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Model-based systems engineering approach to the study of electromagnetic interference and compatibility in wireless powered microelectromechanical systems

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Abstract

Electromagnetic Interference and Compatibility (EMI–EMC) are a serious problem in Microelectromechanical Systems (MEMS), and specially in powered by wireless energy transfer MEMS. Most MEMS have dimensions in the order of 1 mm or less, thus, most of the suitable electromagnetic radiation sources have wavelengths larger than this, making isolation of electromagnetic effects very difficult. Model-Based Systems Engineering (MBSE) can be an excellent tool to deal with EMI—EMC in MEMS during early design phases. In this work, we present a problem-solving procedure and integration of EMI—EMC in MEMS from a Model-Based Systems Engineering perspective. This approach is described in detail by a real example using a procedure based on nine steps fully integrated with the proposed systems engineering methodology. For example, the use of context diagrams (IBDs) and N SQUARE charts to describe EMC interactions is explained in detail. The system is formed by a Wireless Power Transfer (WPT) subsystem working near 2.45 or 4.5 GHz coupled to an electromagnetic micromotor. This micromotor contains copper microcoils which can receive electromagnetic radiation directly at the same time that the WPT subsystem. The greatest difficulty is, then, to power the WPT while isolating the micromotor, and optimizing the coupling interface. A summary of the most important EMC concepts and tools are reviewed from the systems engineer perspective and possible problems during the design and testing phases are discussed in detail using the example.

KEYWORDS
electromagnetic compatibility, electromagnetic interference, EMI-EMC, MBSE, MEMS, microelectromechanical systems, model-based systems engineering

1 | INTRODUCTION

Microelectromechanical systems (MEMS) are one of the most promising technologies for many sectors and specially for medical applications, allowing continuous monitoring, sensing, and even treatment of many pathologies as described in the works of Panescu[1] and James et al.[2] However, the lifetime of MEMS is severely limited by the duration of their internal power sources. Only nuclear microbatteries offer some hope of long independent MEMS powering, which are reviewed in the papers of Blanchard[3] and Jahangiri et al.,[4] but other issues, even patients' fear or misunderstanding of this approach must be considered. As an alternative to pre-charged batteries, Wireless Power Transfer (WPT) systems allow to continuously power or to recharge periodically the internal MEMS battery using an external WPT system. There are many good very recent reviews of WPT technology in MEMS, for example, the works presented by Dinis et al.,[5] Goh et al.,[6] and Saranya et al.,[7] which show the great interest in this research topic. However, electromagnetic WPT systems have their own problems, like electromagnetic compatibility and interference, among others.

Study of electromagnetic interference and compatibility issues (EMI—EMC) in MEMS is a relatively recent topic and there are not many specific references, in spite of EMC being a consolidated discipline. Most of them are related with individual devices. See, for example, the published work of Kantartzis,[8] Chen et al.,[9] Jmai et al.,[10] Kong et al.,[11] Nevlyudov et al.,[12] and Wu et al.[13] There is a relevant publication from Monti et al.,[14] which is a more general and good review of the state of the art of EMI—EMC problems in MEMS. Monti et al. highlighted several important points: the differences between near-field and far-field coupling in WPT technologies, the problems related to human exposure to electromagnetic radiation, the need to consider both wireless energy and data transfer, effects over digital and analog circuits, several theoretical and numerical approaches to model the link budget and a pair of illustrative examples. A very complete paper about EMC in pacemakers is Campi et al.[15] More information can be found in books and reviews dealing specifically with EMC in integrated circuits.[16–18]

