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A Systems Approach to a Final Year Mechatronics Design Course*

DAVID GUERRA-ZUBIAGA and EDGAR RAMÓN-RAYGOZA
Department of Mechanical Engineering, School of Engineering and Architecture, Tecnologico de Monterrey Campus Monterrey, Monterrey, 64849, México. E-mail: david.guerra@itesm.mx

VIANNEY LARA-PRIETO, ROBERT PARKIN and MIKE JACKSON
Mechatronics Research Group, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK

Mechatronics is the science that studies the holistic design process in which intelligent machines are created to develop efficient and complex processes and products. Mechatronics integrates mechanics, electronics and computer sciences to achieve control and automation. The effective integration of these different components is a complex task that should be accomplished in the design phase. This work presents a systems approach to a mechatronics design course at ITESM, México. In their final year, engineering students are taught a methodology to design a mechatronic product. The methodology includes: the early stages of clients' needs identification, process characterization, literature review, and ideas generation, which lead to both the design and simulation of the mechanical, electronic and control stages. This series of steps is inspired in a number of different design methodologies, which are available from the literature and can be adapted to the available tools and circumstances at the university. This paper describes a practical way to integrate the existing specialised techniques and tools to generate an efficient design of a mechatronic product. Some of the virtual tools that are available to design, evaluate and integrate the different parts of a mechatronic design are also discussed. The systems approach was applied by the students to different mechatronic projects in industry, thus creating good links between university and manufacturing companies with satisfactory results. One of the numerous case studies is described in this paper as well as its outcomes, to provide evidence of the educational value of the methodology.

Keywords: design methodology; mechatronics education; product design

1. INTRODUCTION

MECHATRONICS is the field of technology that deals with the integration of mechanics, electricity, electronics, and control systems as a whole [1–2] by taking into consideration the interaction of these disciplines.

The goal of mechatronics is to have a flexible system that can adapt to its environment, detect critical operation situations and optimize processes that would be dangerous or difficult to control otherwise [3–4]. This is generally achieved using software and electronic devices that implement a control system to respond to external changes [5].

A recent trend has been to incorporate mechatronics into the academic engineering curricula [6–10]. This paper presents a systems approach to a Mechatronics engineering Bachelor program at ITESM, Campus Monterrey, México. It is taught over a semester to an established class named Mechatronics Design Methodology (MDM).

The activities and responsibilities of the students and teacher in this course are resembled to those of Project Oriented Learning (POL). POL is an established didactic technique that incorporates an inductive learning process instead of deductive, so that students can develop skills and abilities that demand an active participation [11].

A particularity of this approach is that it involves collaborative work between students, university's staff and manufacturing companies. The methodology presented in this paper is the result of an iterative process that includes the development of more than forty real industrial projects.

Many of the available methodologies are focused on a specific discipline such as mechanics, electronics or control design as independent elements [4–5]. This paper also contributes by presenting an approach to integrate existing specialized techniques and tools. In addition, the relationship between students, university staff, experts and manufacturing companies is described.

2. EXISTING MECHATRONICS DESIGN METHODOLOGIES

Design methodology is defined by Pahl and Beitz [12] as a 'concrete course of action for the design of technical systems that derives its know-

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ledge from design science and cognitive psychology and from practical experience in different domains'. This section discusses different design methodologies specifically intended for the area of mechatronics, both from the academic and industrial points of view.

Gausemeier [13] presents a sequence of design steps in a virtual three-dimensional space in order to develop a product. This scheme suggests that there is no clearly defined procedure for designing and developing mechatronics products in engineering, but only a process consisting of alternate synthesis and analysis steps.

The VDI guideline 2206 shows a flexible procedure model with three main parts: a general problem-solution cycle at micro-level, a V-model at macro-level, and the processing of tasks that occur repeatedly during the development process. The V-model is a cycle that begins with the requirements for the product in order to define a system design specifying the principle solution [14].

Dieterle [3] presents a design methodology from the point of view of industrial requirements. The methodology is called 'Systems Engineering Mechatronic' and its targets are high design efficiency and high design quality. In order to achieve these, this methodology is based in the VDI V-model at customer, system and component levels.

