A Proposed Approach to Mechatronics Design and Implementation Education-Oriented Methodology

Farhan A. Salem
Alpha center for Engineering Studies and Technology Researches, Amman, Jordan.
Mechatronics program, Department of Mechanical Engineering, Faculty of Engineering, Taif University, 888, Taif, Saudi Arabia.
Email: salem_farh@yahoo.com
Ahmad A. Mahfouz
Department of Automatic and Mechatronics Systems, Vladimir State University, Vladimir, RF
Alpha center for Engineering Studies and Technology Researches, Amman, Jordan. Email: ahmad_atallah@yahoo.com

Abstract

Mechatronics engineer is expected to design engineering systems with synergy and integration toward constrains like higher performance, speed, precision, efficiency, lower costs and functionality. The key element in success of a mechatronics engineering education-program, and correspondingly, Mechatronics engineering graduates, is directly related to a well-structured mechatronic system design course and the applied structural design methodology. Guidelines for structural design methodology and tools for the development process of mechatronic products, that can be applied in educational process is highly required. This paper proposes mechatronics systems design education-oriented methodology, which aims to integrate multidisciplinary knowledge, in various stages through the design process and development of mechatronics product. The proposed mechatronics design methodology is described, discussed and applied with the help of example student final year graduation project; design and implementation of mechatronics mobile robotic guidance system in the from of smart wheelchair- Mechatronics Motawif, to help and support people with disabilities and special needs to perform specific predetermined tasks, particularly, performing Al Omrah and motion around holy Kaba, Makka.

Keywords: Mechatronics, Design methodology, Parallel design, Synergistic integration, Modeling/ Simulation, Prototyping, Mobile robot, Motawif

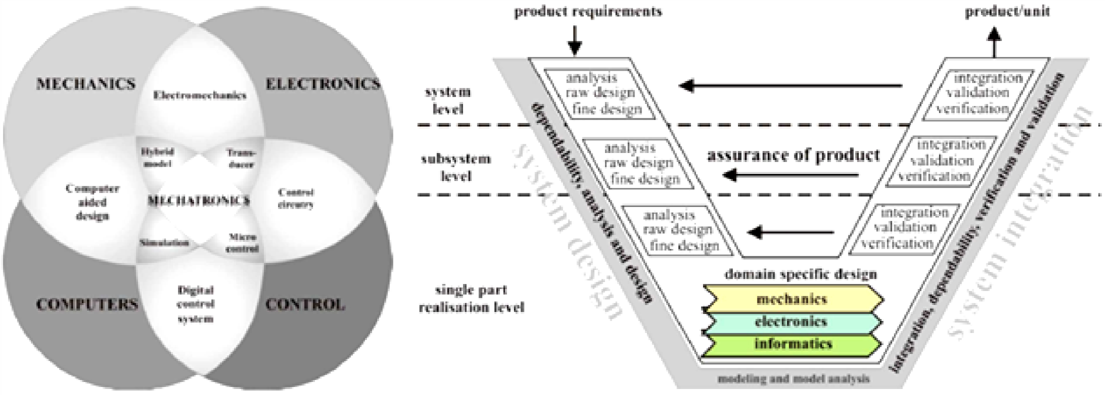
1. Introduction

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 require a multidisciplinary engineering systems approach to solve them, such modern multidisciplinary systems are called mechatronics systems, correspondingly, engineers face daunting challenges, and to be competitive, in labor market, engineers must provide high value by being immediate, innovative, integrative, conceptual, and multidisciplinary, engineers must have depth in a specific engineering discipline, as well as multidisciplinary engineering breadth, with a balance between theory and practice, in addition, they must have breadth in business and human values, an engineer with such qualifications is called Mechatronics engineer.

Mechatronics engineer is expected to design products with synergy and integration toward constrains like higher performance, speed, precision, efficiency, lower costs and functionality, and in order to evaluate concepts generated during the design process, without building and testing each one, the mechatronics engineer must be skilled in the modeling, analysis, and control of dynamic systems and understand the key issues in hardware implementation [1]. The key element in success of a mechatronics engineering program, and correspondingly Mechatronics engineering graduates, is directly related to the applied structural design methodology, and engineering educators face daunting challenges, where due to different disciplines involved, the mechatronics design process may become very complex, therefore specific guidelines for structural design methodology and tools for the development process of mechatronic products, that can support students in solving mechatronics design tasks with their specific properties and can be applied in educational process is highly required. This paper proposes mechatronics design education-oriented methodology, which aims to integrate multidisciplinary knowledge, in various stages including; pre-study process and problem statement, conceptual design, optimal selection and synergistic integration, modeling, simulation, prototyping, analysis and physical implementations in development of mechatronics product and to fulfill above desired requirements.

There are many definitions of mechatronics, regardless of the definition, Mechatronics is defined as multidisciplinary concept (Figure1(a), 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, is it 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. Industrial and scientific evolutions of mechatronic products have led to substantial experience, and as a natural consequence industrial guideline have emerged for the product design of mechatronic products. [2]. Depending on type of mechatronic system, different industrial, scientific and educational recourse introduce different design approaches and models, including [2-13][16][21][34]. A major role in these guideline methodology models are based on VDI2206 (2003) guideline, which is devoted particularly to the design methodology for mechatronics systems and suggests to carry out the development process of mechatronics according to so called V-model (Figure1(b)); The proposed V-model has been adopted from software engineering and adapted for mechatronics requirements, which are distinct from *case to case*, the aim is to establish a cross-domain solution concept which describes the main physical and logical operating characteristics of the future product, the input (Left side) to this V-model is defining and analyzing all requirements of the total system, the sub-functions and sub-systems are defined and to be developed simultaneously by the cooperating development teems, Next (Base side of V-model) verifying sub-function and testing sub-systems through modeling and model analysis in mechanical engineering, electrical engineering and information technology domains. Next (Right side of V-model) the verified sub-function and tested sub-systems are integrated, and the performance of the integrated system is checked, if it has to be improved, the initial operation phase can be repeated. The proposed mechatronics education-oriented design methodology is based on VDI 2206 guideline and different industrial, scientific and educational recourse. the proposed methodology, consists of a systematic specific simple and clear design steps (shown in diagram 2(a)(b)) that can help and support engineering educators, non experienced student or group of students, easy to memorize and follow, in solving mechatronics design tasks, the proposed design steps to be applied, described and discussed with the help of example student graduate project-smart mechatronics mobile robot-Motawif.

The modern advances and synergetic integration of different domains caused the application field of mechatronics systems to differentiate into the conventional mechatronic and Microelectromechanical - micromechatronic systems – MEMS (deals with classical mechanics and electromechanics) and nanoelectromechanical- nanomechatronic systems– NEMS (deals with quantum theory and nanoelecctromechanics)[3].



(a) (b) V- model, VDI 2206 2003[2]

Figure 1 (a) Basic principle; mechatronics circular-model, (b) Mechatronics design V-mode

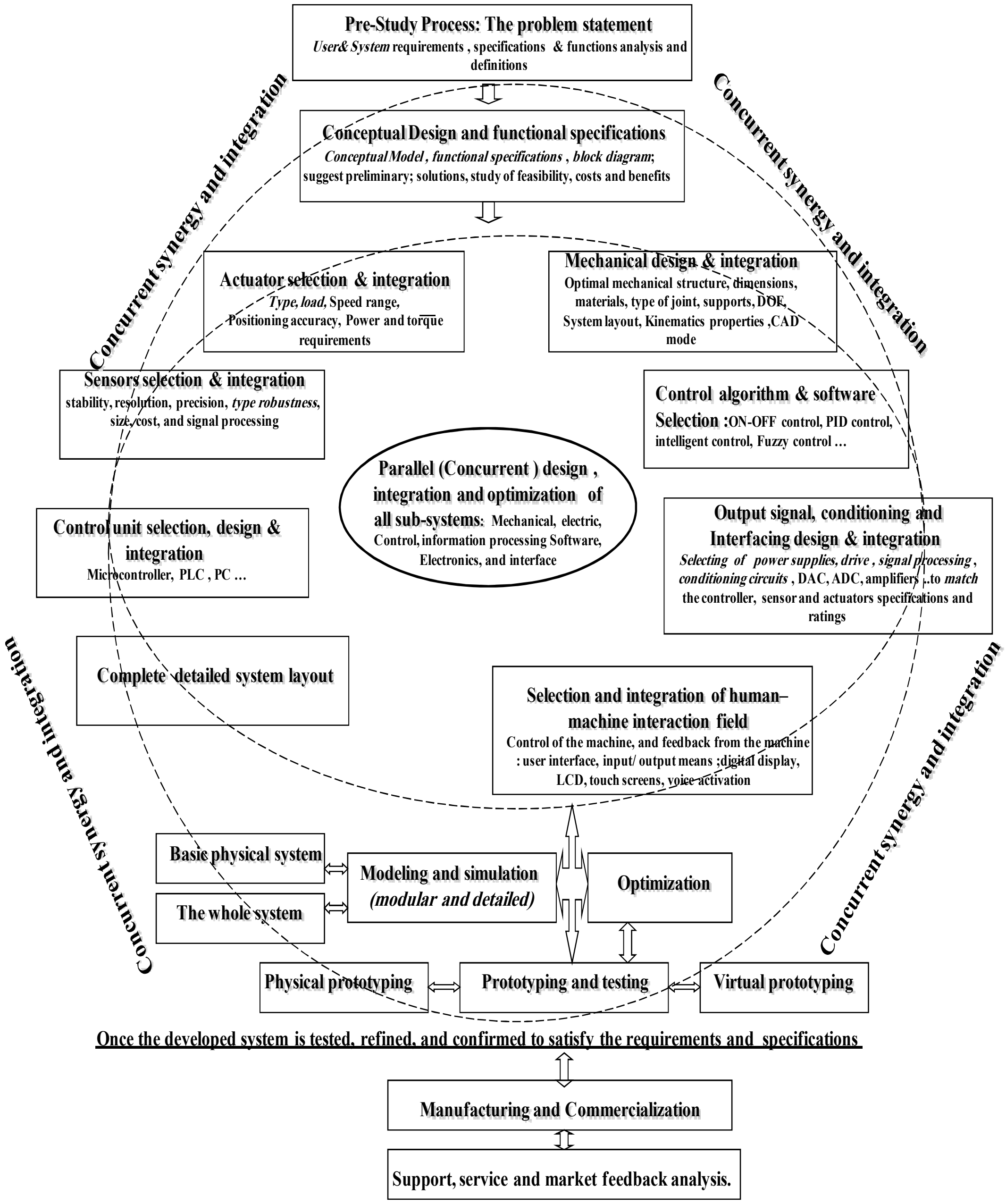


Figure 2(a) Guideline for mechatronics systems design education-oriented methodology

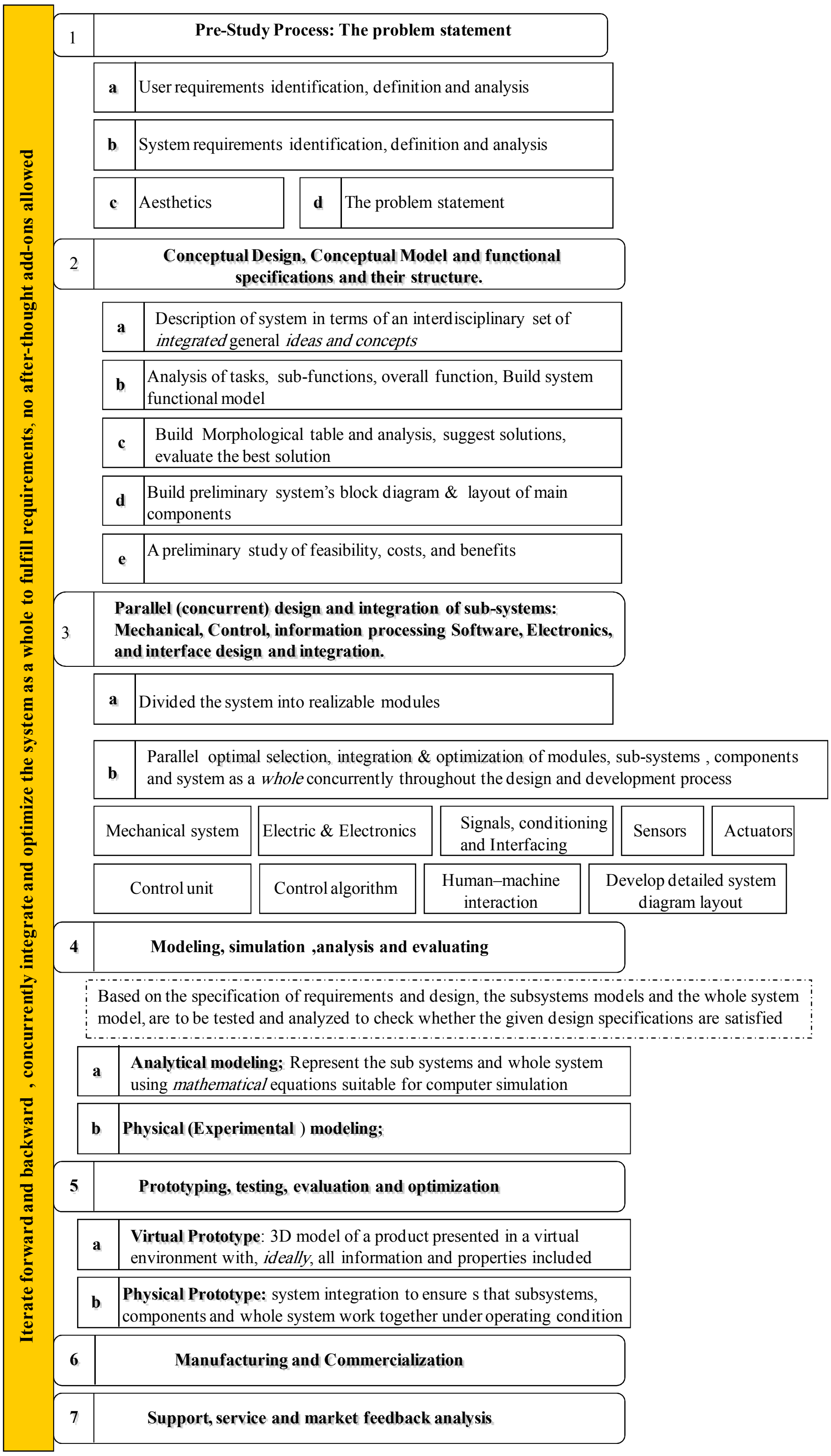


Figure 2(b) Guideline for mechatronics systems design education-oriented methodology

2. Proposed Guideline for mechatronics systems design education-oriented methodology

2.1 The Pre-Study Process- problem statement; it is the process of gathering as much information as possible about the product and its future applications, all possible conditions of operation, the environmental factors, and the specifications with respect to quality, physical dimensions, and costs. Studying, analyzing and defining target user (Customer), user needs and requirements, system requirements, aesthetics, and target market, resulting in a preliminary design specification, which has to be updated continuously according to the new information gathered during the development process.

