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KNOWLEDGE-BASED SYSTEMS IN DESIGN OF MECHATRONIC PRODUCTS

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Abstract. *Mechatronic devices and control systems are fundamental to safe operational condition of complex vehicles, especially aircrafts. In order to ensure reliability of aircraft mechatronic systems, with consequent improvement in safety, it is necessary to pay special attention to failures in these devices and their consequences in other subsystems from the early design phases. In this process, an important element to be considered is the electromagnetic compatibility, which deals with electrical and magnetic relations among components or between subsystems operating in the same electromagnetic environment that may produce interference and malfunction. This paper presents a literature review on fault analysis in mechatronic and electronic control systems caused by electromagnetic problems, followed by the description of a knowledge-based system (KBS) prototype for the early design phases focused on electromagnetic compatibility and reliability of mechatronic systems. The prototype includes a knowledge base on mechatronic design. Rules and object-oriented modeling implemented as knowledge representation techniques. Results are evaluated and discussed by experts in mechatronics and design. The paper also discusses issues on expandability and validation of KBS prototype.*

Keywords: *Knowledge-Based Systems, Mechatronic Systems Design, Electromagnetic Compatibility.*

1. INTRODUCTION

Faults in mechatronic systems can have many causes. Lewis (1996) proposed a classification for sources of variability of performance characteristics: (a) Variability in the manufacturing processes; (b) variability in the operating environment; (c) product deterioration. The first is the main cause of premature failure (infant mortality), the second can lead to random failures and the third leads to failure by wear of product items. Statistically, the bathtub curve, shown in Figure 1, represents failure rates of a particular system or component during its life cycle. In this bathtub curve, it is observed that some failures occur early in the life cycle and, usually, are related to design or manufacturing problems. Wear failures are more concentrated at the end of product life. However, random failures may occur at any time during product use. These failures are less predictable and usually cause sudden problems.

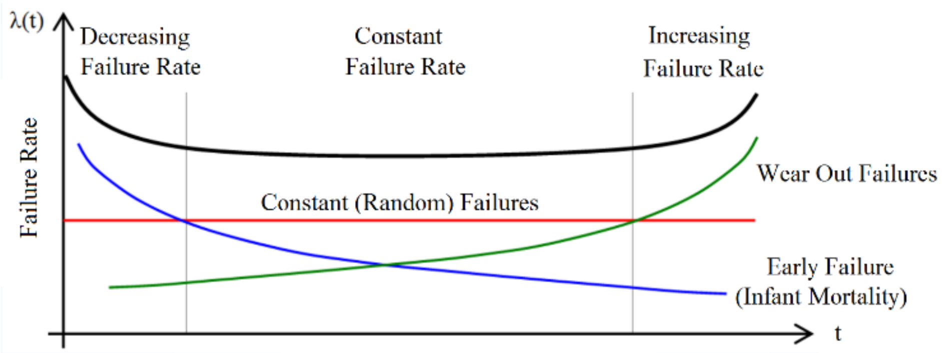

Figure 1. Bathtub curve, representing failure rates throughout the product life cycle (adapted from Smith, 2011).

Electromagnetic interference is a problem associated with electromagnetic compatibility (EMC) that may cause a simple malfunction or even the destruction of electronic circuits with catastrophic consequences. A severe interference in an electronic circuit can often cause the circulation of electric current higher than the limit specified to the circuit, leading to excessive generation of heat, risk of fire or damage to equipment. From another angle, the circuit under the action of a potentially interfering signal may be susceptible to this interference, which can influence its integrity or electromagnetic compatibility in the operating environment. To Chao Ma et all. (2010), EMC is a state that all devices in a system can work compatibly and functioning without errors in their intended environment.

In the early design stages, especially in the informational and conceptual design phases, the designers´ expertise in the embedded electronics can be used into a knowledge base. Such application represents the potential of this expertise to support the design through a computer system, to meet the reliability and integrity of the designed system in relation to EMC.

