)* Basic control ; the lowest level of control, and corresponding to the device level- e.g. controlling servomotors and other actuators of the production machines, *b)* Procedural control ; intermediate level of control -data collected, changing set points , parameters in basic control, and changing controller's gain constants , error detecting, *c)* Coordination control; the highest level in control. It is corresponds to the supervisory control level, these levels are shown in Figure 12(b,c)

V.IV FORMS OF COMPUTER CONTROL OF MANUFACTURING SYSTEMS

As noted, PC can be made suitable for industrial environment. There are several ways in which digital computer can be used to control a process, the most commonly used: *a)* Computer process monitoring; the computer is *not* used to directly control the process, but used to observe of the process and associated equipment, collecting and recording data from the process, *b)* Direct digital control-DDC; applied when many processes are occurring simultaneously and must be coordinated, because the output of one process is the input of another. Using *single large* computer, all local processes can be implemented, monitored, and adjusted from the same place,

enhance total system performance, the drawback is that the whole plant is dependent on that one computer, *d)* Distributed control systems –DCS; The advent of small microprocessor-based controllers has led to a new approach called *distributed computer control*, each process has its own separate controller located at the site. These local controllers are interconnected via a LAN, so that all controllers on the network can be monitored or reprogrammed from a single supervisory computer, Once programmed, each process is essentially operating independently. This makes for a more robust and safe system, because all the local processes will continue to function even if the supervisory computer or network goes down)*, c)* Supervisory control.
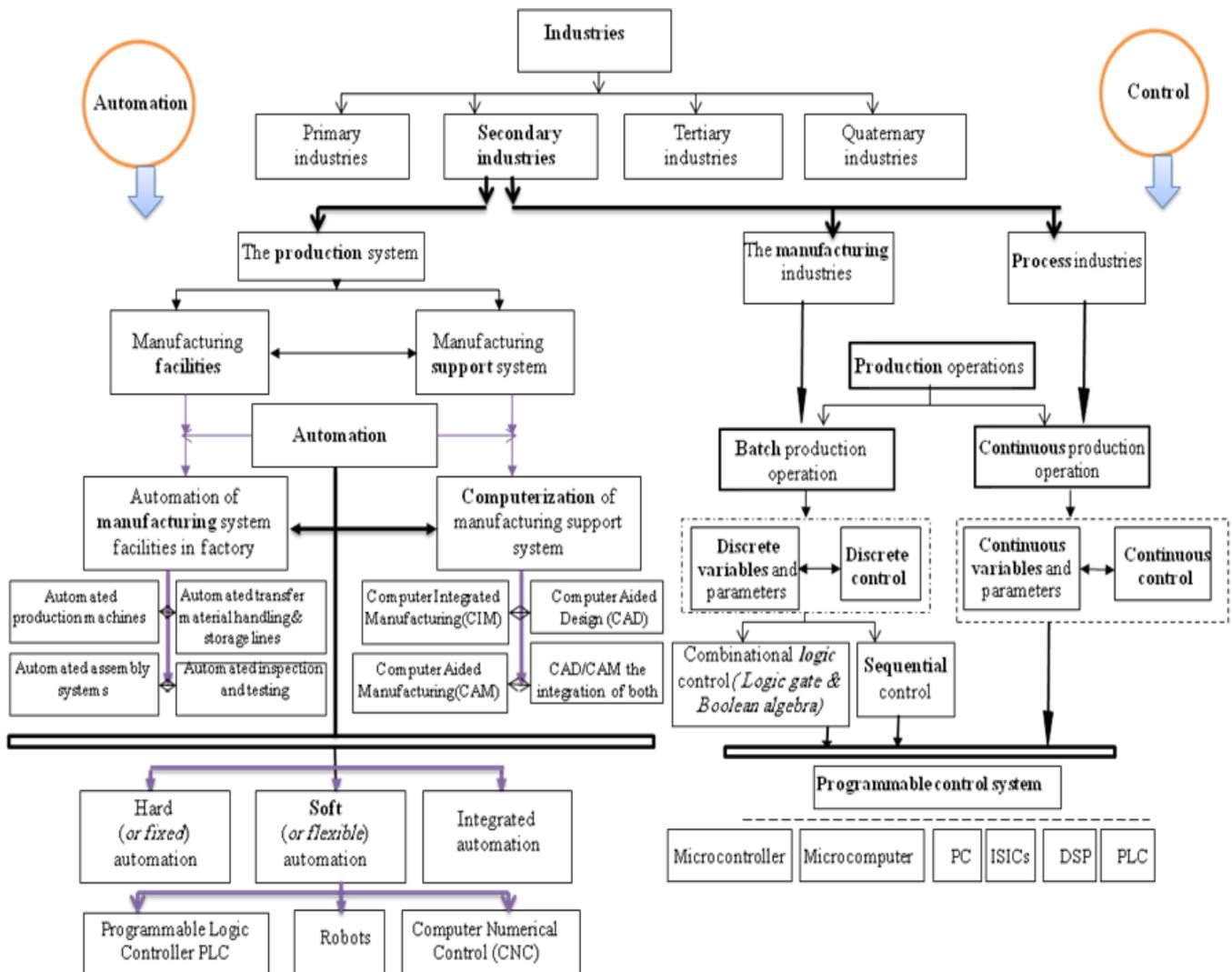