2.1.1 User's requirements analysis; to acquire necessary information to identify, understand and discover potential user, user's needs, interests, requirements and define system functions.

1) Understanding user requirements is an integral part of design and is critical to the success of final product.

2) users seldom know what they want or need, systems engineers must enter the customer's environment and find out the user need and requirements, and how the users will use the system, design must exceed, not merely meet, customer expectations, **3)** Creativity of designers is required for the transfer of user requirements into innovative consumer product.

2.1.2 System requirements analysis; well-defined product requirements, to create a detailed *functional* specifications and defining the full set of system *capabilities* to be *implemented*. There are two types of system requirements;

1) Fixed or Mandatory system requirements; the minimal requirements necessary to satisfy the customer's *operational* need.

2) Soft or Tradeoff system requirements; after understanding the mandatory requirements, Engineers *propose* alternative candidate *designs*, all of which satisfy the mandatory requirements. Then the tradeoff requirements are evaluated to determine the preferred designs. Treating user and system requirements as the same thing will create problems for projects.

2.1.3 Aesthetics In some instances this is not important, particularly where the device or structure is not seen. However, for many consumer products or structures a pleasing elegant design is required and colour, shape, form and texture should be specified [14]

2.1.4 The problem statement: it is a list and description of problems that is given to a problem solving team as a sort of brief, before they attempt to solve the problem. The problem statement is more important than problem solving, before attempting to find solution (design and built) for a given a problem, it is very important understanding what is problem and to state it in clear unambiguous manners and terms. The problem statement includes: description of what the problem, who has the problem, the user's needs, and user and system requirements, states the goals of the project, defines the business needs, prescribes the system capabilities and method used to solve the problem. The problem statement starts with a description of *the* top-level functions that the system must perform, and it might be better to state the problem in terms of the deficiency that must be ameliorated [15]

2.1.2 The problem statement of "Smart mechatronic robotic guidance system-Mechatronics Motawif in the form of smart wheelchair"; Analysis of Local Makka Al-Mukarramah market, show a potential market for commercialization of "Smart mechatronic robotic guidance system-Mechatronics Motawif in the form of smart wheelchair" that can be used to help people with disabilities and special needs to perform Omrah, and feel safer about their surroundings. The potential users want the wheelchair; to be used as smart mechatronics Motawif to help and guide them in performing all Al-Omrah rituals and motions, particularly, eliminates the support and/or help from other peoples, easy to use and to maneuver, moves and stops are accomplished with suitable speed and with minimum kicks (overshoot), simple and easy to understand and use interface, cost-efficient operate on lower costs, a stable seating, seat to be level, suitable backrest angle that should provide support and balance for the upper body, A chair that is versatile/adaptable, a wheelchair that is easy to transport and space saving ***size*** of Height: about 1 meter Width: 0.60 meter and Length: 0.60 meter.

Aesthetics: chair that looks aesthetically pleasing makes the user look good and feel confident.

Target user and market:, to be sold ,or mainly, rent to pilgrims, particularly, pilgrims with disabilities and special needs who want to perform Al Omrah without the help of others, and feel safer about there surroundings. Other forms of the system can be used in industry and hospitals.

User and system requirements analysis, including system mandatory and soft or requirements and description are shown in Requirements analysis Table.1

Table.1 Requirements analysis

			Unit-Value	Requirements TYPE			
Requirements				**Mandatory (fixed) Req.**	**Soft Req.**	**Quantitative Req.**	**Qualitative Req.**
Mechanical structure & dimensions	Smart Wheelchair	Height:	100 cm	Fixed			Qual.
		Width:	60 cm				
		Length:	60 cm				
Material & mechanical Skeleton	See Fig.6 & Table 3				Soft		Qual
Power	Electric battery		12-24 V				Qual
Actuators	Electric motors.			-	Soft	Quan.	Qual.
Sensors	Path finder; line, color,			-	Soft	Quan..	Qual.
	Load, speed						
	Obstacle det., Timers						
Controller	Simple, compact , cost effective			Fixed	Soft		p
Control algorithm	Simple, precise, quick, efficient, easy to program			Fixed			Fixed
Transmission	Gears, belts		*n*		Soft		Qual.
Allowable speed	Suitable speed, Minimum kicks		0.5 m/s, in 1 sec.	Fixed	-	-	Qual.
Allowable user weight	Max. Allowable		120 kg		Soft		Qual.
Manual control	Joy-stock , switches				Soft		Qual.
User interface	Simple and easy to use and understand			Fixed	-		Qual.
Machine aesthetics design	Chairs looks aesthetically pleasing makes the user look good and feel confident.			Fixed			Qual
Cost effective							
…							

2.2 Conceptual Design; Conceptual model, functional specifications and their structure.

In mechatronics design approach, it is important to consider the system as a whole throughout the development process from the very start of the design process. Conceptual design is an early stage of design in which designers are building a description of the proposed system in terms of an interdisciplinary set of integrated general *ideas and concepts*, describing product and product's overall function, of its most important sub-functions, that will be employed in solving a given design problem and their supporting analysis, generating solutions without detailed design parameters and decide how to interconnect these concepts into an appropriate system architecture. Conceptual design acts as a *blueprint* for the subsequent design and implementation stages. The general concept needs to be expanded into an implementation model without detailed design parameters. One of the most important secrets of the successful design is to keep design options open as long as possible.

Conceptual design is usually evolve from user and system requirements, **1)** Define the overall tasks and functions, which are to be carried out by the system. **2)** Break down the overall function into subsystems or even components to which suitable operating principles or solution principles are assigned. **3)** Build system functional model and depicting the flow of information between the system's required components **4)** Build

Morphological table and corresponding analysis; suggest solutions, evaluate the best solution. It has to be decided about each of the following **a)** which problems should be solved mechanically, (preliminary *mechanical* structure). **b)** Which problems should be solved electronically, (preliminary *electronic* structure). **c)** A preliminary ideas about the necessary mechanical structure, sensors, actuators, and interfaces. **5)** Generate decisions about the dominant mechanical properties, (e.g. sizing, volume, DOF, joints types) yielding a simple model that can be used for controller design, control software development and to initiate the CAD design, Choices and decisions can be made with respect to the mechanical properties needed to achieve a good performance of the controlled system. **6)** Build preliminary system block diagram of main components. **7)** A preliminary study of feasibility, costs, and benefits. During conceptual design stage a new requirements may arise within the process which should be considered. The conceptual design is always refined developed and optimized during various design phases. During the conceptual design phase few people are involved (mechanical designers, the technical personnel) in the development project.

2.2.1 Conceptual Design: 'Smart mechatronic robotic guidance system- Mechatronics Motawif': based on user and system requirements, it is required to develop mobile Mechatronic robotic guidance system, in the form of smart wheelchair (Figure 3), to be used as Mechatronics-Motawif, to help and support people with disabilities and special needs in performing Al Omrah rituals and motions and feel safer about their surroundings. A product like this must eliminates the support or help from other peoples, easy to use and to maneuver, Moves and stops are accomplished with suitable speed and with minimum kicks (overshoot), Simple and easy to understand and use interface, cost-efficient operate on lower costs, a stable seating, seat to be level, suitable backrest angle that should provide support and balance for the upper body, A chair that is versatile/adaptable, A chair that is easy to transport space saving wheelchair ***size*** of Height: about 1 meter Width: 0.60 meter and Length: 0.60 meter. The novelty in the desired system design is in that; there are three different types of wheelchair: self-propelled, electric, and attendant-propelled, but no, smart self controlled wheelchair.

The ' Smart Mechatronic Robotic Guidance System-Mechatronics Motawif' ' is a mobile line follower robotic system in the form of smart wheelchair, it is to design an *integrated sensor array* that will be mounted on mobile platform. A single battery will power the sensors, as well as, a control unit, drive circuit, and actuators. The two *rear* wheels are responsible of moving the wheelchair, but are also used to turn the wheelchair in any required direction depending on the difference of speed of wheels' rotation between the right and left wheels (*differential drive style*).To give wheelchair a human-like property of responding to stimuli, it is required to select and design an effective closed loop control system and control algorithm, where control unit takes an input signals from sensors and controls the actuators and correspondingly speed of wheels' rotation, actuators will maneuver wheelchair to stay on a predetermined course, while using feedback mechanism for constantly correcting the errors in moves. The control is done in such a way that when a sensor senses desired path, the system follow it and in response to any deviation from the path, a signal from control unit is sent to the motors to slow down or even stops, then the difference of rotation speed makes it possible to make turns, or when sensor sense the presence of an object in the front side in a prescribed distance, signal from control unit is sent to stop motors until object is removed.

The tasks (functions), to be carried out by the proposed design: system is intended to help the elderly and disabled to Perform Al Omrah and/or Al Hajj, mainly performing predetermined time driven motions in the form of Altawaf around holy Kaba and/or Alsa'ee between Alsafa and Almarwa, counts motions and sound corresponding Doaa, Robot-Motawif will have the obstacle detection feature, stops when an object is located in the front side, main of these tasks are illustrated in Figure 4(a).

The functional structure block and preliminary flowchart of proposed mechatronics system is shown in Figure 4(b).

Morphological table and analysis (see Table 2 **):** *Finding solutions* for each function in functional block, including: switching system ON-OFF, Path and obstacle detection, motions, stops, turns, timing, counting, sounding. Next, *filtering the solution*s: for *every* solution does the solution satisfy all the requirements? Is there a solution which is really similar or evens the same? c) If yes, condense them to one solution. Finally evaluating the optimal concepts and if satisfies customer needs, optimal solutions can be selected.

Preliminary block diagram and layout representations of proposed system and main components are shown in Figure 4(c), an assembled CAD model for the robot to be introduced.

A preliminary economic analysis: *feasibility, cost-benefit evaluation:* For now, it can be declare that, it is possible to design and build such mechatronics system, to perform required tasks, and achieving most user needs and to be cost effective, major components are available and can be bought from local market, the total and final cost analysis, as well as, cost-benefit evaluation can be done after accomplishing theoretical selection and design of the whole system, the suggested design can be very helpful for pilgrims with disabilities or special needs .

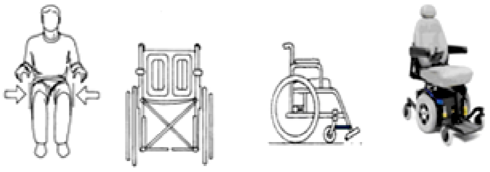


Figure 3 Preliminary concept of robotic guidance system, in the form of wheelchair.

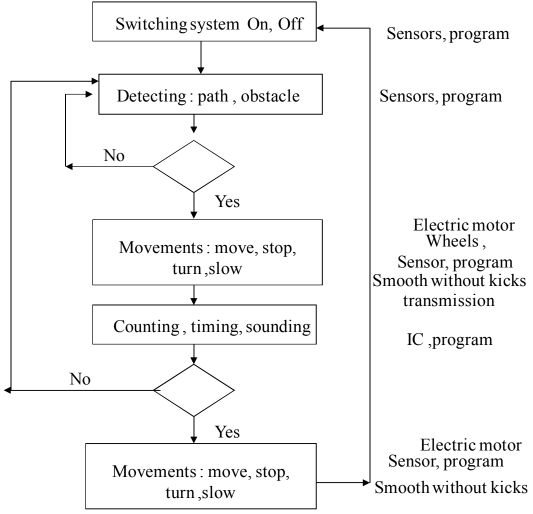


Figure 4(a): Functional block diagram.