TCG is a university company that has been formed to give mechatronics training and consulting. They teach and implement the following design procedure. Basically, the proposed procedure begins with a description of the desired system. Then a physical and mathematical model is generated and simulated to observe its behaviour. Next, the control system is designed and a closed-loop simulation is performed to compare it with the previous one and finally make the required modifications [5].

The methodologies presented in [3, 13–15] concur in providing a concept solution concretized for each engineering domain and then integrating them into a whole system. [13] and [15] believe that the key element of the design process should be the modelling and simulation of the product. These statements are also supported in the design approach taught at ITESM and described in this paper.

From both the academic and industry perspectives, it is believed that mechatronics design methodologies should be addressed in engineering education [3, 5]. Teamwork in a project-oriented base is also presented as a challenge for students [3, 16]. A procedure to design real-world situations in industry is showed in [5]. The one presented here involves a more complete process. A design structure matrix is actually used in [15] but it just shows the relations between sub-system components needed to fulfil requirements. In this paper, IDEF0 and QFD techniques are addressed to achieve a more in-depth analysis.

3. ENVIRONMENT OF THE PROPOSED MECHATRONICS DESIGN METHODOLOGY

The Mechatronics Design Methodology (MDM) described in this paper enables the design and development of products and systems in a Product Life-cycle Management (PLM) environment [17]. For this reason, the main stages of PLM will be described as well as the project logistics and coordination to give readers a clear idea of the environment in which the MDM was implemented. This is shown in Fig. 1 and will be explained in further detail in the following sections.

3.1 Relationship between PLM and MDM

During the life-cycle of a product, several phases can be identified: product design, process development, production, distribution, use and disposal. These are shown at the outer part of Fig. 1. PLM is a way to integrate the information and knowledge

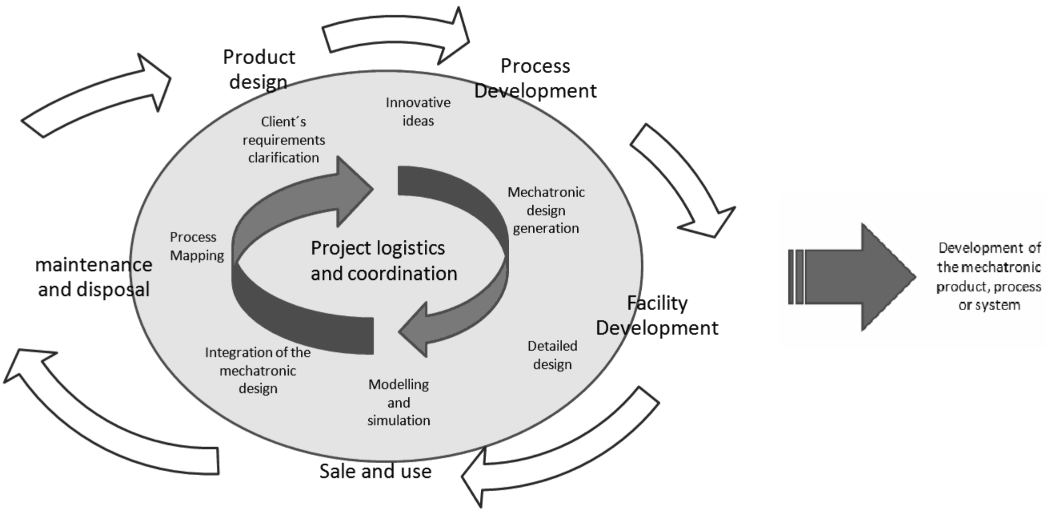

Fig. 1. Mechatronics Design Methodology environment.

produced during this process in order to improve and increase innovation for a given product [18].

Product Design is the first stage to be addressed by PLM [19]. It includes listening to the customer, process identification and an up-front product definition. Identification of the clients' requirements and innovative ideas generation are steps included in this stage of the MDM to help the students and experts to put forward a better project plan. It is important to mention that new developments that have a wrong starting plan are likely to fail [20].