This paper presents the development of a knowledge-based system (KBS) for mechatronic system design. Section 2 introduces issues concerning reliability and the complexity featuring a mechatronic system design. Section 3 presents the knowledge-based systems basic aspects and different applications. In section 4, the development of KBS prototype, its current stage and future developments are discussed. The process of verification and validation of the KBS, future developments and some conclusions are presented in last section.

2. MECHATRONICS DESIGN: COMPLEXITY AND RELIABILITY

A modern definition to mechatronic systems consider the resulting integration of electrical/electronic systems, mechanical parts and information processing. Figure 2 presents these involved domains in a simplified way.

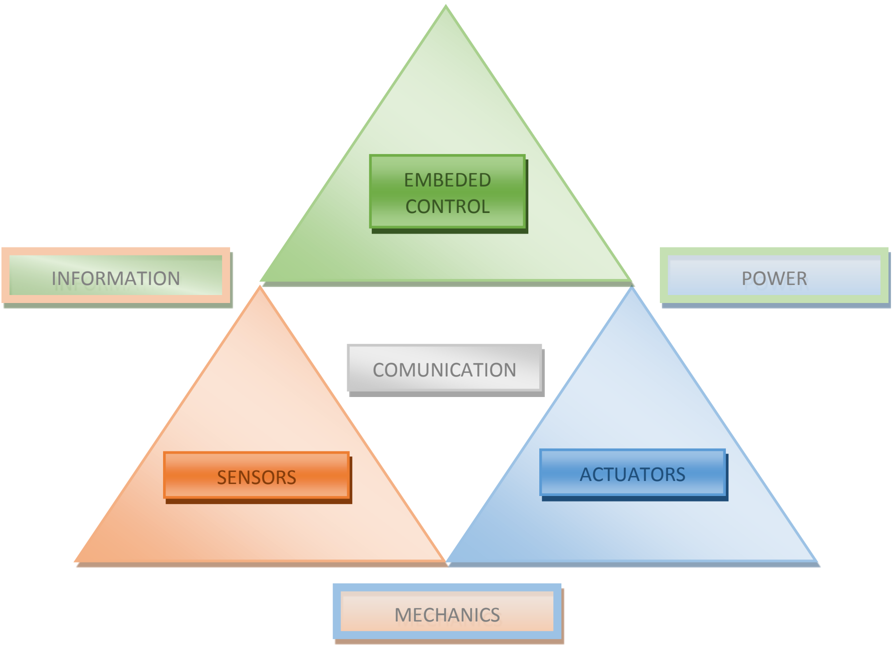

Figure 2. Mechatronics domain (Adapted from Schoner, 2004)

A modern definition to mechatronic systems consider the resulting integration of electrical/electronic systems, mechanical parts and information processing. Figure 2 presents these involved domains in a simplified way. The actuator, in the blue triangle, manage actuation forces and speed as a result of electronics and mechanics combination. The embedded control, in green, is the union between the electronic domain and software domain. In amber, the sensors monitor and inform to the system different dynamic conditions, allowing a correct response to the undesired variations of the actuators. It is considered as the overlap between the mechanic and information domain. Finally, the communication, in white, can see as the central piece of the system, especially for distributed systems. The mechatronic system, as one of the most essential part of a modern product, plays a critical role when the products become smarter and more complex (Zheng et al, 2014).

A mechatronic system requires multidisciplinary approaches to its modeling, design and implementation. This integrated approach carries an intrinsic complexity into system design process and numerous researches are on-going in order to find out optimal methods. A mechatronic product should have higher efficiency, higher precision, accuracy, reliability and safety, be more cost-effective, flexible and functional, mechanically simpler and environmentally friendly compared to other systems. The design of a multidomain system with a variety of components requires simultaneous considerations and the integrated design of all its components and features. Therefore, mechatronic system design is a major challenge and no single ‘‘best’’ approach exists for the design of a mechatronic system. (Silva & Behbahani, 2013; Barbieri, Fantuzzi & Borsari, 2014).