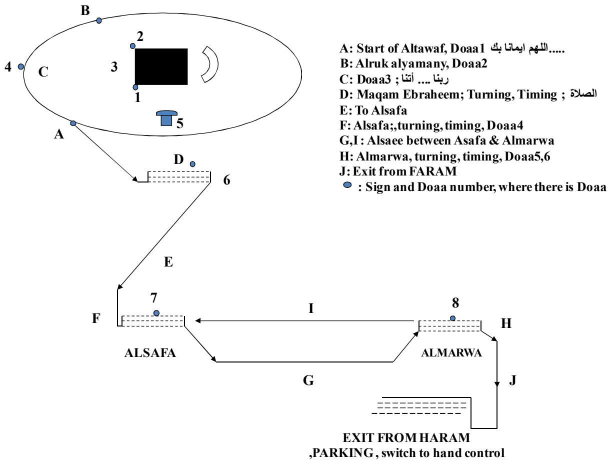
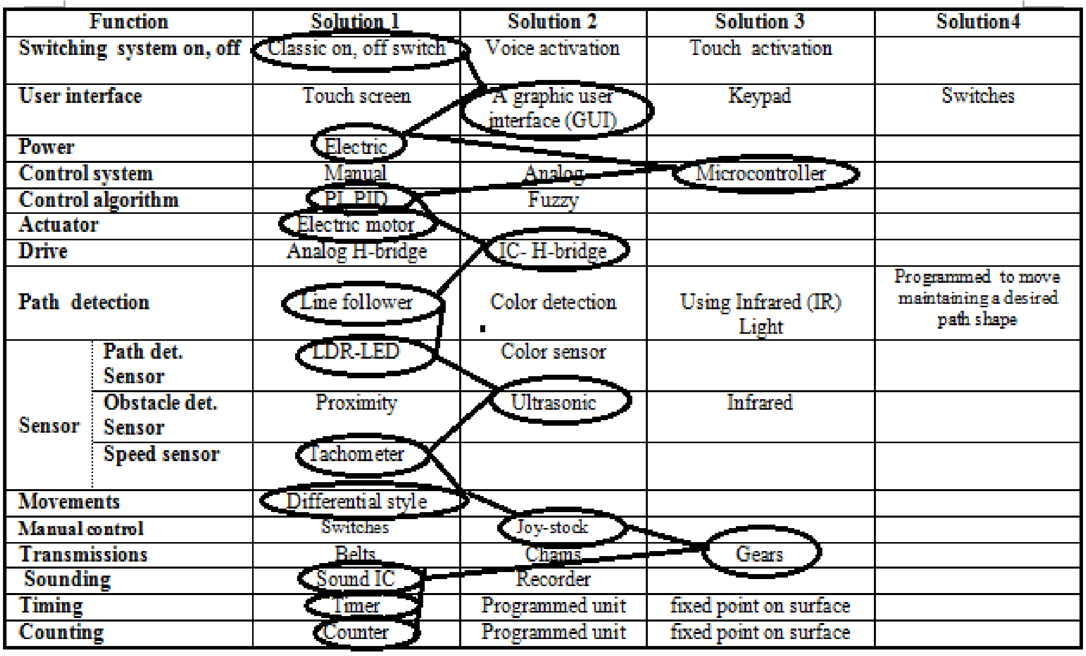


Figure 4(b) Performing Altawaf and Alsa'ee; tasks to accomplish, step by step; sequences, locations, and corresponding action for each step.

Table 2 Morphological table, analysis and evaluation of the best solution.



Function		Solution 1	Solution 2	Solution 3	Solution4
Switching system on, off		[✓ Classic on, off switch]	Voice activation	Touch activation	
User interface		Touch screen	[✓ A graphic user interface (GUI)]	Keypad	Switches
Power		[✓ Electric]			
Control system		Manual	Analog	[✓ Microcontroller]	
Control algorithm		[✓ PI, PID]	Fuzzy		
Actuator		[✓ Electric motor]			
Drive		Analog H-bridge	[✓ IC- H-bridge]		
Path detection		[✓ Line follower]	Color detection	Using Infrared (IR) Light	Programmed to move maintaining a desired path shape
Sensor	**Path det. Sensor**	[✓ LDR-LED]	Color sensor		
	Obstacle det. Sensor	Proximity	[✓ Ultrasonic]	Infrared	
	Speed sensor	[✓ Tachometer]			
Movements		[✓ Differential style]			
Manual control		Switches	[✓ Joy-stock]		
Transmissions		Belts	Chains	[✓ Gears]	
Sounding		[✓ Sound IC]	Recorder		
Timing		[✓ Timer]	Programmed unit	fixed point on surface	
Counting		[✓ Counter]	Programmed unit	fixed point on surface	

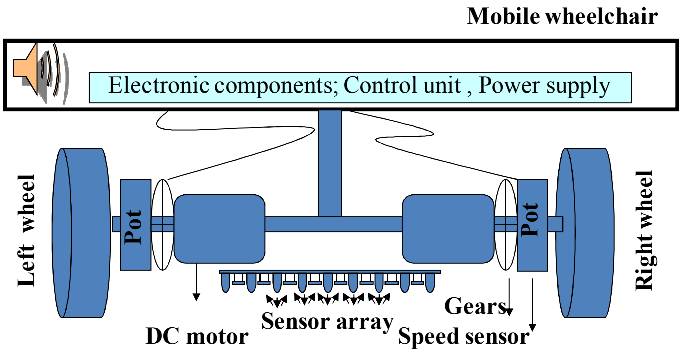


Figure 4(c)

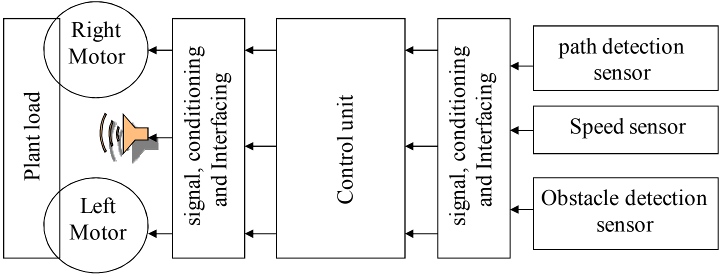


Figure 4(d)

Figure 4**(C)**(d) Preliminary system and block diagram layout representations of proposed system including main components

3.3 Parallel (concurrent) selection, design and integration of sub-systems and whole system: Mechanical, Control, information processing Software, Electronics, and interface design and integration.

Mechatronics engineer is expected to design products with synergy and integration toward constrains like higher performance, speed, precision, efficiency, lower costs and functionality, also the mechatronics engineer must be skilled in the modeling, simulation, analysis, and control of dynamic systems and understand the key issues in hardware implementation. Mechatronics systems design is Modern interdisciplinary design procedure; it is a concurrent selection, evaluation, integration, and optimization of the system and all its 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. The ideal process of *concurrent or simultaneous* engineering is characterized by parallel work of a potentially distributed community of designers that know about the parallel work of their colleagues and collaborate as necessary; sharing of knowledge in a common database builds a basis of cooperative design, since a shared database is the place where all design results are integrated [33]. The design of mechatronic systems can be facilitated using a methodology called *systems engineering*. Systems engineering is an interdisciplinary collaborative robust approach that integrates disciplines and technologies to the design, creation, and operation of systems to ensure that the customer's needs are satisfied throughout a system's entire life cycle. once the system is specified after a problem statement, conceptual design general problem solving procedure and determination of all necessary requirements, it can be divided into realizable *modules* the optimal selection, modeling, evaluation, the exchange of information between different modules ((Figure 5(b)) and models of different domains (e.g. MCAD, ECAD), and synergetic integration of modules and all components to be designed in parallel and collaboratively with respect to the realization of the design specifications and requirements in the different domains, to produce an overall optimal design, it is desired that (sub-) models be reusable.

A mechatronic system will consist of many different types of interconnected subsystems (components and elements). As a result there will be energy conversion from one form to another, particularly between electrical energy and mechanical energy. This enables one to use energy as the unifying concept in the analysis and design of a mechatronic system [7].

3.3.1 Mechatronic – basic approach

Regardless of the type of mechatronic system, there is a need to understand the fundamental working principles of mechatronic systems before approaching the design procedure of a mechatronic product. The general scheme, shown in Figure 5(a), is an example of a mechanical system which is a power-producing or power-generating machine. The basis of many mechatronic systems is the mechanical part, which converts or transmits the mechanical process. Information on the state of the mechanical process has to be obtained by 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 convert into manipulated variables for the actuators (e.g. motors) 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. The potential benefits of mechatronics come from the innovation potential of the technologies and the functional and spatial integration of the technologies [2].

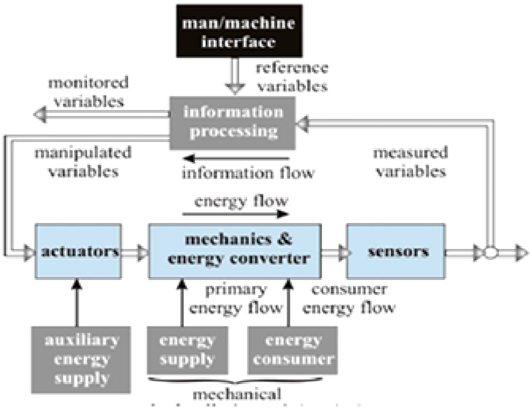


Figure 5(a) Working principle of mechatronic products auxiliary [16]

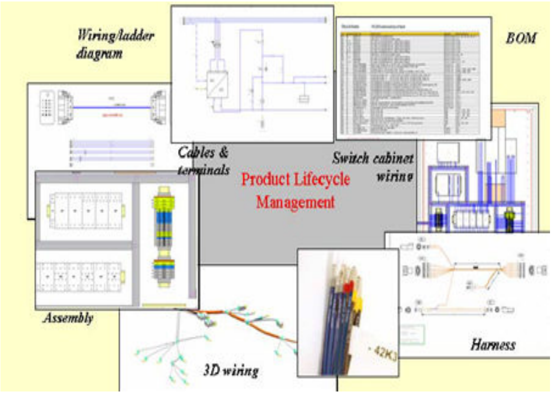


Figure 5(b) Exchange of information between different models

3.3.2 Ways of integration

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). 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. The integration by information processing is based on advanced control function [10].

The *principle of synergy* in Mechatronics means, an integrated and concurrent design should result in a better product than one obtained through an uncoupled or sequential design [7].

3.3.3 Mechanical systems are concerned with the behavior of matter under the action of forces; such systems are categorized as rigid, deformable, or fluid in nature. 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 simply the analysis and prediction of whole system effects and performance, it is important that during an early stage of the design a proper choice can be made with respect to the mechanical properties needed to achieve a good performance of the controlled system.

1) Identify functional requirements and design parameters; the mechanical design involves the selection and design of all mechanical aspects in full details, to meet the machine system requirement specifications, it is crucial since it forms the skeleton of mechatronic systems. **2)** Identify the necessary mechanical structure, dimensions, materials, type of joint combination, (revolute joints prismatic joint) supports, and the required number of degrees of freedom etc. **3)** During the mechanical design process, suggest advices related to hardware integration and imbedding issues such as positioning of sensors, actuators and microcomputers**.** **4)** Build constructive specifications using e.g. CAD/CAE tools, static and dynamic models for individual components, whole system and system layout.

3.3.3.1 Mechanical systems design 'Smart mechatronic robotic guidance system': Refering to user and system requirements, the functional requirements and design parameters for proposed design are listed below. The optimal and necessary mechanical structure is shown in Figure 6 (a) and main components are listed in

Table 3. **Performance specifications;** For smooth driving for comfortable riding and minimum kicks (overshoot), the required optimal output linear velocity of the wheelchair is 0.05 m/s, in 2 seconds, the optimal wheel radius is 0.075 meter. **Size and dimensions**: space saving wheelchair; Height: about 1 meter, Width: 0.60 meter, Length: 0.60 meter. **Weight:** A lighter wheelchair is usually an advantage for both an active user and a career the average wheelchair mass 55 kg, range for user weight 50:120 kg. **Seat size*:*** Maximum stability will be achieved if the user's body fits comfortably into the chair seat. **Footrest length (**Figure 6 **(b)):** If an angle of 90° between the user's thighs and hips is achieved, most people will be comfortable if their knees are also at an angle of approximately 90°. **Backrest height (**Figure 6 **(c)):** The upper body is stabilized by the support from the backrest, which should be high enough to stabilize the upper lumbar region. Above this level, the backrest height is a matter of individual need and/or personal preference. **Arm support** (Figure 6 (d)): When armrests are properly adjusted they should support the user's forearms comfortably with the elbows at 90°. If they are too high, the user's shoulders will be hunched; if they are too low, the user will tend to slump to one side **[17*]**. **Wheels: Tires** to choose wheel diameter and material to result in the required linear velocity, where the relation between wheel radius and linear velocity is given by $V=\omega*r$. Pneumatic - offer a better shock absorption than solid ones but may puncture. Puncture-proof - filled with a jelly like substance; need less maintenance. Solid - hard-wearing but can provide a rougher ride. **Gear ratio :** can be finally selected after final actuator type selection, To choose the gear ratio value to result in the required torque and output linear velocity, and correspondingly to choose Gear's material, number of teeth , radius.

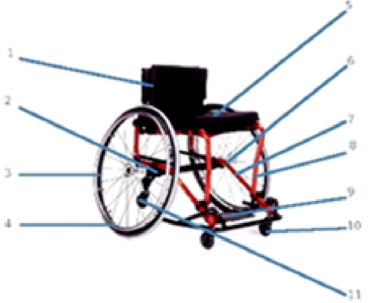


Figure 6(a) Skeleton of wheelchair systems[17].

1	Backrest	*10*	Anti-Tip Casters
2	Rear Axle	*11*	Anti-Tip Casters
3	Rear Wheels	*12*	Breaks
4	Handrims	*13*	Tipping Levers
5	Seat:	*14*	Seatbelts:
6	Frame	*15*	Push Handles
7	Traverse bar	*16*	Upholstry
8	Front Rigging	*17*	Armrests
9	Front Casters	*18*	Metal Skirt

Table 3

Figure 6(b) Footrest length

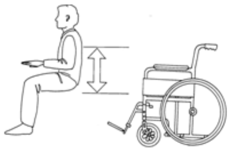
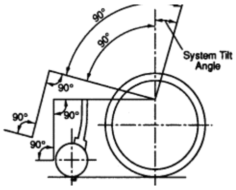


Figure 6(c) Backrest height [17]



Dimensions

Figure 6(d) Arm support

3.3.4 Actuators selection and integration; Converts an information signal from the control unit, into energy acting on the basic system. In mechatronic systems, the actuator runs a certain kind of mechanical load process. This can be a position, speed, acceleration, torque (force), power or a combination. The selection of actuator type in a design depends on load process, power and torque requirements, position accuracy, speed range, available volume, transmission, integration in whole construction, surrounding, control unit, drive, and costs that playing the important roles; **1)** To select and identify actuator, as completely as possible from commercially available units (e.g. electric, pneumatic, hydraulic..) to match the kinematic and dynamic requirements that meets the demand specifications. The factors must be taken into consideration when selecting the type of actuators to use include; actuator type, motion, load, power capacities, speed range, and positioning accuracy**, 2)** Suggest advices related to actuators placement and integration issues. *Power and torque requirements***:** In sizing the motor, student should be able to meet both the power requirements as well as the torque requirements. The student has to have an appreciation of any out of balance loads and load related inertias.