Model-Based Systems Engineering (MBSE) presents many advantages to analyze, design, manufacture, and test complex systems, as explained in the papers of Bjorkman et al.,[19] Henderson et al.,[20] Campo et al.,[21] Henderson et al.,[22] Madni et al.,[23] and Delicado et al.[24] However, a systems engineering approach for EMI—EMC problems in MEMS, detailed guidelines or a summary of best practices has not been found in literature. The main novel contribution of the present work is the description and example of a systems engineering approach for EMI—EMC problems in MEMS. From a historical perspective, EMC from a systems point of view can be inferred from the problems of electromagnetic interference in aircraft and later spacecraft. Some of the oldest papers about RFI (radio frequency interferences) in aircraft are devoted to the study of "static noise" produced by corona discharge in the aircraft's metallic structure. For example, see the papers of Hucke,[25] Starr,[26] Gunn et al.,[27] Tanner et al.,[28] and Nanevicz et al.[29] From the 1960s the Space Race enormously accelerated the research about EMC at the same time that Systems Engineering emerged. For example, see the paper of DiMaggio et al.,[30] where even the name "Electromagnetic Compatibility" as a broader discipline, not only concerned with RFI, was already fully acknowledged and one of the first handbooks about EMC was discussed. The reading of the paper of Johnson[31] is also very instructive, although the paper is not exclusively focused on EMC issues.

In addition to the classical references of Keiser,[32] Paul,[33] Ott,[34] Violette et al.,[35] Weston,[36] and Christopoulos[37] macroscopic EMI—EMC for systems engineers has been treated in some publications, for example, the one of Shapira.[38] This publication reviews some of the most important points that a systems engineer must consider taking into account EMC in the design of a system. EMC is by itself a discipline with a strong systems background and, in fact, EMC can be considered a hybrid between systems engineering and electromagnetism, or similarly, electromagnetism from a systems perspective. Although most textbooks on EMC have chapters describing systems design, some recent publications are specifically devoted to systems-level EMC, like the ones of Osburn,[39] Gonschorek et al.,[40] Duff,[41] Zheng,[42] and Su et al.[43] Other books present EMC from the perspective of larger systems, like vehicles,[44,45] railways,[46] or aerospace engineering.[47,48] Some of the main common problems in MEMS and EMI—EMC is packaging (shielding) the system to isolate it from unwanted interactions with the environment. This is directly related to interface analysis in Systems Engineering, which is, by itself, a very important topic. Most publications describe a general framework and make recommendations for good writing and management of the Interface Requirement Documents (IRDs), Interface Description Documents (IDDs), and Interface Control Documents (ICDs). For example, the works of Wheatcraft[49] and Vipavetz et al.[50] describe the best practices to define and document interfaces.

Most studies of mechanical, magnetic, and thermal interfaces in MEMS, examples can be seen in the papers of Muñoz-Martínez et al.,[51,52] have been made under the umbrella of "MEMS packaging." There are many very good references dealing with optimal packaging of MEMS, for example, the publications of Gilleo,[53] Pham,[54] Wong et al.,[55] and Tilmans et al.[56] The most common method to try to isolate MEMS from RFI is to create a Faraday cage package by means of metallic coatings, if the MEMS cover is not metallic itself. Generally, a first nickel coating is applied over a ceramic, glass, or plastic package. After this, it is easy to perform another electrolytic plating of copper or gold. However, if the MEMS is designed with biomedical applications in mind, we must remember that nickel is allergenic, so that a biocompatible metal capsule, for example made from titanium, or a pure gold plating are the best options. Another difficulty could be the connection of the MEMS metallic covering with a suitable earth, because an electrically floating MEMS can respond as an electromagnetic resonator instead of being properly isolated. Other techniques, common in macroscopic systems, like filtering, are not suitable in general for MEMS. However, RF MEMS are used as filters and filtering can be applied by a larger system to the input and output signals from MEMS.[57] Another serious problem with MEMS is protection from electrostatic discharges (ESD). To avoid damage to the components, proper conductive packaging and careful manipulation must be used.

MEMS packaging can be the most expensive part of the whole device. For example, in Larnbilly et al.[58] it is said that "the cost of MEMS packaging typically accounts for 75% or more of the sale price of the device" and John et al.[59] estimate that "the packaging cost of MEMS products in general is about 70%." In our case, a biocompatible package transparent to microwaves in the antenna area, but which acts as a Faraday cage in the micromotor part is a real challenge. The costs can amount to tens of thousands of euros and a completely satisfactory solution has yet to be found. Obviously, EMC principles must be used from the beginning in the systems engineering of the device. For general references about the use of other MBSE approaches to the design of biomedical devices, see, for example the works of Evin et al.[60] and Corns et al.[61] In this work a smooth integration between EMC and interface management from a MBSE perspective will be developed.