Březina and Singule (2006) consider that the conception of mechatronics systems results from the integration of knowledge from different areas of physics and technical disciplines. The purpose of mechatronics is to use this synergic process to obtain a product with highest technical and economical parameters. In design phase tools should be able to appropriately conceive the tasks from mechanics, electrical engineering, electronics, control and data processing. Is fundamental the development of methods and tools to ensure the quality and to predict reliability and implementation of these methods and tools into the process of product designing. These authors talks about need breaking through the barriers between a traditional conception of mechanical engineering and electrical engineering and a control including computer sciences in industry and secondary and tertiary education. The requirements laid upon mechatronic systems development ought to consider paying highest attention to the early stage of designing process, shared modelling of technical systems and, work in an interdisciplinary team.

Mechatronic systems are characterized by high complexity. Here, reliability is an important factor. The great number of product recalls and increasing warranty costs indicate that some common failures are recognized very late in the development process. There is a need for reliability analysis methods and tools, which can be applied to the conceptual design, so that failures can be detected at an early stage. Dorociak (2012) presents a method for early probabilistic analysis of an advanced mechatronic system reliability based on its principal solution. In addition, early fault tree analysis (FTA) on the principal solution is used, which allows failure propagation modeling. The presented method provides identification of system critical weak points and respective countermeasures can be defined. The method advantages are shown in a case study in railway technology.

In Janfrei et al. (2013), an intelligent 110kV substation operation is analyzed. Its merging unit is an analog to digital converter used to communicate power signals to the control system via Ethernet LAN. Firstly, the merging unit abnormity is verified to identify the electromagnetic interference causes. In the sequence, experiments specified by the IEC61000-4 EMC standard are carried out to verify the merging unit performance. Moreover, the merging unit structure is improved until it operates normally. Furthermore, electromagnetic disturbance signals are recorded, and their amplitude and time-frequency are analyzed. Finally, some suggestions to improve anti-interference performance are given.

The working environment of control unit is not always adequate for intelligent circuit breaker, often electromagnetic interference is one important factor. In Fu et al. (2011), hardware and software were applied as anti-interference measures to ensure EMC, in order to improve the circuit breaker reliability. External and internal interferences were defined depressed by hardware, and software was an important complement. The resulting design proved to meet intelligent control protection and embedded network real-time communications.

The interaction among different domains is a decisive factor for the establishment of functions and specified performance of the entire system. Thus, supporting systems for this task, such as simulation models are critical to decision making, especially in the early stages of design and before committing to expensive tests.

Considering the mechatronic products complexity, with the integration of different disciplines as mentioned above, several authors have proposed methodologies and design tools that seek to overcome the difficulties and provide better results with less effort. (Barbieri, Fantuzzi & Borsari, 2014; Zheng et al., 2014).

In Xue et al. (2012), an electromagnetic compatibility (EMC) method based on Quality Function Deployment (QFD) was constructed to satisfy mission translation for different levels of the EMC indicator. For large electronic systems, two issues are pertinent: How to make the EMC mission requirement? How do you consider it after the preliminary project? This is because there is the difficulty of breaking down EMC indicators as well as making a comprehensive EMC analysis on a system which usually takes into account only the designer's expertise. The entire QFD process transformed the qualitative analysis into quantitative analysis, providing basis for the systemic EMC indicator.

A theoretical model is developed by Ales et al. (2014) to express the electrical parameters of modern embedded electronic circuits using a switching function (which determines how the semiconductors are controlled) and the Fourier series decomposition. Experimental validation is performed in a frequency range from some Hertz up to 80 megahertz. The model is then used in a simple electrical network, to compute the electrical parameters of this network. Measurements confirmed the accuracy of the proposed model for the design of optimal filters for electromagnetic compatibility.