3.3.5 Sensors selection and integration; Sensors converts a state variable of the basic system, into an information signal to the control unit. In a mechatronic systems, the sensor measures a certain kind of process variable, this can be a position, speed, acceleration, torque (force), power or a combination**,** when measuring controlled variables, several characteristics become important: the integration with the process, the dynamics of the sensor, stability, resolution, precision, robustness, size, cost, and signal processing **1)** To select and identify sensor as completely as possible from commercially available units (e.g., switches, potentiometer, tachometers, incremental optical encoders, resolvers…) to meet the task requirements. **2)** Suggest advices related to sensor placement and integration issues the integration of sensors and signal processing, on common carrier, or one chip.

3.3.6 Output signal, conditioning and interfacing selection, design and integration; Selecting sensors and actuators is followed by selecting and integrating power supplies, drive, and signal processing conditioning circuits, in order to interface the system components. In this stage, Power supplies, amplifiers, converters DAC, ADC, amplifiers, analog signal conditioning circuits, and power transistors are selected in order to *match* the sensor, controller and actuators specifications and ratings. The *real-time interface* process falls into the electrical and information system categories. In mechatronics, the main purpose of the real-time interface system is to provide data acquisition and control functions for microcomputer. The purpose of the acquisition function is to reconstruct a sensor waveform as a digital sequence and make it available to the computer software for processing. In this stage suggest advices related to Interface placement and integration issues

3.3.7 Control unit selection and integration: The most critical decision in the Mechatronics design process is the control unit selection (physical controller).The controller is the central and most important part (brain) of the mechatronic system, it reads the input signals representing the state of the system, compares them to the desired states, and outputs signals to the actuators to control the physical system. There are a number of possible options including but not limited to: Microcontroller/microprocessor (e.g. PIC-microcontroller), Programmable logic controller (PLC), computer control; desktop/laptop, Digital Signal Processing (DSP) integrated circuits. In this stage suggest advices related to Control unit placement and integration issues**.**

3.3.8 Control algorithm selection: The control unit and control algorithm selections are directly related to each other, there are many controller algorithms that can be used for mechatronic systems including but not limited to : ON-OFF control, P, PI, PD and PID control, intelligent control, Fuzzy control, adaptive control, Neural network control. The main factors that might influence the decision on selecting certain control unit and algorithm include; simplicity, space and integration, processing power, environment (e.g. industrial, soft..), precision, robustness, unit cost, cost of final product, programming language, safety criticality of the application, required time to market, reliability and number of products to be produced.

3.3.8.1 Control system design: The term control system design refers to the process of selecting feedback gains structures and parameters 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. [18-19].

3.3.9 Selection and integration of human–machine interaction field: Control of the machine, and feedback from the machine which aids the user (e.g operator , customer) in making operational decisions, including but not limited to : efficient, simple and easy to understand and use interface , enjoyable to operate a machine, simple input/ output means such as LEDs, digital display, LCD, touch screens, voice activation.

3.3.10 Develop complete and detailed system block diagram layout: Based on system's sub-systems and components selection, design and integration, a complete and detailed system block diagram layout is developed, showing interconnections and interrelation and energy flow.

3.3.11 Parallel (concurrent) design, integration and optimization of sub-systems and whole system: 'Smart mechatronic robotic guidance system': The proposed design of smart wheelchair is an application form of line follower mobile robot, intended to help and support people with disabilities and special needs to perform specific predetermined tasks particularly, motion around holy Kaba, Makka. Two, top and side, views of proposed system design are shown in Figure 7. Such mobile Robot can be designed and built using the following components; two in-line with each other actuators, two drive circuit for each actuator, embedded sensors for path detection, range detection and speed sensors, a control unit embedded within the system and based on inputs state, capable of controlling two drive channels, controls the motion of wheelchair robot. Usually, mobile platforms are supported by two driving rear wheels; and with stability augmented by one or two front caster wheel(s) . The two rear wheels are responsible of moving the robot, and used to turn the robot in any required direction depending on the difference of speed of wheels' rotation between the right and left wheels.

3.3.11.1 Actuators selection and integration: The accurate control of motion is a fundamental concern in mechatronics applications, where placing or moving an object in the exact desired location or with desired speed with the exact possible amount of force and torque at the correct exact time, while consuming minimum electric power, at minim cost, is essential for efficient system operation. Motion control is a sub-field of control engineering, in which the position or velocity of a given machine are controlled using some type of actuating machine. The actuating machines most used in mechatronics motion control systems are DC machines (motors). There are many DC machines that may be more or less appropriate to a specific type of application each has its advantages, limitations and disadvantages; electric motors are characterized with excellent performance in motion control, due simple principle of working, quick instantaneous and accurate torque generation, also are capable of generating high torque at low speed, can operate efficiently over a greater range of speeds, as well as ease of designing and implementing controller to achieve optimal instantaneous, precise, comfortable, smooth and safe motion control performance with low cost and in most cases are reversible, the actuating machines most used in mechatronics motion control systems are DC motors. Based on user and system requirements to meet the demand specifications, the suitable actuator selection is brushed DC motor, Wheelchair uses two commercially available brushed DC Motors, shown in Figure 8(a), its specifications and features include:; Motor Size: 71mm, , Power: 100W, 150W, 2 Poles, 4 Poles., Supplied Voltage = 12V DC ~ 36V DC, Speed 800 ~ 5000rpm, Operation Mode S1.

Actuator placement and integration (Figure 7)**:** to physically integrate mechatronics system components,(mechanical design, electronic, sensor, microcomputers and aesthetics), the selected actuator is embedded within mechanical design and to be located beneath wheelchair seat, connected through gears to wheel, a speaker is actuator used to sound corresponding Doaa, is to be integrated in mechanical design, near use head.

3.3.11.2 Sensor selection, design and integration: The proposed design requires three types of sensors; a) line sensor for path detection, is one that will gather information about the position of a path, and in turn generate signal send to controller software, b) obstacle detection sensor *for obstacle detection.* These sensors have to gather and provide a maximum number of information about path traced, and obstacles in front. Based on user and system requirements to meet the demand specifications, the following two commercially available sensors are selected, c) speed sensor to measure output speed. Based on user and system requirements, morphological table analysis, and selecting best solution, the following sensors is selected and integrated:

3.3.10.2.1 Ultrasonic proximity sensor: Ultrasonic sensors, shown in Figure 8(b), are commonly used for a wide variety of noncontact presence, proximity, or distance measuring applications. Ultrasonic sensors are employed wherever distances have to be measured in the air, since they not only detect objects, but they can also indicate and evaluate the absolute distance between themselves and the target. Changing atmospheric conditions such as temperature are compensated during evaluation of measurement. These devices typically transmit a short burst of ultrasonic sound toward a target, which reflects the sound back to the sensor. The system then measures the time for the echo to return to the sensor and computes the distance to the target using the speed of sound in the medium.

3.3.11.2.2 LDR-LED based line sensor: the predetermined path to track is chosen to be black line over white background. To recognize, detect and track this path, the suitable sensor selection is LDR-LED based line sensor, assembled together in pairs, (see Figure 9), this selection is done because it available, inexpensive, simple, easy to built, interface, and can be easily adapted to many different environments, the main disadvantage of this sensor that it's slow response to light intensity changes.

A line sensor *array* is designed to be composed of 8 cells (Figure 9 (a)) , each cell is composed of a *LED sender and a LDR receiver (*Figure 9 (b)). The sender sends,(emits) light that shall be reflected by the path or soundings, the receiver receives the reflected light and in response generate signal to send to controller. Each LDR circuitry is designed as a voltage divider circuit as shown in Figure 9. The desired resistor value should provide a voltage that covers the *on and out* black line path conditions, the output of the sensor circuit is an analogue voltage that is used as an input to the control unit (e.g. microcontroller, PIC).

3.3.11.2.3 Speed sensor (Tachometer); for controlling the motion performance of wheelchair, in particular, smooth driving for comfortable riding and minimum kicks, the required optimal output linear velocity of the wheel chair is to be 0.05 meter per second, a suitable, an inexpensive, available and easy to interface sensor used to measure the actual output motor angular speed, ω_L is Tachometer.

Sensors placement and integration (see Figure 7**):** To physically integrate mechatronics system's components, the selected sensors to detect the path must not be too high nor too low above the surface and will be located on the base of the wheelchair to provide protection against obstacles at close range, the light or color sensor must be far enough in front of the wheels (but not too far) so that it is able to discover a deviation in the line soon enough, so that the robot can adapt in time Sensors to detect obstacles to be located on the front side of the wheelchair. Tachometer is to be integrated through coupling with electric motor shaft.

3.3.11.2.4 Sensors Algorithm: The smart wheelchair uses obstacle detection and line sensors to detect presence of an object and the path (black line), the control unit decides the next move according to readings from these sensors based on a given algorithm. Ultrasonic sensor example algorithm: the safe distance to stop the wheelchair, if an object presence in the front, is 25 cm,

```
Step 1:   Read : distance to object.
Step 2:   If distance > 50 cm
            Move, or , keep velocity of 0.5 m/sec
          elseif   40 cm < distance <= 50 cm
            Decrease velocity to 0.3 m/sec
```

```
        elseif    25 cm < distance <= 40 cm
        Stop all motions
Step 3 :  Go to step 1
```

3.3.11.3 Control unit selection and integration : Embedded Microcontroller is optimal selection, since it is inexpensive single chip computer, easy to embed into larger electronic circuit designs, also, because of their versatility, Microcontrollers add a lot of power, control, and options at little cost; capable of storing and running programs, programmed to perform a wide range of control tasks, the optimal microcontroller is PIC16F917 Microcontroller, supplied with 5VDC and shown in Figure 8(c)**,** although any PIC with A/D capability would meet this criterion.

3.3.11.4 Output signal, Conditioning and Interfacing selection, design and integration:
The sensors' outputs (tachometer, line and obstacle detection) are inputted to the microcontroller, the selected microcontroller type is supported with ADC pins, to convert the input analog sensor readings to digital value. Depend on the inputs state, the outputs conditions that controlled the H-bridge circuit are provided by (C+) software, and correspondingly the motion of smart mobile robot. A voltage regulator (the IC UA723chip) is to be used to regulate the supply voltage (12 V) lowered to a level suitable for use in the microcontroller (6V), the charge controller and the LDR sensors. a heat sink is to be used to dissipate the heat generated by the long duration used. Different drives (servo-amplifier) can be used including, H-bridge Or H-Bridge in IC's. The H-bridge circuit is supplied with 12VDC and the four bits outputs of microcontroller to drive the desire conditions of electric Motor. Four NPN Power transistors are used as switch to choose the direction of current flows to the Motor, and correspondingly control the motions of wheelchair. L293D, L293D is a dual H-Bridge motor driver, it is a 16 pin chip, so with one IC we can interface *two* DC motors which can be controlled in both *clockwise* and *counter* clockwise direction .a common carrier,(see Figure 5-6). A simplified version of smart wheelchair circuit is shown in Figure 9(e).

human–machine interaction field; manual button to switch machine on-off, as will as, a touch screen, simple ,easy and enjoyable to understand, to control of the machine, and feedback from the machine, supported with LEDs, digital display. All to located and integrated with right arm support.

3.3.11.5 Control algorithm selection: A suitable, simple, precise, easy to program and implement, control algorithm for wheeled mobile motion control could be PID controller and Proportional-Integral (PI) controller with deadbeat response. Because of its simplicity and ease of design, PI controller is widely used in variable speed applications and current regulation of electric motors. A simplified algorithm for a PI and PID control implementation loop is given next [20]:

```
Read $K_P$, $K_I$, $K_P$
previous_error = 0;
integral = 0;
Read target_position    / the required position of robot center.
while ( )
Read current_position;              //the current position of robot center with respect to the line.
error = target_position  – current_position ;  // calculate error
proportional = $K_P$ * error;              // error times proportional gain
integral = integral + error*dt;          //integral stores the accumulated error
integral = integral* $K_I$;
derivative =  (error - previous_error)/dt;   //stores change in error to derivate, dt is sampling period
derivative = $K_D$ *derivative;
PID_action = proportional + integral + derivative;
//To add PID_action to the left and right motor speed.
//The sign of PID_action, will determine the direction in which the motor will turn.
previous_error =error; //Update error
end
```

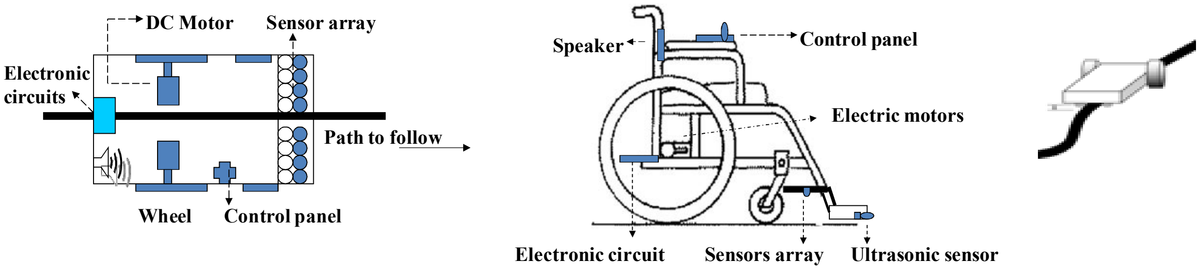


Figure 7 Sensors ,actuator and electronics placement and integration; system layout side and top views

Figure 8(a) Brushed DC Motor.

Figure 8(b)Ultrasonic Sensors

Figure 8(c) PIC16F917

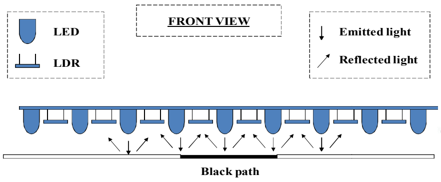


Figure 9(a) An 8 LDR- LED cells sensor.