During the second PLM stage, the focus is on the selection of material and manufacturing processes. Their effective implementation is the fundamental issue in the success of a project management office [21]. The present MDM involves a step for process identification to provide an insight into how the process is currently being done and how it can be improved.

The next phase deals with the facility development. The place in where the product will be processed must be designed in order to optimize the factory flow [19]. With regard to this, some of the projects developed under this MDM have had to design tentative machinery distribution for their solution to have any significance.

In the use and maintenance phase, the product or process faces different operating conditions, some of which could not have been anticipated in the planning process, so it becomes necessary to identify the opportunity areas for their further improvement. What is asked of the MDM course students is that they foresee the issues involved with this PLM phase as much as possible.

The final PLM stage comes when the product has fulfilled its mission and disposal becomes necessary. The recycling concept becomes very important due to global concern for sustainable development [22].

3.2 Project logistics and coordination for the MDM activities

The physical and organizational infrastructure has been considered as being divided into two parts, called University and Industry. As stated above, this methodology focuses on the development of a solution for a particular issue in an industrial environment. The University then applies PLM through hardware, software and human resources to accomplish the desired goal. On other hand, Industry must have an authentic interest in solving a problem, time availability and human resources, as well as the capital to invest in the project. These and the following concepts and relationships are depicted in Fig. 2, which could be placed in the centre of Fig. 1, but has been separated for the sake of clarity and understanding.

MDM experts need to make contact with a company in order to develop a plan for a project. In this first contact, Industry provides the mechatronic projects that the University is going to develop. The Industry then provides access to a manufacturing facility or plant and aid from process experts who are responsible for providing information, as shown on the left of Fig. 2.

The University's competitive advantage is based on its *experts*' and *students*' knowledge and their access to both specialized software and hardware. The experts are graduate students who have or are pursuing either a Masters' or Doctorate degree in the mechanical or control areas.

The mechanical and control engineering experts have a broad vision of how to propose and plan problem solutions, so they also support the teamwork by establishing working guides. The *students* are enrolled into the MDM course. They carry out the research related to the project, process identification, and characterizing customer's needs and the proposal, as well as developing a solution over one semester, guided by the MDM. A project-based High School Mechatronics Course is showed in [16] focusing in POL, Project Based Learning, and self-learning for the students, making them more familiar with real design processes in engineering.

In parallel, there are graduated students behind the hardware, software and logistic infrastructure. These are computer systems administrators and application engineers. In addition, they help the MDM expert directly in coordinating.

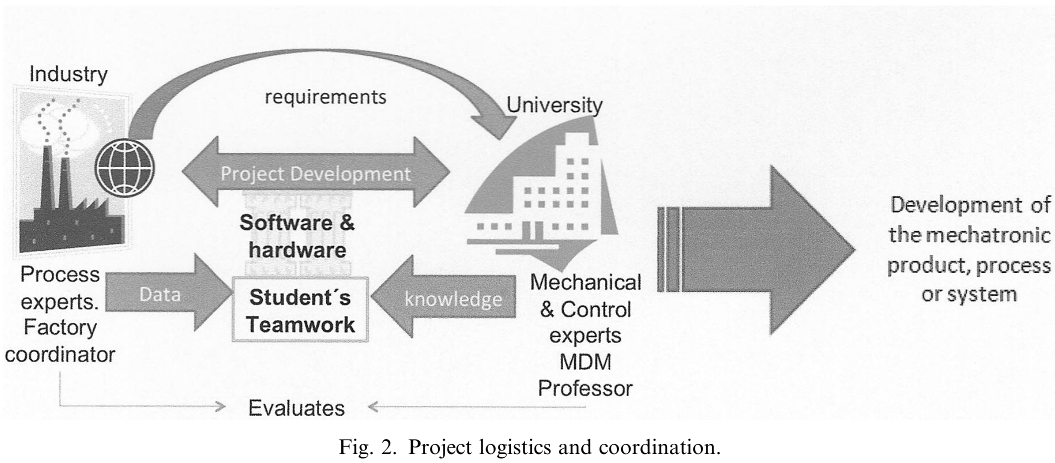

Fig. 2. Project logistics and coordination.