A review of the fundamentals and presentation of the modeling, analysis, and design advances for signal integrity and electromagnetic compatibility in chips and PCBs in the past decades is presented by Wu et al. (2013). The inclusion of effects of parameter variability is considered, and it is demonstrated how statistical simulations can be made available through newly introduced stochastic methods. Finally, the need for training of designers is mentioned, and experience dependent on realistic PCB indicators is illustrated.

Obtaining parasitic parameters and simulating their effects on the production and propagation of electromagnetic energy is carried out using the InCa3D program and the Saber® Sketch circuit simulator. Rangel et al (2009), present the analysis of an electronic ballast related to the propagation of electromagnetic energy and compare with experimental results according to CISPR 15. Obtaining the parameters and simulating the operation of the system considering its nonidealities demonstrates the importance of the dynamic simulation for the prediction of the electromagnetic effects and the limits of electromagnetic compatibility according to current norms.

3. KNOWLEDGE-BASED SYSTEM: SOME FUNDAMENTALS AND APPLICATIONS

Professor Edward Feigenbaum (Stanford University) has defined a knowledge-based system (or expert system) as "… an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution" (Giarratano & Riley, 2005). Such expertise should reflect the human practice in solving problems in daily routines, characterizing the KBS as an intelligent system.

A KBS may have the structure shown in Figure 3. The knowledge base incorporates technical and heuristic knowledge from experts. Working memory has volatile nature, formed by temporary information gathered in each system session. Such information represents data (or facts) of a given problem to be solved. The inference engine processes the information using the knowledge base, proposing solutions. User interface is the means of communication between system and user, where inputs and outputs are exchanged. Explanation facility and knowledge acquisition modules are not always present in a knowledge-based system. The first should be able to explain to the user the presented solutions while the latter must evaluate the solutions and return information to the knowledge base in order to enhance it.

KBS application is quite wide and has its origins in 1970s, especially to aid in medical diagnosis. From 1980s, KBS have increased their popularity and being used in different areas such as business, science, engineering, manufacturing and many other areas where knowledge is well defined (Giarratano & Riley, 2005). In addition to diagnoses, KBS are capable of performing syntheses, such as those performed during product design. Thus, in different areas of engineering, the KBS have been developed especially for fault diagnosis and design synthesis.

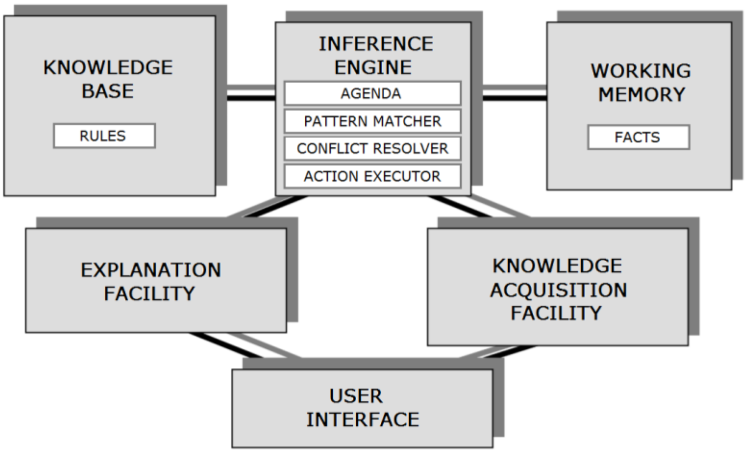

Figure 3. Knowledge-based system basic structure (Adapted from Giarratano & Riley, 2005)

Monticolo et al. (2014) presents a knowledge-based system built to manage heterogeneous distributed information and considering the social and collaborative aspects of professionals involved in an engineering design. The goal is to build a corporate memory that support professionals from different fields of knowledge involved in a design process to perform their activities. The system aims the construction of a flexible corporate memory, which suits the tasks of each professional.