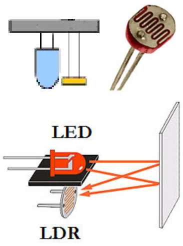


Figure 9(b) LDR- LED cell

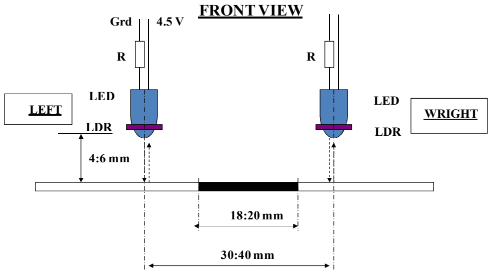


Figure 9(c) LDR- LED

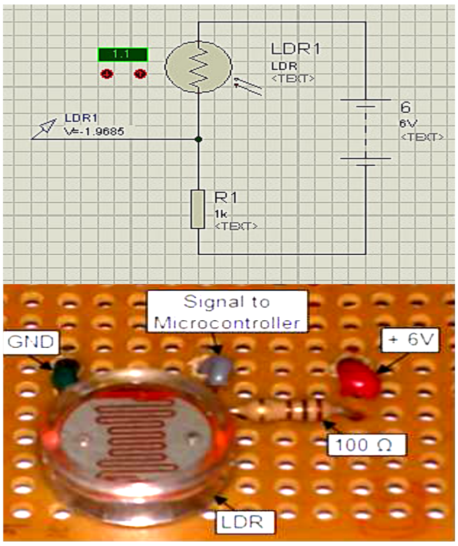


Figure 9(d) LDR- LED simulation and implementation

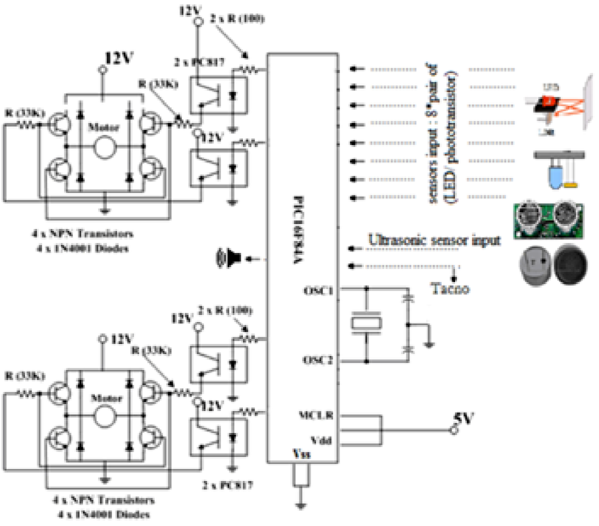


Figure 9(e) Microcontroller based wheelchair control circuit and interfacing diagram [20]

3.4 MODELING, SIMULATION, ANALYSIS AND EVALUATION

The key essential characteristics of a mechatronics engineer are a balance between two skills; modeling/analysis skills and experimentation/hardware implementation skills. The mechatronics design approach challaenge conventional sequancial design approach, by connecting machine design 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 [9]. First define the following concepts: ***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 process of construction 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. ***Topological modeling:*** a mathematical approach that allows to structure data based on the principles of feature adjacency and feature connectivity (describes and interlinks the function-performing elements), 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 [2-3]. ***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. ***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. 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. ***Unmodeled errors*****,** Unfortunately 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**.**

The integrated approach of computer simulation and virtual prototyping, by allowing virtual testing of designs in early, integrate interdisciplinary design processes without a need to switch tools in the design process, highly reduce design risks and costs development process, facilitates communication between design teams and helps in clearly understanding the system and in defining requirement specifications for optimization of control-components selection.

Modeling, simulation, analysis and evaluation processes in mechatronics design consists of two levels, subsystems models and overall system model with various sub-system models interacting similar to real situation, all engineering subsystems should be included in overall system model: mechanical, electrical and electronic components. There are two types of modeling process, were models can be obtained by either a theoretical approach based on physical laws, or an experimental approach based on obtained measurements from the system.

a) Analytical modeling: 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 calculations and predictions (systems analyzing). Analytical component modeling 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.

A flow of modeling, simulation analysis and evaluation for mechatronics systems design and integration could be as follows (Figure 10 (a)), establish the goals to achieve; based on the specification of requirements and design. Develop physical model; represent the integrated physical system using physical model. Develop the functional block diagram and show interconnections of sub-systems and components. Develop mathematical model (subsystems and whole system), Develop mathematical mode; represent system by correct dynamic equations (differential equations). Solve the differential equation (simulation). Analyze and evaluate the design analytically. System optimization; the achievement of optimal performance for the required system performance specifications .Iterating this procedure. Based on the specification of requirements and design (as well as assumptions, performance predictions) the subsystems models and the whole system model, are to be tested and analyzed, specifications to test and check whether the given design specifications are satisfied, specifications can be made in a variety of forms including rise time, peak time, percentage overshoot, steady-state error, settling time, bandwidth, gain margin, phase margin, time constants, damping ratio, optimal value of a performance index, pole and zero locations. If the specification are not satisfied, , modifications can be made, if the specifications are satisfied *the model can be Optimized*, finally the prototype is built and tested, if the prototype behaves as required, the design need not advance any further [21]. Commercial software tools available to design, model and simulate mechatronic systems, include MATLAB/Simulink, labview, Scilab/Scicos, Ptolemy, JMathLib [22] CAE tools,3D-CAD softwares Pro/Engineer, CATIA, and SolidWorks for visualization and collision detection ,MATRIX-X, ACSL, these tools allow the stydy and analysis of components interaction and variation in design. In [2] presented an example *on the modeling process of mechatronic product*, on the proposed procedure to form accurate and relevant models of mechatronic products, and presented in the diagram, Figure 10(b).

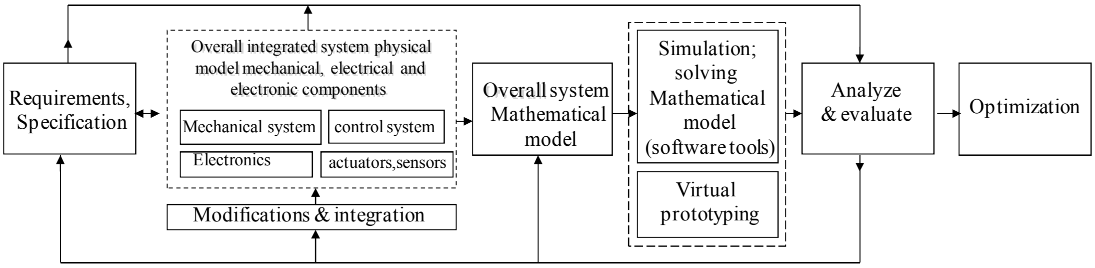


Figure 10(a) flow of modeling, simulation analysis and evaluation for mechatronics systems design.

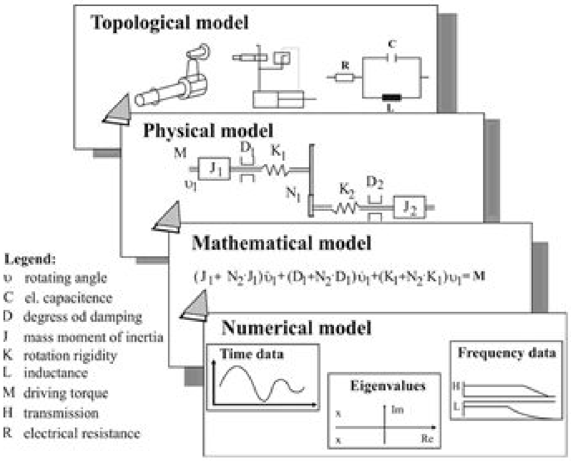


Figure 10(b) The modeling process of mechatronic product [2]

3.4.1 Modeling, simulation, analysis and evaluation:' Smart mechatronic robotic guidance system': The proposed design of mobile robot, in the form of smart wheelchair, motion control is simplified to a PMDC motor motion control, the simplest and widespread approach to control the mobile robot motion is the *differential drive* style, it consists of two in-lines with each other DC motors. Both DC motors are independently powered so the desired movements will rely on how these two DC motors are commanded, there are many motor motion 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 DC machines and corresponding motion control strategy for specific application and desired overall response. The most basic design requirements of a given electric DC motor are to rotate at desired angular speed $\omega = d\theta/dt$ and to achieve desired angular position, θ , at the minimum possible steady-state error e_{ss} , also the motor must accelerate to its steady-state speed, $\alpha = d^2\theta/dt^2$ as soon as it turns on, this means it is desirable to have a minimum suitable settling time , T_s that will not damage the equipment (e.g. T_s in less than 2 sec), and the minimum suitable overshoot, Mp (e.g. Mp less than 5%). and zero steady state error**.** . Often, the goal for a control system is to achieve a fast response to a step command with minimal overshoot, a more suitable response is achieved applying design for deadbeat response. Different researches introduce different methodologies and approaches for mobile robot modeling and controller design, including [23-30]

3.4.1.1 Motors sizing: to specify, preferably, motor and drive combination that can provide the torque, speed and acceleration as required by the mechanical set, Proper motor sizing will not only result in significant cost savings by saving energy, reducing purchasing and operating costs, reducing downtime, etc.; it also helps the engineer to select and design better motion control systems. Motor constant K_m is the most convenient figure of merit for sizing DC motors for any motion control application. K_m defines the ability of the motor to transform electrical power to mechanical power. Physically, K_m represents the available torque T per square-root watt of *input* power in Watt ; and given by: $K_m = T/\sqrt{P}$ Where: The load torque and power supply are normally specified. $P = I^2 R$ .the power dissipated by the motor. $T = K_t * I$, Peak torque at Vp, R : armature resistance. K_t : Torque constant, I: armature current, K_m and K_t ,can relate by substituting $P = I^2 R$ and $T = K_t * I$, this gives: $K_m = K_t/\sqrt{R}$.

3.4.1.2 Modeling of basic physical sub-system model with no control involved; The Actuator sub-system modeling*:* Design of controllers involve 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. The plant, the PMDC motor is an example of electromechanical systems with electrical and mechanical components, a simplified equivalent representation of PMDC motor's two components are shown in Figure 10 (c) .The equations of motion for the wheelchair robot will consider the simple case of single-degree-of freedom motion, moving forward and reverse. A simplified model of a symmetric half of system is constructed as shown in Figure 10 (d) and used to write the equivalent model.

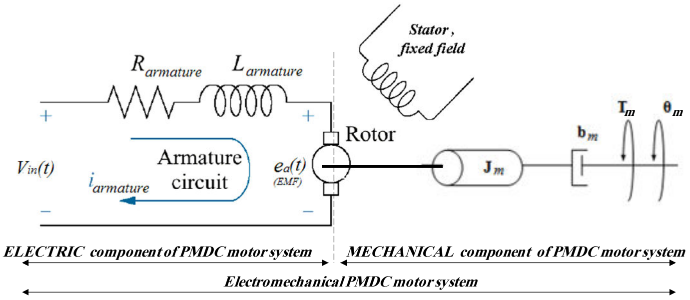


Figure 10 (c) Schematic of a simplified equivalent representation of the PMDC motor's electromechanical components

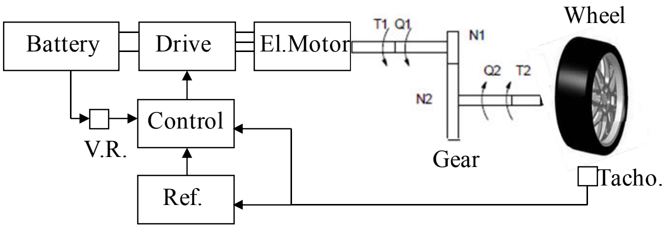


Figure 10(d) A simple model of half of the wheelchair.

Different researches on motion control, modeling, simulation and control of electric motor and mobile robots, can be found including [23-30]. Applying a voltage to motor coils produce a torque T_m in the armature, the torque developed by the motor ,T_m is related to the armature current, i_a by a torque constant, K_t and given by the following equation:

$$\text{Motor Torque} = T_m = K_t * i_a \qquad (2)$$

The back electromotive force, EMF voltage, e_a is induced by the rotation of the armature windings in the fixed magnetic field. The EMF is related to the motor shaft angular speed ,ω_m by a linear relation given by:

$$e_a(t) = K_b * d\theta_m(t)/dt = K_b \omega_m \qquad (3)$$

Equation that describes the *electrical characteristics* of DC motor is obtained applying Kirchoff's law around the electrical loop, gives:

$$(1)\ V_{in} = R_a * i_a(t) + L_a\left(\frac{di_a(t)}{dt}\right) + K_b \frac{d\theta(t)}{dt} \qquad (L_a s + R_a)\, I(s) = V_{in}(s) - K_b s\theta(s)$$

The torque, developed by motor, produces an angular velocity, $\omega_m = d\theta_m/dt$, according to the inertia J and damping friction, b, of the motor and load. Performing the energy balance on the PMDC motor system, equation that describes the *mechanical characteristics* of DC motor is given by:

$$K_t * I(s) - J_m\ s^2\theta(s)\ ?\ b_m * s\ \theta(s) = ? \Rightarrow K_t I(s) = (J_m s + b_m)\, s\, \theta(s) \quad (2)$$

Based on derived equations, the PMDC motor open loop transfer function without any load attached relating the input voltage, $V_{in}(s)$, to the shaft output angular velocity, $\omega(s)$, is given by:

$$G_{speed}(s) = \frac{\omega(s)}{V_{in}(s)} = \frac{K_t}{\left\{\left[(L_a s + R_a)(J_m s + b_m) + K_t K_b\right]\right\}} = \frac{K_t}{\left[(L_a J_m)s^2 + (R_a J_m + b_m L_a)s + (R_a b_m + K_t K_b)\right]} \qquad (3)$$