Figure 12(a) Production, Manufacturing control and automation in production system.
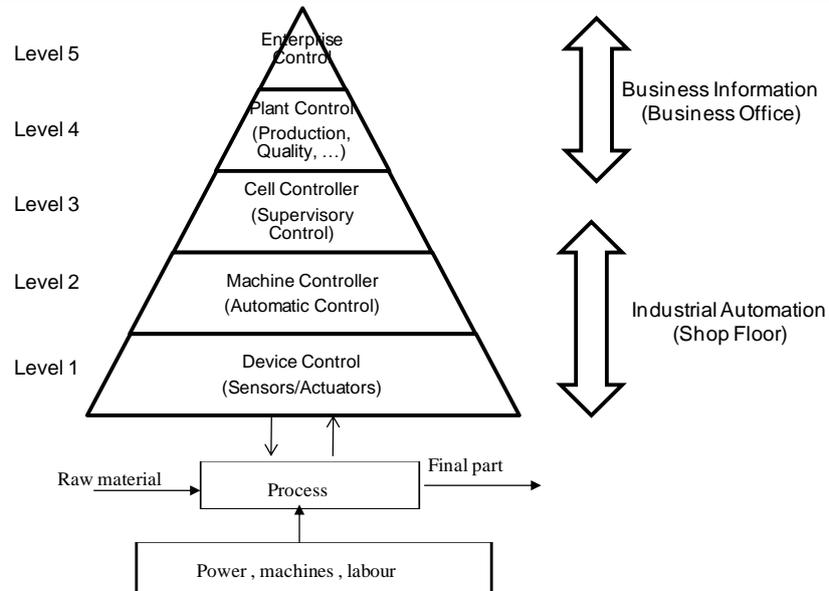
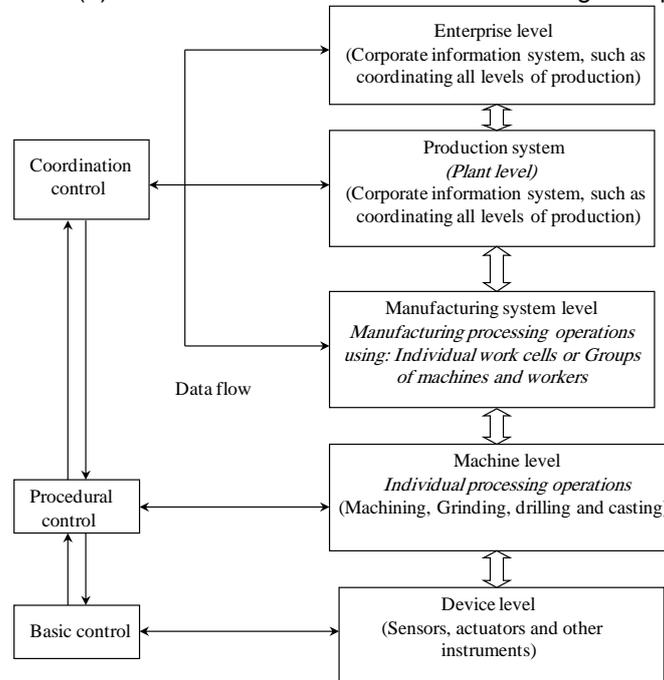Figure 12 (b) Levels of automation in a manufacturing enterprise**]**

Figure 12(c) Control levels into the levels of automation in manufacturing enterprise
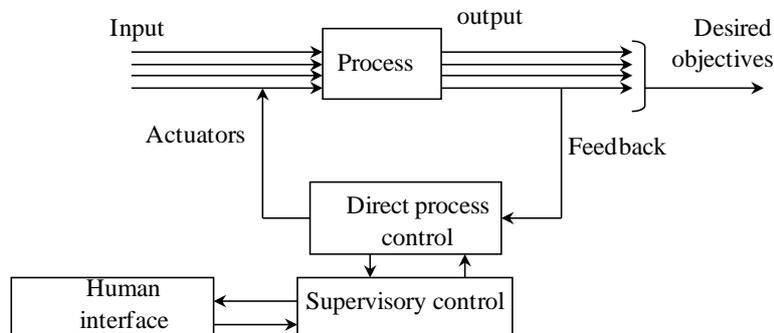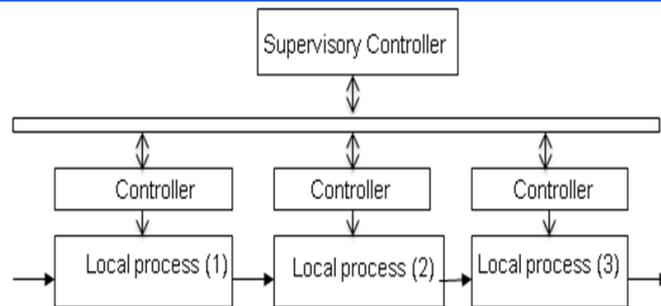
Figure 12(d) Supervisory control

Figure 12 (e) Distributed computer control using local controllers[15][40-42]
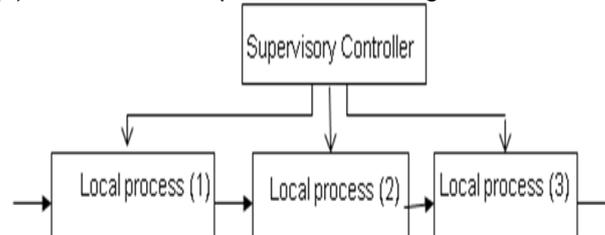

Figure 12 (f) Direct computer control of three processes[15][40-42]

CONCLUSION

To support educators and help students in solving Mechatronics design tasks with their specific properties, this paper focused on control systems and control algorithms subsystems selection, evaluation, design and synergistic integration stage in Mechatronics systems design and development methodology, main concepts, classifications, role, description of main features and selection criteria are presented and discussed.

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