Sensors play a vital role in the performance and safety of the systems in which they operate, often characterized as complex systems. Therefore, distinguishing the sensor abnormal behavior from its nominal operation is a quite complex task in many cases. This is due the system dynamics and external disturbances that can mask sensor malfunction. Another problem is to distinguish between sensor and system failure with similar symptoms. Silva et al. (2012) develops a KBS prototype for detection, disambiguation and mitigation of faults in sensors. The system uses object-oriented modeling, rules and semantic networks to treat the most common faults, such as bias, drift, loss of gain and signal loss, as well as failures in the system.

Other engineering applications have been developed, in our research group, to show KBS potential include: fluid power system design (Silva and Back, 2000), cogeneration power plants design (Matelli, et al., 2009), hermetic compressors diagnosis (Pedroso and Silva, 2014), among others.

Design for environment (DfE) has become a requirement, imposed both by new legislation as the social recognition of the need for active environment protection. Thus, engineers and designers have an important role in choosing environmental considerations in design process, providing low environmental impact products. There are different tools and techniques to the DfE, but designers have difficulty in selecting the most appropriate to their project. Hernandez et al. (2012) consider that experienced designers can know the best tools or, the least, where to start to search for them. In addition, these experts have other important non-technical knowledge, as personal experiences, resource allocation and management priorities.

Ribaric, Marcetic and Vedrina (2009) present a KBS for diagnosing building facade insulation in a non-destructive process that employs electromagnetic waves in the light spectrum (infrared thermography and RGB). The IR and RGB images are pre-processed independently and merged into single information that is parsed and stored in a database. The expertise makes up a knowledge base in the form of production rules, used in processing with fuzzy logic to perform diagnosis and present output through a graphical interface.

Future cars are being designed through computers and many performance and safety tests are done using computer models. Before the first hardware prototype is built, many critical design decisions about EMC problems are taken. Consequently, it becomes increasingly important to conduct the first review of the electromagnetic compatibility related design before the complete hardware is available for testing. Automotive EMC systems experts examine the relevant aspects of an automotive project still on the computer to determine the design features that are capable of causing EMC problems (Hubing, 2006).

4. KNOWLEDGE-BASED SYSTEM PROTOTYPE

In the product development, conceptual design aims to generate alternatives capable to meet design requirements. This phase demands creativity and broad expertise, its results are the specification of one or more solution principles (Matelli, 2015).

In order to demonstrate the potential of a KBS approach to design a mechatronic system, this paper presents as example a UAV (Unmanned Aerial Vehicle), specifically a drone, whose block diagram is shown in the Figure 4. In this research, our main interest is the sensor network and the electromagnetic compatibility as a design constraint.

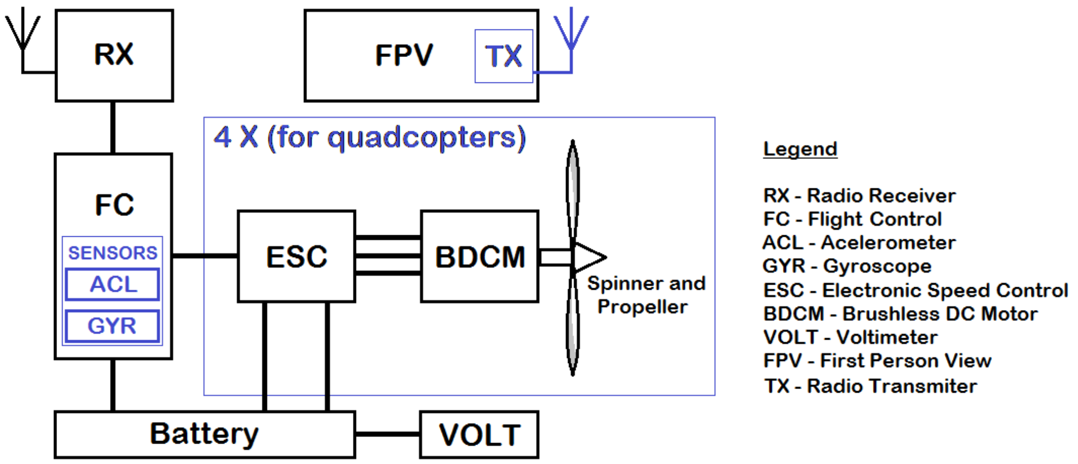

Figure 4. Mechatronic system: drone block diagram (by authors).