Finally, the University staff delivers results in the form of a mechatronic product. The students earn an academic grade based on the customer's satisfaction.

4. MECHATRONICS DESIGN METHODOLOGY

It is important to remember that the goal of this systems approach is to teach students how to integrate different tools into a mechatronic solution for a project. This series of steps is inspired in different design methodologies available in the literature and adapted to the available tools and circumstances at the university. For more complete design methodologies with different techniques and tools at each of the design phases consult [12, 23]. The methodology followed in the class is presented in Fig. 3. The V shape is adopted to show that the steps go from general to specific (at the detailed design definition and modelling and simulation stages), and then to more general again.

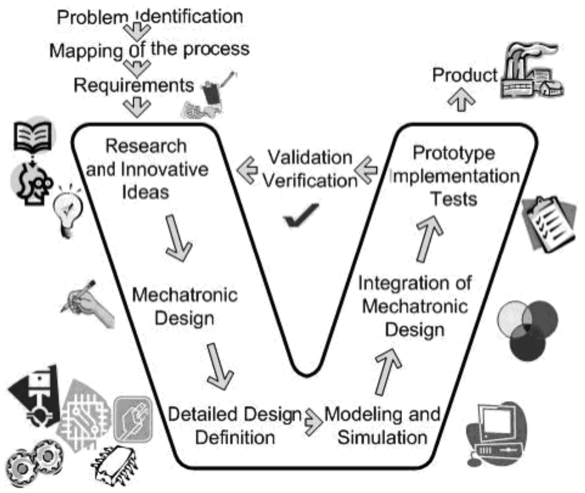

Fig. 3. Mechatronics Design Methodology combined with the V model.

Before applying the methodology, it is necessary to diagnose the problem reported by the company and establish the factors that could have a strong impact on the problem. The first can be achieved using an Ishikawa Diagram, which is also referred to as *cause and effect*. On the other hand, the Pareto Chart helps in the identification of the most common causes that impact a problem at least 80% of the time [24]. Figure 4 shows an example of how these tools can be related.

4.1 Mapping of the integral product development process using IDEF0

Once the problem has been diagnosed, the first step is to represent the process related to the project using IDEF0 in order to get a better understanding of it and to identify the factors that are related to it. Four types of interrelations exist: entrances, exits, control elements and mechanisms or resources. The functions are represented by rectangles and the connections by arrows [25]. There may be different levels of detail for a single function. The main level is represented by A-0. The first sublevel is represented by A-0, followed by A-1, A-2, etc. A maximum of six or five levels is customarily accepted. The latter is represented by Fig. 5. Other techniques of functional modelling can be found in [12, 23].

4.2 Client's requirements clarification using QFD

The next step is to identify and clarify the client's requirements as well as the way in which these demands could be satisfied, establishing a relationship between these parameters according to their