State space representation of PMDC open loop sub-system: The state variables (along with *the input* functions) used in equations describing the dynamics of a system, provide *the future state* of the system. Mathematically, the state of the system is described by a set of first-order differential equation in terms of *state variables*. The state space model takes the below form, rearranging Eqs.(1) and (2) to have the two first order equations given by (4)(5), relating the angular speed and armature current:

$$\frac{dx}{dt} = Ax + Bu \qquad \frac{d\omega}{dt} = \frac{K_t * i_a}{J_m} - \frac{b_m * \omega}{J_m} - \frac{T_L}{J_m} \quad (4)$$

$$y = CX + Du \qquad \frac{di_a}{dt} = -\frac{R_a * i_a}{L_a} - \frac{K_b * \omega}{L_a} - \frac{V_{in}}{L_a} \quad (5)$$

Looking at the DC motor position θ, as being the output, and choosing the state variable position θ_m, velocity ω_m and armature currents i_a, Substituting state variables, for electric and mechanical part equations rearranging gives:

$$\begin{aligned} x_1 &= \theta \\ x_2 &= \frac{d\theta}{dt} \Leftrightarrow \\ x_3 &= i_a \end{aligned} \qquad \begin{aligned} x_1' &= \frac{d\theta}{dt} = x_2 \\ x_2' &= \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt} = \frac{K_t * i_a}{J_m} - \frac{b_m * \omega}{J_m} - \frac{T_L}{J_m} \Leftrightarrow \\ x_3' &= \frac{di_a}{dt} = -\frac{R_a * i_a}{L_a} - \frac{K_b * \omega}{L_a} - \frac{V_{in}}{L_a} \end{aligned} \qquad \begin{aligned} x_1' &= \frac{d\theta}{dt} = x_2 \\ x_2' &= \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt} = \frac{K_t * i_a}{J_m} - \frac{b_m * \omega}{J_m} - \frac{T_L}{J_m} \\ x_3' &= \frac{di_a}{dt} = -\frac{R_a * i_a}{L_a} - \frac{K_b * \omega}{L_a} - \frac{V_{in}}{L_a} \end{aligned}$$

Looking at DC motor speed, as being the output, the following state space model obtained:

$$\frac{d}{dt}\begin{bmatrix} \dot{\theta} \\ i \end{bmatrix} = \begin{bmatrix} -\frac{b}{J} & \frac{K_t}{J} \\ -\frac{K_b}{L} & -\frac{R_f}{L} \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L} \end{bmatrix} V_{in} \quad (6)$$

$$\dot{\theta} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ 1 \end{bmatrix} + [0] V_{in}$$

3.4.1.3 Wheels, Gears and inertias modeling: The geometry of the mechanical part determines the moment of inertia, the wheelchair platform can be considered to be of the cuboid or cubic shape (*Figure 11)*, with the inertia calculated as shown below, where the total equivalent inertia, J_{equiv} and total equivalent damping, b_{equiv} at the armature of the motor with gears attaches, are given by:

$$\begin{aligned} b_{equiv} &= b_m + b_{Load}\left(\frac{N_1}{N_2}\right)^2 \\ J_{equiv} &= J_m + J_{Load}\left(\frac{N_1}{N_2}\right)^2 \\ J_{load} &= \frac{bh^3}{12} \end{aligned} \quad (7)$$

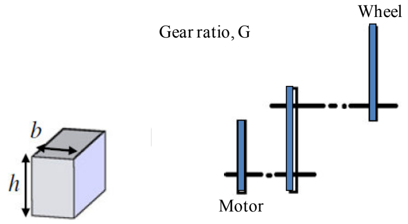


Figure 11 wheelchair inertia and Gear ratio

The inertias of the gears and wheels have to be included in the calculations of total equivalent inertia, as follows:

$$J_{equiv} = J_{motor} + J_{gear} + (J_{wheel} + mr^2) * \left(N_1 / N_2\right)^2$$

Referring to Figure 12, the output linear velocity of wheelchair equals to the linear velocity of any given point on the outer circumference of the wheel, therefore: the speed of wheelchair is equal to the circumference of the wheels multiplied by speed of wheels turning:

$V_{\text{wheelchair}}$ = wheel circumference * ***RPS***

Where: RPM= ***RPS*** *60. Wheel circumference = 2 π r ,The relation between RPM and angular velocity is given by $\omega_{rad/\sec} = RPM\,(2\pi/60)$. The angular velocity in terms of RPM given by: ω = (π RPM)/30

$V_{\text{wheelchair}}$ = wheel circumference * S ⇔ Distance travelled per minute = π x RPM = π x S x 60

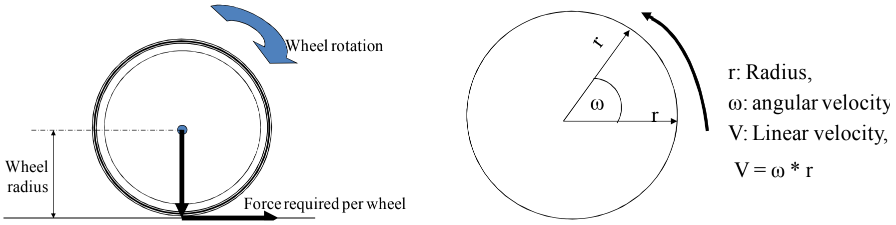


Figure 12 The output linear velocity of wheelchair.

The equivalent mobile robot system open loop transfer function with load and gears attached, in terms input voltage, $V_{in}(s)$, to output shaft angular velocity, $\omega(s)$, is given by:

$$G_{speed}(s) = \frac{\omega_{robot}(s)}{V_{in}(s)} = \frac{K_t / n}{\left[(L_a J_{equiv})s^2 + (R_a J_{equiv} + b_{equiv} L_a)s + (R_a b_{equiv} + K_t K_b)\right]} \qquad (8)$$

3.4.1.4 Sensors sub-system modeling: Tachometer is a sensor used to measure the actual output mobile robot angular speed, ω_L. Dynamics of tachometer can be represented using the following equation:

$$V_{out}(t) = K_{tac} * d\,\theta(t)/dt = V_{out}(t) = K_{tac} * \omega$$

The transfer function of the tachometer is given by:

$$V_{out}(s) \quad \omega(s) = K_{tac}$$

Tachometer constant: we are to drive our wheelchair system, with linear velocity of 0.5 the angular speed is obtained as:

$$\omega = V / r = 0.5/0.075 = 6.6667 \text{ rad / s},$$

Therefore, the tachometer constant, for $\omega = 6.6667$, is given as: $K_{tac} \overset{?}{=} 12 / 6.6667 = 1.8$

3.4.1.5 Smart wheelchair System (plant) dynamics modeling: When deriving an accurate mathematical model for mobile system it is important to study and analyze dynamics between the road, wheel and platform and considering all the forces applied upon the mobile platform system. Several forces are acting on mobile platform when it is running, the modeling of a mobile platform system dynamics involves the balance among the acting on a running platform forces, and these acting forces are categorized into road-load and tractive force. The road-load force consists of the gravitational force, hill-climbing force, rolling resistance of the tires and the aerodynamic drag force and the aerodynamics lift force, where aerodynamic drag force and rolling resistance is pure *losses*, meanwhile the forces due to climbing resistance and acceleration are conservative forces with possibility to, partly, recover. This resultant force is the sum of all these acting forces, will produce a counteractive torque to the driving motor, i.e., the tractive force. Figure 13 shows that changes in the road surface inclination angle, α is a disturbance introduced to the system, therefore it is required to design controller to be robust and should have a disturbance rejection. The disturbance torque to mobile platform is the total resultant torque generated by the acting forces.

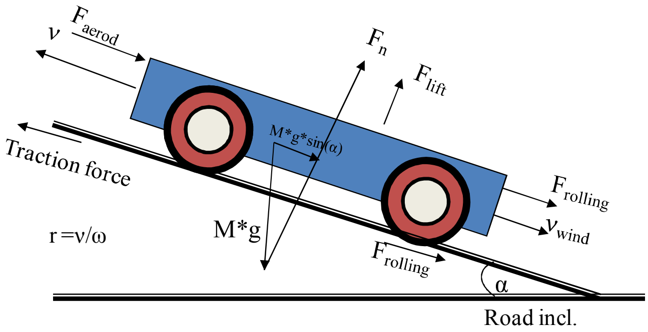


Figure 13 Forces acting on moving mobile robotic platform [20].

Rolling resistance force, $F_{rolling}$, and rolling resistance torque are given by:

$$F_{rolling} = F_{normal\_force} * C_r = M * g * C_r * \cos(\alpha) \qquad (9)$$

$$T_{rolling} = (M * g * C_r * \cos(\alpha)) * r_r$$

M : The mass of the electric vehicle and cargo (*Kg*). *g:* The gravity acceleration *(m/s^2)*. v: the vehicle linear speed, C_{r0} the friction coefficient for wheel mechanism that accounts for friction in the wheel bearings and other speed-dependent retarding torques,

Aerodynamic Drag force , F_{aerod} the force opposing the motion of the vehicle due to air drag, wind resistance, **F_{aerod}** , and the aerodynamics torque are given by:

$$F_{aerod} = 0.5 * \rho * A * C_d * \upsilon_{vehicl}^2$$

$$T_{aerod} = \left(0.5 * \rho * A * C_d * \upsilon_{robot}^{\ 2}\right) * r_r \qquad (10)$$

The hill-climbing resistance force F_{climb}; While the mobile platform is moving up or down a hill, the weight of the mobile platform will create a hill-climbing resistance force directed downward, this force will oppose or contribute to the motion, ***F_{climb}*** torque are given by:

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

$$T_{climb} = F_{slope} = (M * g * \sin(\alpha)) * r_{wheel} \qquad (11)$$

The angular acceleration force F_{acc_angle},
F_{acc_angle}, is the force required by the wheels to make angular acceleration and is given by:

$$\mathrm{F}_{\mathrm{acc\_angle}} = J\frac{G^2}{r_{wheel}^2}a \qquad (12)$$

The angular acceleration torque is given by:

$$T_{\mathrm{acc\_angle}} = r_{wheel} * J\frac{G^2}{r_{wheel}^2}a = J\frac{G^2}{r_{wheel}}a$$

The needed energy of mobile platform, the requested power in kW that mobile platform must develop at stabilized speed can be determined by multiplying the total force with the velocity of the platform:

$$P_{Total} = (\sum F) * \upsilon = F_{Total} * \upsilon \qquad (13)$$

Substituting derived dynamic equations and applying the total torque to electric motor equation, will result in mathematical model of mobile platform dynamics, given by (14).

3.4.1.6 overall Smart wheelchair system modeling , with no control involved: Based on equations derived and describing DC motor, wheelchair dynamics and speed sensor, the next open loop transfer function, relating the armature input terminal voltage, $\mathrm{V_{in}(s)}$ to the output terminal voltage of the tachometer $V_{tach}(s)$, with most load torques applied are considered, is given by:

$$G_{open}(s)\frac{\mathrm{V_{in}}(\mathrm{s})}{V_{tach}(s)} == \frac{K_{tach} * K_t}{(L_a s + R_a)(J_m s + b_m) + (L_a s + R_a)(T) + K_b K_t}$$

Where: T the disturbance torque, is all torques including coulomb friction, substituting and rearranging gives:

$$G_{open}(s) = \frac{2K_{tach} * K_t}{2b_{equiv}L_a s^2 + r^2 M L_a s + 2b_{equiv}R_a s + r^2 M R_a s + C_r L_a s + 2J_{equiv}L_a s + 2K_b K_t + C_r R_a + 2J_{equiv}R_a} \qquad (14)$$

3.4.1.7 Control system modeling: A suitable controller for wheelchair mobile motion control could be PID controller and Proportional-Integral (PI) controller with deadbeat response. A negative closed loop feedback control system with forward controller and corresponding simulink model shown in Figure 14 (a)(b) are to be used.

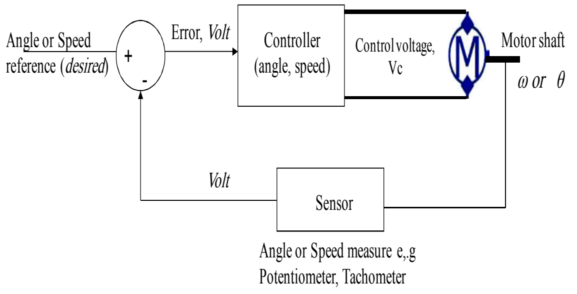


Figure 14 (a) Block diagram representation of system control

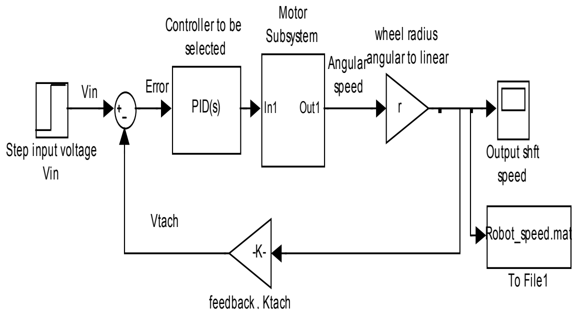


Figure 14 (b) Preliminary simulink model for negative feedback with forward compensation

3.4.1.7.1 PID controller modeling and design*:* PID controllers are commonly used to regulate the time-domain behavior of many different types of dynamic plants. The gains are to be tuned experimentally to obtain the desired overall desired response. The PID controller transfer function is given by:

$$G_{PID} = K_P + \frac{K_I}{s} + K_D = \frac{K_D s^2 + K_P s + K_I}{s} = \frac{K_D\left[s^2 + \frac{K_P}{K_D}s + \frac{K_I}{K_D}\right]}{s} \qquad (15)$$

The sign of the controller's output, will determine the direction in which the motor will turn