Best practices will be explained using a real example of a medical MEMS device with a WPT micromotor. The use of EMC best practices as soon as possible in the system design can have an important impact on costs. In our own estimation, for the medical MEMS example described in this work, the redesign and fabrication of a new micromotor would cost 150,000 euros, while EMC testing amounted to 10,000 euros. Therefore, even a minimal error in an EMC specification in a medical context, would imply more than a 100% increase in cost (redesign + fabrication + testing). If the number of iterations increases, the costs can be prohibitive.

2 | SYSTEMS ENGINEERING APPROACH TO EMC IN MEMS

The complexity of modern electronic MEMS and integrated circuits demands an EMC systems-level approach from the beginning, even before a physical architecture is completely defined. This is especially relevant for medical applications operating in the complex environment of the human body with very stringent medical regulations. The cost of an EMC failure or non-compliance in later stages of design can be disastrous. Another important characteristic of systems level EMC is that testing must be designed and integrated from the beginning, because EMC phenomena are extremely complex at this level, to the point that they cannot be reliably simulated, producing unpredictable effects, that may demand a theoretical analysis. Besides, every product must comply with extensive and stringent national and international EMC regulations that demand thorough testing from components to systems. EMC engineering is probably one of the most problem-solving oriented disciplines in the whole of engineering, making it ideal for a systems view. This is so evident, that many EMC engineers compare their discipline to detective work, trying to identify all potential sources of problems, to the point that even terms like “victim” and “aggressor” are used. Even conceptually, the extent and reach of EMC raises questions about the definition of a system.

Systems engineering is an iterative process where the final refined physical architecture cannot be produced until the end. The question is: How an EMC system analysis can be performed without a definite physical architecture? It does not seem possible to conduct EMC analyses from the functional architecture alone, even if detailed requirements are available. The only answer is that EMC studies must be done for all candidate physical architectures and then perform a trade-off analysis of the best alternatives. This can be a very costly and time-consuming task, even more because discrete models based on circuital analysis are not enough in general and full electromagnetic simulations using computationally intensive techniques are necessary, like finite elements (FEM), finite difference time domain (FDTD), or transmission line matrix (TLM). When complex geometries are involved and the number of components is increased, the computational effort can be prohibitive or the results are unreliable. Thus, physical prototypes must be built and tested in order to study their EMC characteristics. Paradoxically, then, a very stringent modular approach must be enforced in EMC design, to isolate every subsystem as much as possible, even knowing that the electromagnetic behavior of the whole system can be considerably different than the mere sum of its parts. In practice, even the testing of a complete system can be impractical or even impossible, so that the modern concept of “EMC margin” arises, especially in the context of spacecraft systems engineering.[62–64] For example, in page 35 of ECSS-E-HB-20-07A,[65] the EMC margin is defined as: “The ratio between the susceptibility threshold and the interference present on a critical test point.” And it is specified: “The minimum margins shall be 20 dB for safety critical circuits, and 6 dB for mission critical circuits.” A similar approach can be used for the design of medical grade MEMS. Uncertainties are not mentioned in the reviewed documents and we must understand these margins as a minimum, so that better performances are expected.

A very important and practical division of EMC system analysis is (from the smallest scales to the largest):

- Intrasystem EMC. Studies EMC from the perspective of single electronic components, parts, circuits and single subsystems. Every subsystem should behave electromagnetically as an isolated unit as possible, so that a modular approach in design and testing can be used. Of course, this is only an ideal that in the case of WPT MEMS is very difficult to achieve.
- Intersystem EMC. Analyses EMC problems between subsystems or even complete physically separable systems.
- Environmental electromagnetic effects (E3). Investigates electromagnetic interactions between the system and its natural environment. The “natural environment” can change with scale. For example, for a surgery tool design, at least three environments are of concern: the patient’s body, the surgery room and the external world.