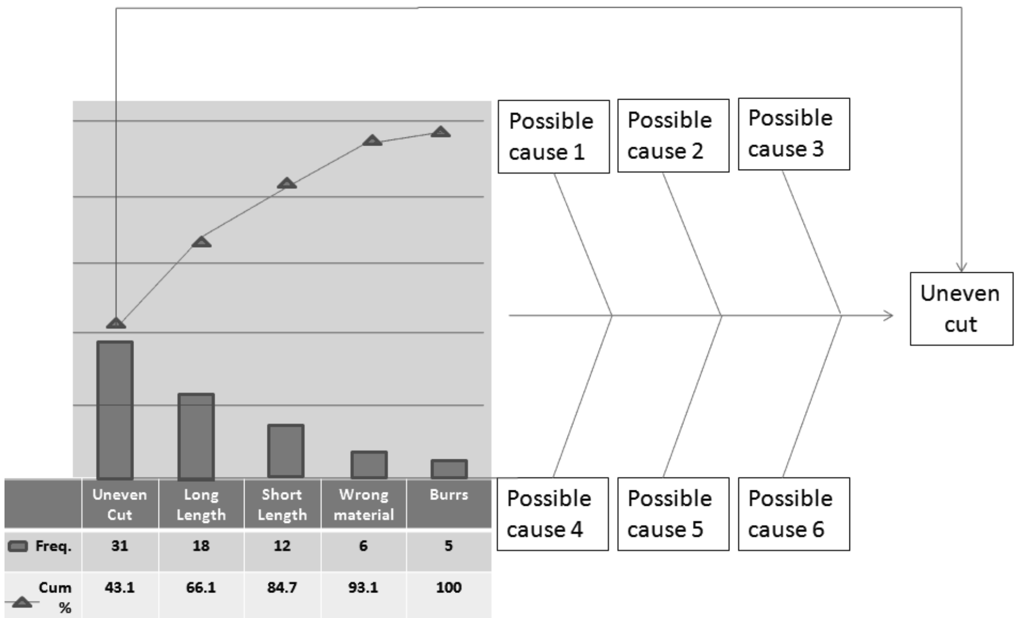

Fig. 4. Ishikawa–Pareto diagrams interaction.

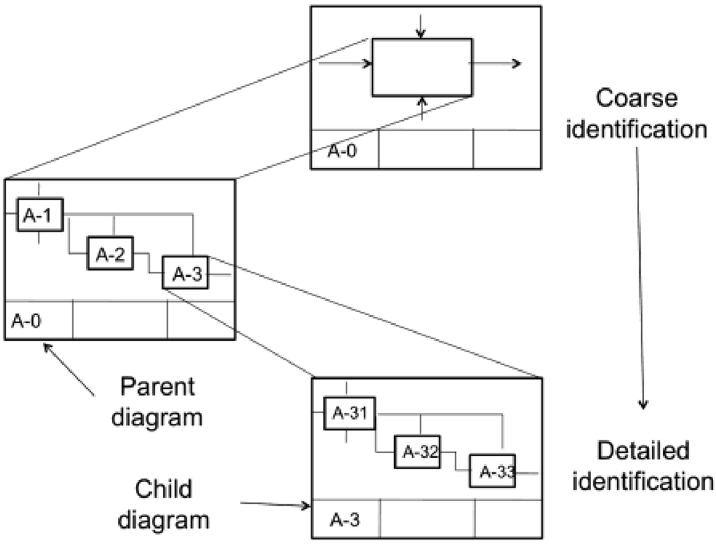

Fig. 5. IDEF0 subsystem representation (adapted from [26]).

importance. This is achieved using QFD. Quality Function Deployment (QFD) is a means of identifying the customer's requirements, such as needs or demands. It then translates them into relevant technical requirements throughout each stage of the product development process. From the MDM point of view, it helps in the identification of what the client needs, how the solution should be achieved and the importance given to that solution, as well as for benchmarking the particular mechatronic project [27–28].

4.3 Innovative ideas for the mechatronic product development

It is necessary to review and analyse the state of the art around the solution to be developed in order to generate innovative ideas for the new mechatronic product, process or system. For this reason, this MDM allows a search for patents and articles from journals to synthesize them into useful information for the project. This is a common way of getting to grips with what is being done regarding the project and how it can be applied to it. Furthermore, it is recommended that you use a knowledge management tool such as TechOptimizer® to reach the solution. This software has access to patent databases and also includes product and principles analysis. TechOptimizer® is able to link physical and chemical principles, as well as patent data, to the requirements of the solution being developed.

4.4 Mechatronic design generation

The goal of this stage of the methodology is to come up with a concept of how the project should be developed. It is important to remember that the mechatronic solution is a synergy between mechanics, electricity, electronics and control systems.

Before the solution is designed, some of the difficulties that might be faced should be anticipated. The solution must also comply with the requirements imposed by the process itself and the customer. At this point, the data retrieved with IDEF0 and QFD will be useful to propose a targeted solution. Moreover, valuable information can be obtained with the literature review from information databases, journals and patents. Either consciously or unconsciously, all the knowledge provided by the sources mentioned will help the students to focus on the real needs and possible feasible solutions.

This is the phase where the collaborative work starts being fundamental. Even when the MDM students have a common academic background, their points of view may often be different. These discrepancies should be taken as something good for the project development, because they allow students to have discussions about how the solution must be planned. The goal of this stage is that students start developing the solution. This can be done by hand drafting their ideas.