A Knowledge-Based System prototype is proposed, with the overall objective of assisting designers of mechatronic systems in the search for design solutions that meet reliability and integrity requirements. Considering these criteria, the first prototype development stage, presented here, is dedicated specially to analyze EMC in sensors and transducers network. Specifically, we seek solutions to the problems of electromagnetic emissions (EMI - electromagnetic interference) that may cause electronic subsystems malfunction or even failures due to components deterioration. These problems directly affect reliability and system integrity. Typically, KBS development involves: a) feasibility analysis; b) knowledge acquisition; c) knowledge representation; d) computational implementation; e) system verification and validation.

A. Feasibility Analysis

A feasibility study was carried out to verify if this artificial intelligence technique is compatible and effective for the engineering problems in product design. Whereas EMI problems, their causes and means of electromagnetic energy propagation are not easy to determine in the early design stages, this scenario often entails the need for reasonable reworking cost. The complex physical relationship among various systems in the same electromagnetic environment is a hard design problem.

Thus, there is a strong relationship between the experiences of EMC engineers and technicians, obtained through test results and re-engineering, with the basic factors to be considered as critical in the early stages of an electronic product design. Such expertise combined with other technical knowledge are key to build the knowledge base and can be obtained through interviews with experts, project development monitoring, technical literature, and industrial catalogs, among others. Thus, in addition to technical literature, there are experts in mechatronics design, with an EMC background, available to respond questions and contribute to the knowledge base. Our feasibility study concluded the following outcome:

a) To focus on a KBS development limited to support the early conceptual design mechatronic system design (to solve EMC problems);
b) Currently, several designers lack EMC expertise;
c) New engineers and undergraduate students may use the resulting KBS prototype as apprenticeship tool;
d) We have access technical resources as well as interested EMC experts.

B. Knowledge Acquisition

Knowledge elicitation is carried out mainly through technical literature research (catalogs, books, datasheets, reports, papers) and questioning to experts in the field. In general, such knowledge presents a heuristic nature. According to Giarratano and Riley (2005), "… heuristics are rules of thumb or empirical knowledge gained from experience that may aid in the solution but are not guaranteed to work. However, in many fields, such as medicine and engineering, heuristics play an essential role in some types of problem solving". Therefore, the expertise of EMC designers has a large value for KBS applied to product development.

Knowledge acquisition is considered the bottleneck of KBS development (Giarratano & Riley, 2005). In this research, the first author is an EMC expert and works with others. Unstructured interviews and questionnaires were applied to acquire knowledge related to EMC. Some questions addressed to experts and their responses are presented here.