3.4.1.7.2 Proportional -Integral (PI) controller with deadbeat response modeling and design *:* Because of its simplicity and ease of design, PI controller is widely used in variable speed applications and current regulation of electric motors. Deadbeat response means the response that proceeds rapidly to the desired level and holds at that level with minimal overshoot, [23]. The characteristics of deadbeat response include; Zero steady state error, Fast response, (short rise time and settling time) and minimal undershoot, ±*2%* error band. PI-controller transfer function is given by:

$$G_{PI}(s) = K_P + \frac{K_I}{s} = \frac{(K_P s + K_I)}{s} = \frac{K_P\left(s + (K_I / K_P)\right)}{s} = \frac{K_P(s + Z_o)}{s} \qquad (16)$$

PI controller represents a pole located at the origin and a stable zero placed near the pole, at Z_o=- K_I/ K_P, resulting in drastically eliminating steady state error due to the fact that the feedback control system type is increased by one. The PI pole and zero will affect the response, mainly the PI zero, Z_o=- K_I/ K_P, will inversely affect the response and should be cancelled by prefilter, therefore the required prefilter transfer function to cancel the zero is given by:

$$G_{\mathrm{Prefilter}}(s) = Z_o / (s + Z_o)$$

3.4.1.9 Modeling and simulation in MATLAB/Simulink of the *half and whole* smart wheelchair system with control involved: The following nominal values for the various parameters of a PMDC motor used : V_{in}=12 v; Motor torque constant, K_t = 1.188 Nm/A; Armature Resistance, R_a = 0.156 Ω ; Armature Inductance, L_a = 0.82 MH ;Geared-Motor Inertia: J_m = 0.271 kg.m^2, Geared-Motor Viscous damping b_m = 0.271 N.m.s; Motor back EMF constant, K_b = 1.185 rad/s/V, gear ratio, n=3, wheel radius r =0.075 m, The following nominal values for the wheelchair parameters; wheelchair height, h= 0.920 m, wheelchair width, b = 0.580 m, the distance between wheels centers = 0.4 m, The total equivalent inertia, J_{equiv} and total equivalent damping, b_{equiv} at the armature of the motor are ,J_{equiv} =0.275 kg.m^2 , b_{equiv} = 0.392 N.m.s. The most suitable linear output speed of suggested mobile robot is to move with 0.5 meter per second, (that is ω=V/r = 0.5/ 0.075 = 6.667 rad/s. Tachometer constant, K_{tac} = 12 / 6.667=1.8 rad/s.

Figure 15(a), show Simulink model of the *half* smart wheelchair system, system considering all sub-systems and dynamics, the simulation of overall whole smart wheelchair system is shown in Figure 15(b), applying Proportional-Integral (PI) controller with deadbeat response characteristics and pre-filter. Running model for Zo =1.9 and Kp =1.1, will result in torque/time, current/time, angular speed/time, linear speed/time response curves, shown in Figure 15(c). by adjusting Zo and Kp , any such desired. Replacing the PI controller characteristics, in Figure 15(a), with PID block with, gains (K_P=0.623624252918818 , K_I =1.15839303547577 , K_D=-0.0353790380687044, and filter coefficient 17.626942024477), running this model will result in response curves shown in Figure 15(d) , the PID gains can be adjusted using PID tuning block.

*Robot differential drive Model*ing, simulation is represented in overall system model in Figure 15(b), whole system response for straight, curvature and circular motion are shown in Figure 15(e).

3.4.1.8 Electronics and interfaces simulation and testing; simulation in Proteus: To test and evaluate the selection, circuit design, programming and interface of each of microcontroller, software, electronics, H-bridge and/or L93D IC, transistors, sensors, PWM signal and motor speed, the system with all components can be simulated using ISIS-Professional Proteus, 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 simulation is shown in Figure 16, after testing, evaluating and optimizing various aspects, the final simulation results show the correctness of written program, interfaces, components, and microcontroller, all these can be used to build the optimal physical circuit

3.4.1.9 Analysis and evaluation: Applying (PI) controller with deadbeat response controller, Several observations can be made, first, for *12 V* input, the wheelchair system will reach output angular speed of *6.67 rad/s* that is *0.5 m*/s in allmostly *2 s*,. Second, the mobile wheelchair system draws about *7.8* Amp, peak and about *A* continuous in operation. The response curve shows achieving smooth driving for comfortable riding and no kicks (overshoots), the system take suitable time (2 seconds) to reach desired output linear speed, the system is robust against disturbance, all design and user requirements are met. If the design specifications are still not met, simple modifications to the control components and algorithms should be attempted. If further improvements are needed to satisfy the performance requirements, more sophisticated control techniques and algorithms should be implemented. If the problems persist, we may want to return to the previous step and change the system components or even modify the control system structure. If the performance is still not satisfactory, we should seriously consider replacing or redesigning the plant itself and repeating the design steps outlined above [21]. After verifying the required system design through computer simulation, the given numerical values for whole system and components simulation, particularly, wheelchair dimensions, weight, gear ratio, wheel radius, DC motor parameters, speed sensor, all these components can be acquired in order to assemble-integrate the required system.

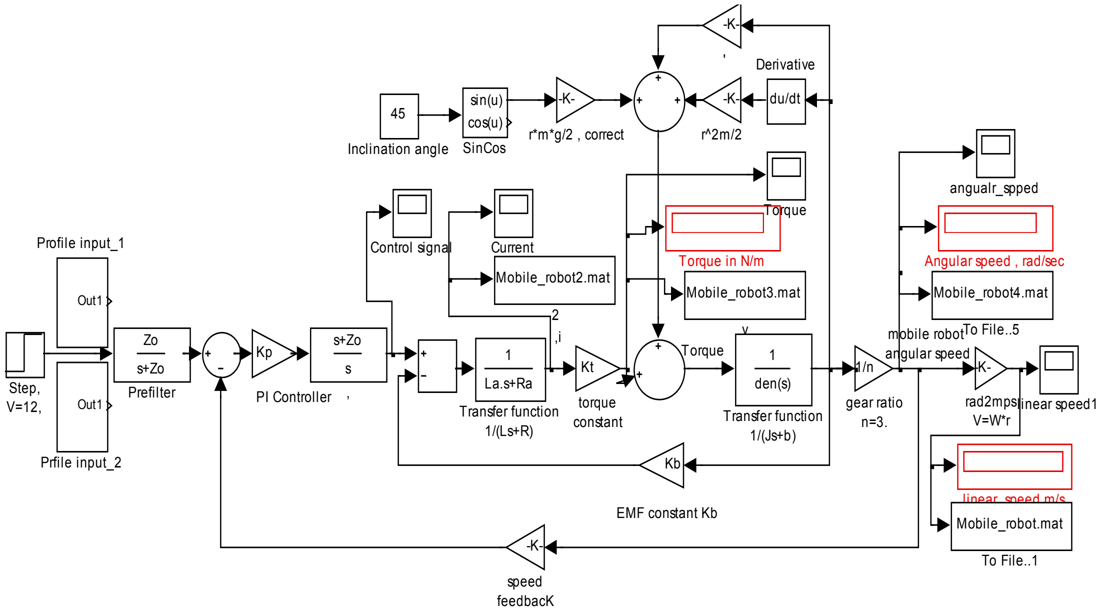


Figure 15(a) simulink model of half wheelchair.

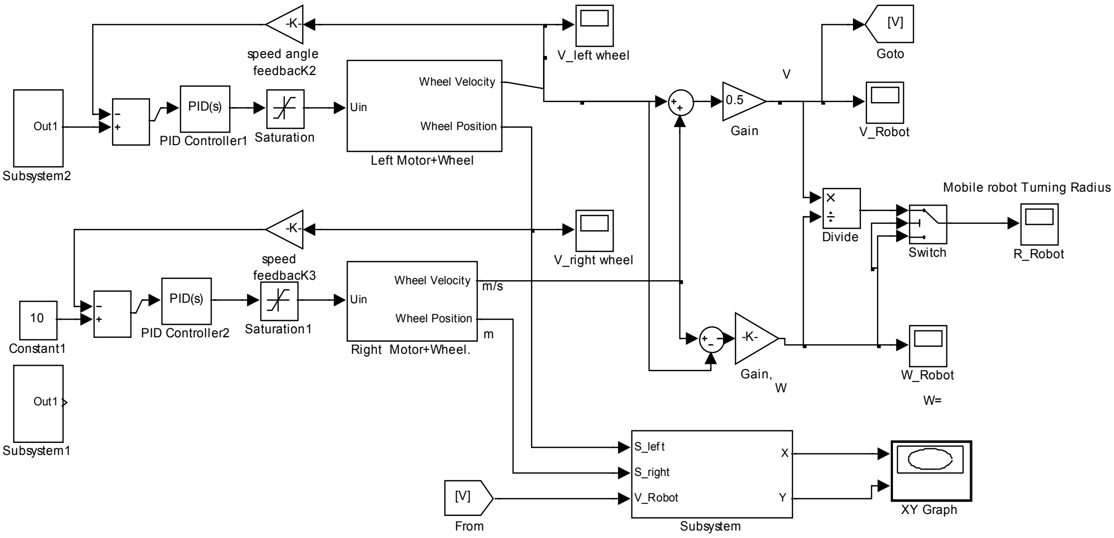
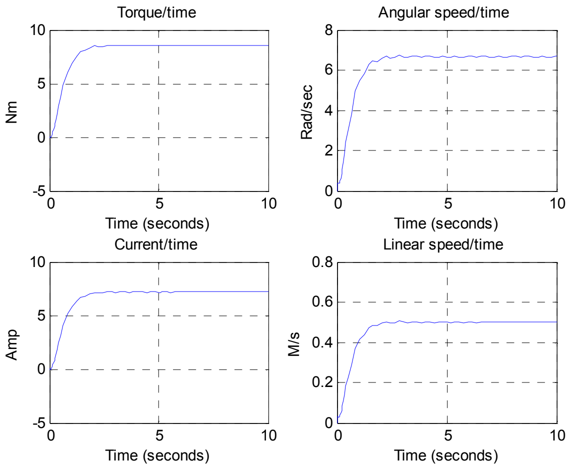


Figure 15(b) Simulink model of overall wheelchair system [20].



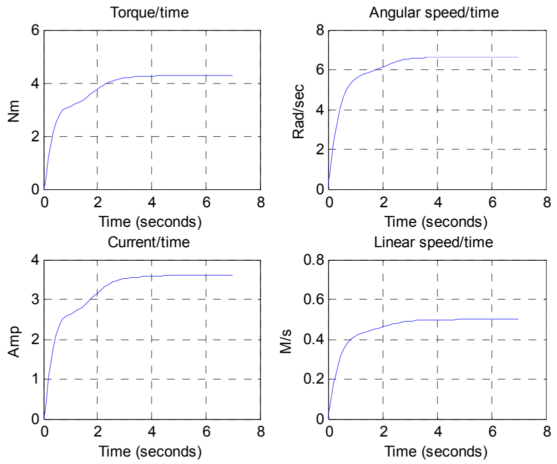
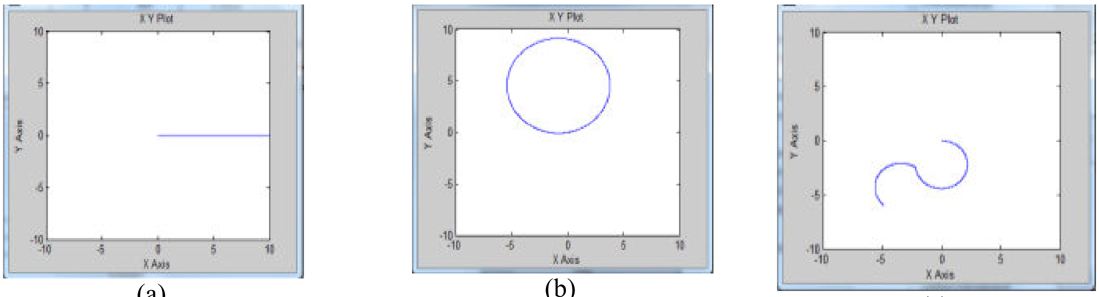


Figure 15(c),. Linear speed/time, torque/time, angular speed/time and current/time response curves of medium mobile robots model with PI controller with deadbeat response.

Figure 15(d) linear speed/time, torque/time, angular speed/time and current/time response curves of the accurate close loop mobile robotic platform model with PID controller.



(a) (b) (c)

Figure 15(d) Three different trajectories of the central point of the mobile robot.

3.5 PROTOTYPING, TESTING, EVALUATION AND OPTIMIZATION

As noted, 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. In order to take into account the unmodeled errors and enhance precision, performance in the design process, the mechatronics design approach includes ***prototyping*** phase. A *prototype* is models used to test, evaluate and optimize various aspects of a new design to enhance precision, performance and gather early user feedback. *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.

Prototyping development may be carried out in the following two forms; ***1) Virtual Prototype*** Virtual prototyping is an aspect of information technology that permits analysts to examine manipulate, and test the form, fit, motion, logistics, and human factors of conceptual designs on a computer monitor. It facilitates communication between different engineering disciplines during the early design process and also provides quality illustrations that help "sell the design or program [31] ,simply, it is 3D model of a product presented in a virtual environment with, *ideally*, all information and properties included, it involves using computer-aided design (CAD) and computer-aided engineering (CAE) software to validate a design before committing to making a physical prototype prototype ***2) Physical Prototype***: System integration to ensure *components* and *subsystems* work together . Testing and evaluation of the should be done under *normal operating conditions* and desired performance specifications and preferably at an actual application environment. The shortcomings of designed system should be identified; correspondingly design of mechatronics system should be refined, and possibly redesigned, to overcome any shortcomings.

3.5.1 Prototyping, testing, evaluation and optimization ' Smart mechatronic robotic guidance system'

3.5.1.1 Virtual prototyping: There are many industrial robotics software simulator for 3D Modeling and Rendering, some has type of robotics software has a simulator that is a "virtual" robot which is capable of emulating the motion of an actual robot in a real work envelope and realistic renderings and movements of the robot in 3D space, examples include RoboLogix and MOBS - Mobile Robot . System simulation in Simulator MOBS is shown in Figure 17 [32].