4.5 Detailed design definition

At this stage of the methodology, the individual designs of the mechanic, electric, electronic and control elements of the project are specified. It is important to incorporate all the information gathered and generated from the previous steps, including the Design Generation. This is a more realistic approach than in the Design Generation, above, so geometrical and functional constraints and tolerances must be established.

There are different tools for designing the mechatronic parts. For example, CATIA® is very useful for product design. Other options include SolidEdge® and Pro-Engineer®, but they are mainly applied to mechanical components. CATIA® also has a module for designing electrical and electronic components, electrical connections for facilities and circuit boards.

However, there is other specialised software that would be better for use on electronic and electrical circuits. Examples of this are MultiSim® and Electronics Workbench®. PSpice® is also recommended for complex or precise electric circuits.

Regarding control systems, MatLab® includes a module called SimuLink® for the complete design of the required control system.

4.6 Modelling and simulation support for the mechatronic design through software

Companies rely on tests to prove that their products are within the clients' specifications or grant guarantees for them. Nowadays, there is a more cost- and time-effective way to perform tests than making experimental studies or physical prototypes. This is called *Virtual prototyping*. It helps to model and simulate engineering designs [30]. It is based on the assumption that the virtual system is modelled as close as possible to the real system. Even when the system could be modelled on paper, it is recommended that Computer-Aided Engineering (CAE) and Computer-Aided Manufacturing (CAM) is used to evaluate the model.

There are many useful software applications for performing models of the mechatronic design's parts. For example, ADAMS® may be very good for simulation and model kinematics. MatLab® includes SimMechanics® to do mechanical modelling. LabView® may be a good option to simulate control systems. ProgramCC® may be used to model and simulate this kind of systems as well. Both MultiSim® and PSpice® are capable of simulating electronic and electric circuits. On the other hand, MultiSim® has a friendlier interface.

However, there are not many options regarding process simulation and modelling. This is the main advantage of DELMIA®, which has modules to simulate ergonomics, facilities and NC manufacturing. There are other CAM software options, however most of them do not include any other kind of simulation or modelling. For example, CutViewer® is a good simulator for NC codes, but does not have any development tools. In addition, Resource Simulation (also known as IGRIP) from DELMIA® is useful to simulate mechanisms and robotics behaviour. It has the advantage of being fully integrated to CATIA® to modify parts' design in order to fit the manufacturing process, since this is the PLM approach.

According to the specific project and needs, the appropriate software and the combination of them to use would be defined. An environment for multi-domain systems simulation called Visual Modelica Laboratory (Vimola) was developed, presenting better characteristics than their commercial equivalents, Dymola and MathModelica [31].

4.7 Integration of the mechatronic design

It is important to remember that mechatronics involves the synergy between mechanics, electronics, electricity and control systems. These concepts will be explained in this section, because

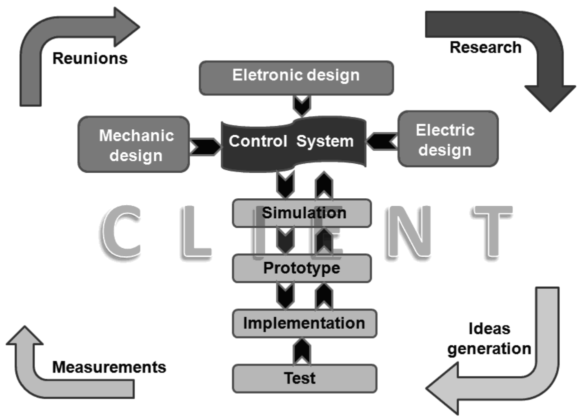

Fig. 6. Integration of a mechatronic design.

they are important in order to understand their integration.

Mechanics is easily differentiated from electronics and electricity. However, the difference between the last two is not that simple, since both of them involve electric power. An easy way to differentiate between them is to understand that electricity deals with the production, transfer and consumption of electric energy, while electronics has to do with the emission, behaviour and effects of electrons. On the other hand, control systems deal with energy and/or signals transformation to produce a desired behaviour in a given system [29].