1) What is the main cause of EMI in sensor and transducers network?
   When close devices operate at high frequencies (> 10 kHz), electric noise (currents) flows by wires and components and can produce malfunction or physical destruction in their electronic circuits.
2) In relation to layout, what are the main guidelines in design for EMC?
   Normally, a printed circuit board (PCB) has a multilayer construction. In addition, different circuits such as digital control and power drive can be very close in compact devices (as in a drone). Crosstalk takes place if circuit tracks are parallel, which should be avoided. Also, if high value switched current circulates in a given circuit, a strong AC magnetic field is produced, which can cause interference in nearby sensitive circuitry. In addition, voltages at components terminals (solder pad) compared to the ground plane produce capacitive effects, resulting in circulation paths to the interfering currents. PCB reference planes shield radiated fields, preventing such fields coupling signal and power tracks above this plane (stray inductance). However, reference planes can facilitate the EMI conducted by capacitive parasitic effects.
3) Regarding the technology of electronic switches circuits (ESC), such as transistors and diodes in a drone, what are the criteria to minimize EMI occurrence?
   Bipolar junction transistors (BJT) have slower switching than MOSFET, providing a minor impact of EMI. The faster MOSFET switching associated with operation at high frequency (> 10 kHz) produces higher harmonic frequencies, which may include high energy and therefore more difficult to be minimized, usually resulting in radiated EMI problem. Consequently, attention should be taken when operating at high frequency, such as the use of soft switching, separation of source-victim circuits or use of shielding.
4) In what situations can one use filter and shields?
   If one cannot employ design techniques to minimize EMI, such as soft switching and physical separation of source-victim circuits, the use of filters and shields becomes strongly recommended to prevent EMI. Increase in cost, weight and volume are disadvantages of using these barriers.

Technical literature such as books, journal papers and test reports were used to complement the knowledge gathered from the experts.

C. Knowledge Representation

Before implementing technical and heuristic guidelines in a KBS prototype, knowledge representation is required. In this research, rules and object-oriented modeling are employed as representation techniques.

Rules are assertive type IF >> THEN. The following pseudo-code is an example of a rule implemented in the prototype.

IF ESC circuits topology is Full-Bridge
& 9 kHz ≤ switching frequency ≤ 30 MHz
& current per phase ≥ 20 A
& separation of source-victim circuits ≤ 5 cm

THEN shield noise sources and filter signal cables

Figure 5 shows the relations between the sensor and transducers network classes in a drone design. Unified Modeling Language (UML) is used to represent class relations. The Process Block (Environment + Plant) represents the installation environment with all drone parts and others electronic and electromechanical equipment. Drone signals and electromagnetic noise in the environment, produced by different equipment, compose the needed information to determinate sensors features. The Control Block represents the actuations under the drone system to provide an accuracy work. This block consists of a digital processor and the power drivers to determine when and how the motors operate. Sensor and Transducers Block relate to Circuit Block as an assembly relationship. For each parameter to be controlled there is a sensor (or group of sensors) to inform system performance.

By comparing Figures 4 and 5, it is possible note that the Process (Environment + Plant) represents all circuits depicted in Figure 4 operating in a real environment. Relations of electromagnetic energy are modeled, such as speed/position electric signals and electromagnetic noise in the environment. Thus, it is possible to evaluate the susceptibility of sensor circuits to electromagnetic noise present in the operating environment. Sensors and Transducers Network block represent the sensors circuits in the flying control block, FC in Figure 4. Finally, Control Block incorporates data processing inside FC and ESC circuits (Figure 4), where desired control characteristics for sensor selection are modeled.