3.5.1.2 Physical prototyping: All selected and designed Sub-systems and components, were integrated in one first prototype to ensure subsystems, components and whole smart mechatronics Robot-Motawif (shown in Figure 18) work together and meet user's needs and requirements. Testing and evaluation were done under normal operating conditions and desired performance specifications, at first, smart wheelchair was used to perform main motions in performing Al Omrah at a similar to Alharam Alshareef application environment at Mechatronics Sec. Lab., Taif University, Taif, Saudi Arabia 2012, the shortcomings of designed system are identified, and the corresponding design of mechatronics sub-system is refined, and some of components and program aspect were redesigned.

3.6 Manufacturing and Commercialization

Once the developed system is tested, refined, and confirmed to satisfy the required specifications, the processes of technology transfer to industry and commercialization, could begin. Prepare products documents including preparing necessary production and operation structures, infrastructure and an approved business plan, and funds. Suitable plans for commercial development and marketing.

According to the existing practice, engineers, scientists, and technicians provide minimal input into these activities which is not desirable and needs to be greatly improved [21].

3.7 Support, service and market feedback analysis.

The sustained success of products commercial and marketing depends on market feedback analysis and a comprehensive range of customer support and service including a highly experienced team of support and service engineers that enables manufactures to provide a broad spectrum of services including; Consulting Services, Operational Services, Application Services

Market feedback analysis is to use of objective market data, customer satisfaction surveys, interviews, routine interactions and communications, product and service quality and reliability data, to give insight into customers' perspective and expectations of product modifications of design and performance.

4. Conclusions

The key element in success of a mechatronics engineering education-program, and correspondingly, Mechatronics engineering graduates, is directly related to the applied structural design methodology. Based on VDI 2206 guideline and different industrial, scientific and educational recourses, a mechatronics systems design education-oriented methodology is proposed to fulfill mechatronics optimal program requirements. The proposed methodology consists of a systematic specific simple and clear simultaneous design and integration steps (shown in diagram 2(a)(b)) that can be memorized and followed, as well as support non experienced student or group of students in solving mechatronics design integrated tasks. The design methodology aims to integrate multidisciplinary knowledge, in various stages including pre-study process and problem statement, conceptual design, optimal parallel selection and synergistic integration, modeling, simulation, prototyping, analysis and physical implementations through the design process and development of mechatronics product. The proposed mechatronics design methodology is described, discussed and applied with the help of example student graduate project; design and implementation of mechatronics mobile robotic guidance system in the from of smart wheelchair- Mechatronics Motawif, to help and support people with disabilities and special needs to perform specific predetermined tasks, particularly, performing Al Omrah and motion around holy Kaba, Makka.

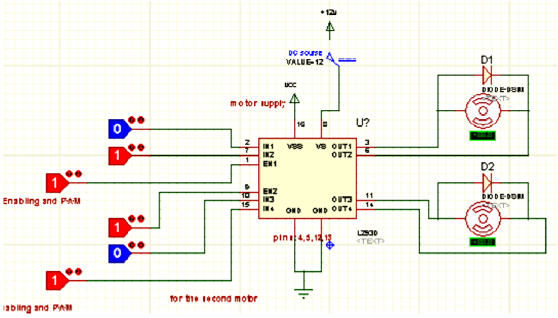


Figure 15(a) simulation of controlling DC motor driver IC L293D

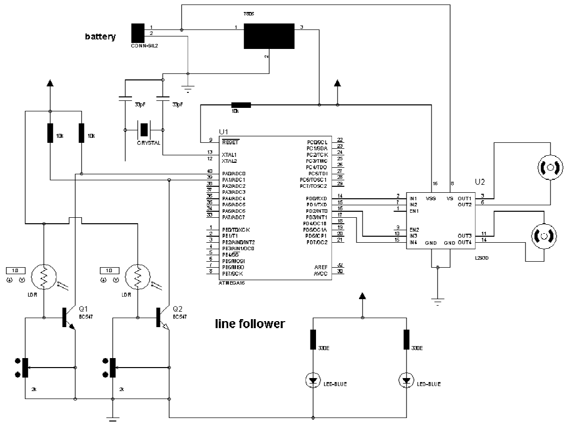
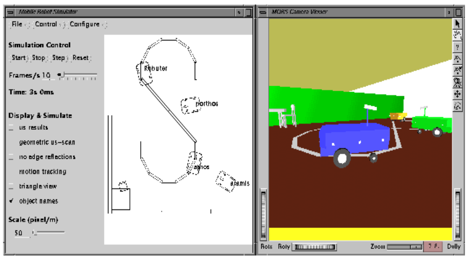


Figure 15(b) overall system simulations in Proteus



Frames/s 10
Time: 3s 0ms
☑ object names
Scale (pixel/m) 50

Figure 17 MOBS Mobile Robot Simulator [32]

Figure 18 The designed smart Mobile Robotic guidance system –Mechatronics Motawif, Mechatronics Sec. Lab., Taif University, Taif, Saudi Arabia 2012.

References

[1] K. Craig, F. Stolfi, “Teaching control system design through mechatronics: academic and industrial perspectives.” Mechatronics, Vol 12, No. 2, pp. 371-381, 2002.
[2] Vasilije S. Vasić , Mihailo P. Lazarević, Standard Industrial Guideline for Mechatronic Product Design , FME Transactions, 104 , vol. 36, No 3, 2008.
[3] Lyshevski, S.E.: Mechatronic curriculum – retrospect and prospect, Mechatronics, Vol. 12, No. 2, pp. 195-205, 2002.
[4] VDI, Verein Deutscher Ingenieure (Ed.), VDI guideline 2206,2004-06, title " Design methodology for mechatronic systems" VDI-Society Product and Process Engineering, Author: Technical Division Product Development and Mechatronics,
[5] Yu Wang, Ying Yu,Chun Xie, Xiaoyang Zhang, Weizhi Jiang, A proposed approach to mechatronics design education: Integrating design methodology, simulation with projects, Mechatronics, November 2012.
[6] Devdas Shetty, Richard A. Kolk, Mechatronics System Design, Second Edition, SI, Cengage Learning, 2011.
[7] De Silva, Clarence W., Mechatronics: An Integrated Approach, CRC Press, 2005.
[8] Robert Bishop, Mechatronics systems, sensors and actuators, fundamentals and modeling, CRC Press, 2nd edition, 2008
[9] Sarah Brady, Multidisciplinary machine building, the institute of engineering technology http://eandt.theiet.org/magazine/2008/12/machine-building.cfm
[10] Rolf Isermann, Modeling and Design Methodology for mechatronics Systems,IEE/SME transaction on mechatronics, VOL. 1, No 1, March 1996
[11] Manfred Lohöfene, design of mechatronics systems and benefits of open source software tools, 9th International Workshop on Research and Education in Mechatronics September 18th-19th 2008, Bergamo, Italy
[12] P. Hehenberger, K. Zeman, Hierarchical structuring of mechatronics design models, Elesevier, 3rd IFAC symposium, volume 2, 2004

[13] J. Burr, Mechatronics design in Japan: a study of Japanese design methods and working practice in Japanese companies. Lyngby: Technical University of Denmark, 1989.
[14] Ken Hurst, Engineering design principles, Elisevier ,2004
[15] Andrew P. Sage, William B. Rouse, system engineering and management, Wiley and sons, 2nd edition, 2009.
[16] Isermann, R.: Mechatronic design approach, in Bishop, R.H. (Ed.): *The Mechatronics Handbook*, CRC Press, Boca Raton, Section I: Overview of mechatronics, ch. 2, p. 3, 2002.
[17] *Main mechanical descriptions and images were quted from : http://www.assistireland. ie/ eng/ Information/Information_Sheets/ Choosing_a_Standard_Self-Propelled_Wheelchair.html
[18] D'Azzo, John Joachim, Houpis, Constantine H, “Linear control system analysis and design: conventional and modern“, 1988.
[19] Hedaya Alasooly, "Control of DC motor using different control strategies" global journal of technology and optimization 2011 .
[20] Ahmad A. Mahfouz, Ayman A. Aly, Farhan A. Salem, "Mechatronics Design of a Mobile Robot System", Submitted and accepeted,I.J. Intelligent Systems and Applications, Submission ID 99, 2012.
[21] L Al-Sharif, A Saleem, and TA Tutunji, Mechatronic system design: The ideal capstone course? 7th International Symposium on Mechatronics and its Applications (ISMA), 2010, also L Al-Sharif "Mechatronics System Design 0908531: Course Notes", Mechatronics Engineering Department, University of Jordan.
[22] Manfred Lohöfener, design of mechatronics system and benefits of open source software tools, *9th International Workshop on Research and Education in Mechatronics September 18th-19th 2008, Bergamo, Italy*
[23] Richard C. Dorf, Robert H. Bishop, Modern Control Systems 12 Ed, Pearson Education, Inc., 2001
[24] Thomas R. Kurfess, “Robotic and Automation Handbook,” Washington, D.C., United States of Amarica, 2005.
[25] Mohsen Shahinpoor, “A Robot Engineering Textbook,”HAPPER & ROW, Publishers, Inc.,10 East 53rd street, New York, NY10022, 1987.
[26] Bashir M. Y. Nouri ,modeling and control of mobile robots Proceeding of the First International Conference on Modeling, Simulation and Applied Optimization, Sharjah, U.A.E. February 1-3, 2005.
[27] Chun Htoo Aung, Khin Thandar Lwin, and Yin Mon Myint, Modeling Motion Control System for Motorized Robot Arm using MATLAB World Academy of Science, Engineering and Technology 42, 2008.
[28] Ramjee Prased, modeling of robotic arm,10804900, Rh680B54,B. TECH (LEET) BCE
[29] Ahmad A. Mahfouz, Mohammed M. K. , Farhan A. Salem Modeling, simulation and dynamics analysis issues of electric motor, for mechatronics applications, using different approaches and verification by MATLAB/Simulink (I). Submitted and accepeted, I.J. Intelligent Systems and Applications, Submission ID 123 , 2012.
[30] Wai Phyo Aung, Analysis on Modeling and Simulink of DC Motor and its Driving System Used for Wheeled Mobile Robot, World Academy of Science, Engineering and Technology 32 2007.
[31] James C. Schaaf, Jr. and Faye Lynn Thompson. “Systems Concept Development with Virtual Prototyping”. Proceedings of the 29th conference on Winter simulation, pp. 941 - 947. 1997. DOI 10.1.1.74.2308
[32] University of Western Australia, MOBS, Mobile Robot Simulator; http://robotics. ee.uwa. edu.au/mobs.
[33] John Billingsley, "Essentials of Mechatronics" , John Wiley & Sons,2006. Kenway Chen, Jitesh Panchal, Dirk Schaefer , an integrated approach to design mechatronics systems: cross-disciplinary constraint modeling" , ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE 2008, New York City 2008
[34] Nikolay Avgoustinov, "Modelling in Mechanical Engineering and Mechatronics: Towards Autonomous Intelligent Software Models" Springer, 2007.
[35] Clarence W. Silva , "Mechatronic Systems: Devices, Design, Control, Operation and Monitoring" , CRC, 2007.
[36] Andrzej M. Pawlak “Sensors and Actuators in Mechatronics: Design and Applications" ,CRC , 2006.
[37] Ryszard Jablonski, Mateusz Turkowski, Roman Szewczyk, "Recent Advances in Mechatronics" , Springer; 1 edition, 2007.
[38] Lu, R.X. A new approach for mechatronic system design: mechatronic design quotient (MDQ), IEEE/ASME International Conference on Advanced Intelligent Mechatronics. Proceedings, 2005
[39] Nadine Le Fort-Piat, Alain Bourjault, " Recent Trends in Mechatronics", ISTE, 2003
[40] R. H. Bishop, “Mechatronics : an introduction”. CRC/Taylor & Francis, 2006.
[41] S. Behbahani; C. W. de Silva, “A New Multi-Criteria Mechatronic Design Methodology Using Niching Genetic Algorithm“. Proceedings of the IEEE Congress on Evolutionary Computation, Vancouver, Canada, 2006p. 327 –332.

[42] Coelho, M.A.O., Trabasso, L.G., Nordmann, R., Felzer, T.Dedini, F.G.A User-Centred Mechatronics Design Method ,11th Mechatronics Forum Biennial International Conference.
[43] Roos F. Wikander J., “Towards a Holistic Design Methodology for Mechatronics”, Mekatronikmöte -05, Halmstad, November 2005.
[44] Roos F., “On Design Methods for Mechatronics – Servomotor and Gearhead”, Licentiate Thesis, TRITA-MMK 2005:02, ISSN 1400-1179, ISRN/KTH/MMK/R-05/02-SE, Jan 2005
[45] Wilfried Voss, "A Comprehensible Guide to Servo Motor Sizing", Published by Copperhill Technologies Corporation, Massachusetts, 2007.

This academic article was published by The International Institute for Science, Technology and Education (IISTE). The IISTE is a pioneer in the Open Access Publishing service based in the U.S. and Europe. The aim of the institute is Accelerating Global Knowledge Sharing.

More information about the publisher can be found in the IISTE's homepage:
http://www.iiste.org

CALL FOR PAPERS

The IISTE is currently hosting more than 30 peer-reviewed academic journals and collaborating with academic institutions around the world. There's no deadline for submission. **Prospective authors of IISTE journals can find the submission instruction on the following page:** http://www.iiste.org/Journals/

The IISTE editorial team promises to the review and publish all the qualified submissions in a **fast** manner. All the journals articles are available online to the readers all over the world without financial, legal, or technical barriers other than those inseparable from gaining access to the internet itself. Printed version of the journals is also available upon request of readers and authors.

IISTE Knowledge Sharing Partners

EBSCO, Index Copernicus, Ulrich's Periodicals Directory, JournalTOCS, PKP Open Archives Harvester, Bielefeld Academic Search Engine, Elektronische Zeitschriftenbibliothek EZB, Open J-Gate, OCLC WorldCat, Universe Digtial Library , NewJour, Google Scholar