A way to start the integration of a mechatronic design is to begin with the idea that the system may be subdivided into simple elements to be analysed, but as part of a whole design.

Figure 6 shows the control system in the centre of the mechatronic integration, because the resulting block diagram from the control system helps in the understanding of how every part of the mechatronic design interrelates. For the diagram to be useful, the mechanic, electric and electronic components needed must be characterized. For this reason, meetings are attended to take measurements, put together the information gathered from research and generate new ideas on how to continue solving the project.

Once the equations of the system had been obtained, simulation trials predict whether the system may work properly or not. This is done as described above. It is important to mention that the design success is based on the client's needs and perception, so there is constant feedback from industry via e-mail, phone calls and visits.

The stages for prototype, implementation and tests are also included in Fig. 6. These are the result of the previous steps in the MDM.

5. PROJECT EXAMPLE

One of the developed projects was the remanufacturing of a CNC machine. The objective of this project was to propose a design solution for a real problem faced by a company specialising in the fabrication of metallic moulds for glass bottles. A specific area of opportunity for the company was in the engraving of metal moulds for glass bottles. The solution had to be economic, environmentally friendly, practical, adaptable, provide a good surface finish and, above all, be capable of significantly reducing the work cycle in order to satisfy the growing demand.

The proposed solution put forward by the students involves the remanufacturing of a CNC machine adapted with a laser-milling device.

With regard to the mechanical design, a reconfigurable mechanical device was designed to adapt the laser milling device in the chuck of the CNC machine, as if it were another tool, and at the same time eliminate the mechanical offset between the chuck and the laser ray. The reconfigurable mechanical device is showed in Fig. 7. It has two main parts: the adapter and the fitter. The adapter solves the problem of the laser's support being perpendicular to the laser ray axis. On the other hand, the fitter allows the whole adapting mechanism to connect to one cone of the chuck of the CNC machine, as a conventional tool. The fitter also eliminates the coarse offset.

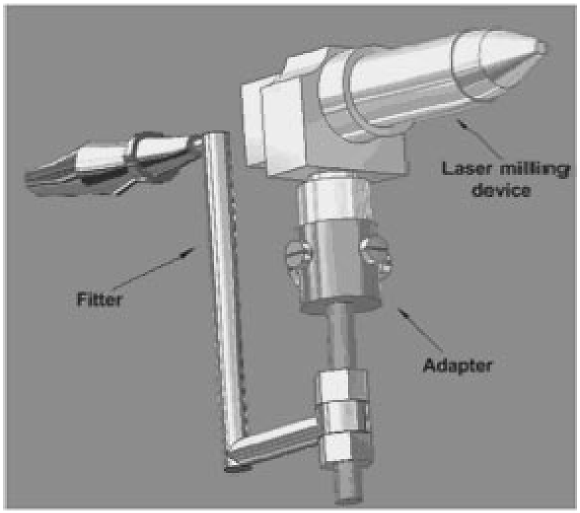

Fig. 7. Assembly of laser device and adapter.

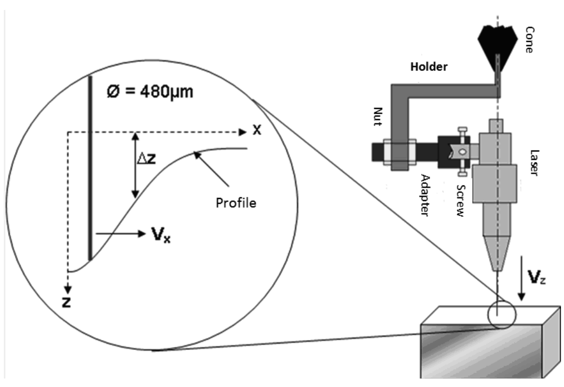

Fig. 8. Variables that determine the velocity of the work piece.

The electrical design was very simple. The electrical specifications of the laser device are compatible with the electrical system used in México, making the device easy to install. in addition, the laser device is controlled by a PLC that monitors the performance and the temperature of the cutting head, establishes limits of travel and controls the crash-avoidance features. The CNC machine receives the machining program code for the engraving design automatically generated by a CAD file. The generated machining code is written in G&M codes, which give the functions and instructions to the CNC machine.