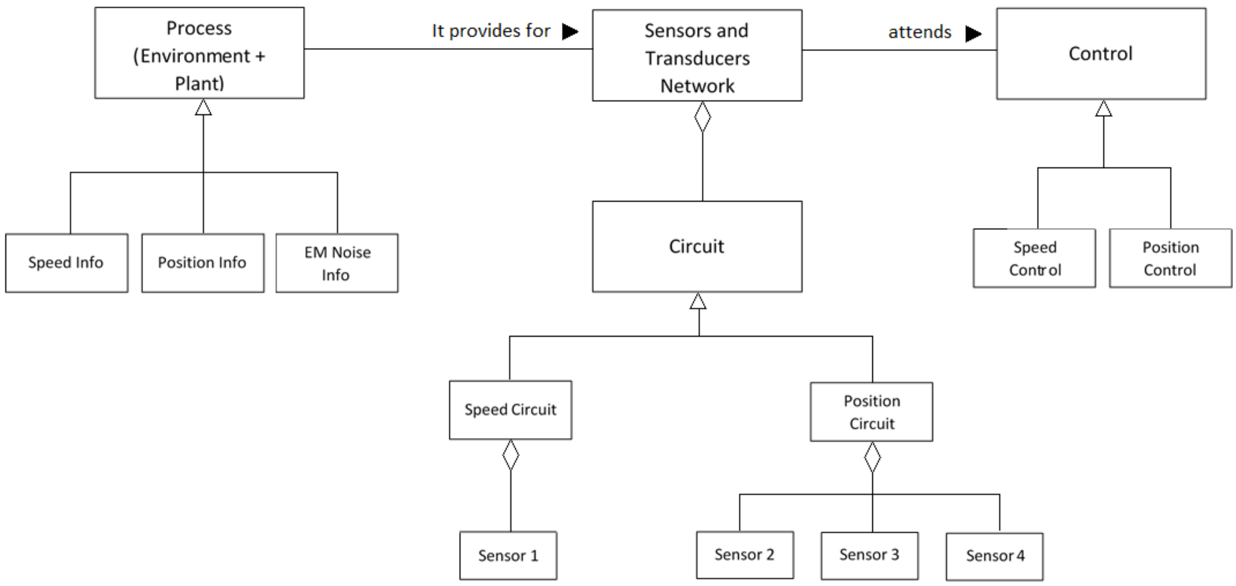

Figure 5. Classes in a drone design (by authors).

As its key features, KBS prototype inputs and outputs were defined, aiming to expand it via incremental approach.

5. REMARKS AND CONCLUSIONS

As a KBS system develops in increments of functional capability, verification and validation (V&V) are essential tasks to promote its quality (Giarratano & Riley, 2005). Thus, each version should pass through the following phases: knowledge acquisition, representation, coding and V&V. As presented above, this paper concentrates only in some of these phases, thus it does not deal with coding.

Giarratano & Riley (2005) propose three stages to V&V. Code and checkout, knowledge verification and system evaluation. The first stage includes verification of implemented code using test data, test drivers and test analysis procedures. Documented source code must be generated as well as user manual in order to feed the system. KBS functionality, limitations and problems must be related. Knowledge verification aims to determine the correctness, completeness and consistency of the system.

This stage is divided in two main tasks: formal tests, where formal test procedures are implemented and test results documented; and test analysis, which provides results evaluation and recommendations.

The last stage is system evaluation, where testing results are summarized and changes recommended. This stage validates user needs, requirements and generates a final report, upon project conclusion, though a typical KBS can always be improved and expanded.

To verify the consistency of the conceptual solutions generated, the prototype will be submitted to predetermined situations on which the results were already known, covering all possible combinations of input data (Silva et al., 2014).

In the current stage of development, a rapid prototype has been implemented with a set of rules and will be extended with classes. The functionality required in this stage comprises the evaluation of topologies and technologies applied to the drive circuits (ESC), PCB layout, separation between circuitry potentially interfering and victim circuits, modes of operation in switched circuits (described by frequency, switching times, and duty cycle) and the need for filters and shields to interfering circuits.

For example, if a combination of the use of motor drives with three-phase topology (full-bridge) with fast switches (6 MOSFET), operated at high frequency, the system must indicate to user about the great possibility of EMI in the circuits of the sensors. It is worth remembering that in a quadcopter there are 4 drives circuits, which increases the potential interference. Thus, the user can evaluate the possible EMI mechanisms and opt for the use of filters, shielding or both. Also, if possible, can perform physical separation between the victim and interfering circuits, to prevent noise coupling.

As this stage ends, an EMC expert should evaluate its development for some input/output data combinations, such as situations where EMC analysis is critical (as combination of high frequencies and hard switches operating simultaneously).

The system will continue to evolve with the implementation of new rules and classes to make its ability to more robust solutions.

The development of KBS demonstrates the potential capacity to assist designers in EMC criteria for the project, representing the possibility to optimize the development of mechatronic products.

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7. RESPONSIBILITY NOTICE

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