Another crucial point is the study of the influence of the signals waveforms, modulations, and software, because most present systems are cyberphysical. For example, in general, digital signals are more robust against EMI, but produce more radio interferences themselves. For medical MEMS, the dimensions of the medical device are so small that digital signal processing is impossible, making the system very susceptible to EMI. Thus, software-based solutions are generally unsuitable for the WPT. However, the external subsystem surely will have a strong software contribution, making the coupling of digital and analog worlds a pressing issue. In this work, a complete integration between MBSE and EMC engineering, inspired by a real MEMS project, is proposed as an application of the ISE&PPOOA methodology explained in the book of Fernandez et al.[66] as a convenient approach to solve the increasingly complex problems produced by electromagnetic compatibility issues in modern systems.

3 | STEPS OF EMC ANALYSIS IN THE CONTEXT OF SYSTEMS ENGINEERING

The main steps of the integration of EMC reasoning into the Model-Based Systems Engineering ISE&PPOOA methodology are represented in Figure 1.

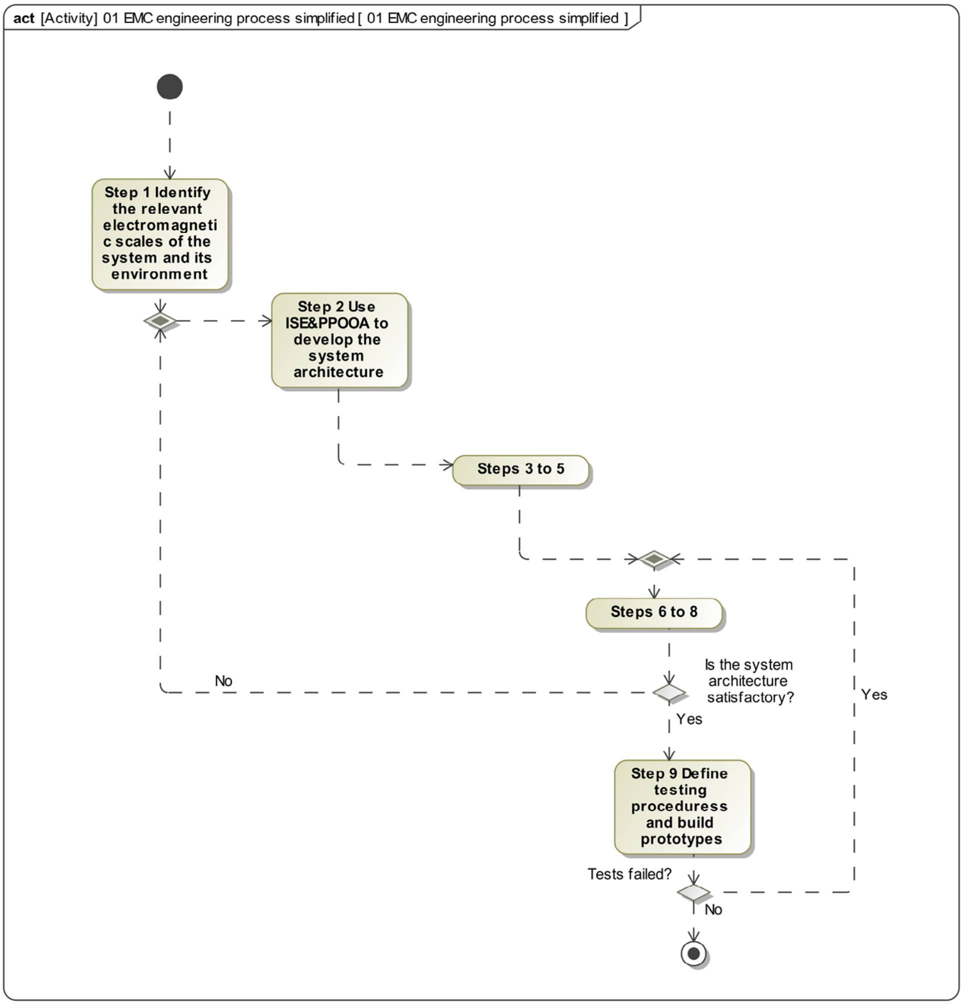

FIGURE 1 Steps of ISE&PPOOA applied to EMC.