It was necessary to determine a proper control method for the laser. The variables to be controlled were the activation and deactivation of the laser beam and the movement of the work piece with respect to the laser beam. As it is a milling process, the tool stays static and the work piece moves. Figure 8 is a schematic representation of some of the variables that determine the velocity of the work piece relative to the laser beam. A simulation was programmed using LabWindows® for graphically analysing the results of the control system.

The laser device helps to decrease the machining time and, therefore, the throughput would increase. It is definitely more economical to upgrade a CNC machine by remanufacturing than to buy or build and entirely new machine. Besides, it is an environmentally friendly solution since the design takes advantage of the already existing CNC machine and the mechanical tools and refrigerant fluids will no longer be needed. It is a practical and adaptable solution because the laser device will receive the machining instructions directly from the CAD file. Laser milling provides a quality surface finish, meeting another of the client's requirements. Last but not least, it is much faster than conventional milling, decreasing the work cycle from 3–5 hours to 20–60 minutes.

6. CONCLUSIONS

This paper describes a detailed step-by-step approach to increasing the mechatronic design performance used by the final year mechatronics course. A particularity of this approach is that it generates collaboration between students, university staff and manufacturing companies. This work also allows the synergy between existing specialized techniques and tools that were not specifically designed to produce a mechatronic product.

The MDM described in this paper enables the design and development of products and systems in a Product Life-cycle Management (PLM) environment. An important element observed in the MDM was a novel 3D modelling and simulation integration technique. This methodology showed a more complete process, including the use of state-of-the-art technology, as well as a complete analysis of customer needs in advance of previous technology works, assuring original product development.

The collaborative teaching method proposed in this work allows the goals of a real project as well as the academics ones to be reached. The assignments of different tasks and responsibilities to the students helped them to get involved in the project. The students also participated iteratively with the experts in the decision making process. This active participation helped to improve the learning process since the students were more motivated to learn. Student could observe the application of theoretical concepts to an industrial problem. Also, they developed valuable skills along the way, including innovation, attitude, commitment, collaborative work and self-learning.

By correctly applying the MDM it is possible to satisfy company requirements for both, product and process designs, as well as the university requirements for teaching mechatronics design to undergraduate students. The resulting design matches the company's requirements and are economically feasible.

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D. Guerra Zubiaga obtained his Ph.D. in manufacturing engineering from Loughborough University, UK in 2004. He is currently part time professor at Tecnológico de Monterrey, Campus Monterrey, for the Mechanical Engineering Department. His research interests are: PLM, Knowledge Management, New Technology Introduction and Product Design. Currently, he is working in industry as Mechanical Technology Leader of the Research and Development department of Prolec-GE.

E. Ramón Raygoza obtained his Masters degree in Manufacturing Systems from ITESM Tecnológico de Monterrey, Campus Monterrey, Mexico in 2007. He is currently pursuing a Ph.D. degree in nanotechnology engineering at the ITESM Tecnológico de Monterrey, Campus Monterrey, Mexico.

V. Lara Prieto obtained her BSc (Hons) in mechatronics engineering from ITESM Tecnológico de Monterrey, Campus Monterrey, Mexico in 2006. She is currently pursuing a Ph.D. degree in mechatronics engineering at the Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, UK.

R. M. Parkin gained his BSc in engineering science from Leicester University and his Ph.D. from Leicester Polytechnic, Leicester, UK in 1976 and 1980, respectively. He was a founder member of the UK Mechatronics Forum and is a Professor of Mechatronics and now Head of the Wolfson School of Mechanical & Manufacturing Engineering at Loughborough University, Loughborough, UK.

M. R. Jackson obtained his BSc (Hons) in mechanical engineering from Salford University, Salford, UK, in 1975. He obtained his Ph.D. through the CNAA and Leicester Polytechnic, Leicester, UK, in 1986. He obtained his MSc in flexible manufacturing systems and robotics at Loughborough University, Loughborough, UK, in 1987. He is currently Professor of Machine Systems at the Wolfson School of Mechanical & Manufacturing Engineering at Loughborough University.