3.1 | Step 1. Identify the relevant electromagnetic scales of the system and its environment during its whole life cycle

It is possible that the system will be surrounded by different electromagnetic environments during its life. For example, considering a MEMS for medical internal applications: Is the whole MEMS encapsulated or only each subsystem? Are there any interfaces between different MEMS subsystems? How many encapsulation levels are necessary? Is a common higher-level packaging which could surround both subsystems necessary or a simple electronic—mechanical—thermal interface between the individual capsules is enough? Actually, the system must operate in different environments:

- When the internal MEMS is stored (possibly in some kind of protective case).
- When the internal MEMS is sterilized, if necessary, or how to keep it sterile until the surgery.
- When the internal MEMS is in the surgery room in open air.
- When the surgeon manipulates the internal MEMS (e.g., there is a high risk of damage produced by electrostatic discharge (ESD)).
- When the internal MEMS is connected to a catheter, new inter-system interfaces must be considered (if the catheter or the new connections contain metal parts, these will act as new electromagnetic interfaces also. For example, a single metal ring in the catheter will have dimensions of the same order as the WPT subsystem, complicating the analysis a lot and altering the EMC behavior of the system substantially).
- When the internal MEMS is inside the patient's body (there are many different bodily environments depending on the electromagnetic properties of the surrounding human tissues and fluids. Some tissues, like fat, are very poor electrical conductors, but inside an artery the electric properties of blood are much more complex. Also, a study of the degradation of possible MEMS encapsulations due to the environment and time must be done).

As can be seen, even at this preliminary design stage, some specific ideas about the physical architecture must be known in order to perform a preliminary EMC study. However, this is not always possible, so that an alternative is to create a list of EMC unit operations, as proposed in our previous work,[67] and translate them into possible physical solutions, as shown in the antenna example. In this way, a rough estimate of the main EMC problems can be inferred.

3.2 | Step 2. Use ISE&PPOOA to develop the system architecture

Once the system architecture is known, Internal Block Diagrams (IBDs) or N SQUARE charts of the physical architecture can be used to build a multiscale view of the different system parts and their interactions. The connectors in the IBDs can be detailed using interface blocks as explained in pages 117–119 of the book of Ebert et al.[68] The IBDs can be complemented with constrain blocks or even parametric blocks to define the involved variables, units, and equations. Then, every connector or cell involved in electromagnetic interactions, both from an energy and signal integrity point of view can be marked. The first level only describes the coarse behavior of the system interactions with the environment. In the case of IBDs, three levels of increasing detail must be defined: system and environment, subsystems and parts.

3.3 | Step 3. Optimize the subsystems EMC isolation

Optimize the subsystems EMC isolation using matrix diagonalization techniques and heuristics for the previous N SQUARE charts, if they are used. Similar techniques can be applied to the context diagrams.

3.4 | Step 4. Search for critical EMC points

A critical EMC point is a part of the system that concentrates EMC energy, making it more susceptible to interferences or, on the contrary, a source of interferences. For example, in microwave circuits, every metallic corner or component lead can behave as an antenna. Thus, surface mounting is almost a necessity. An electromagnetic interface is a part of the system that allows the transfer of EM energy between other parts. An example is an impedance matching circuit between an antenna and an amplifier. Analyze which system physical and signal interfaces coincide with electromagnetic interfaces and search for critical EMC points. For example, the matching circuit between the WPT subsystem and the MEMS is a clear signal, electric, electronic, mechanical, and thermal interface, but it is not so clear that it can be considered a neat electromagnetic interface, because the wavelength of the incident microwave radiation is many times larger than the MEMS dimensions. This implies that the MEMS could act as a more effective antenna than the WPT itself, invalidating the system design completely. Mark such problems in the appropriate scale level of the optimized N SQUARE charts or context diagrams. At this stage, it is convenient to build a model of the system and its general electromagnetic behavior. In most cases, a circuit model is enough for the low frequency parts, although high frequency critical points could demand a more detailed approach, because radiated fields would be involved. The coupling between the circuital parts and the electromagnetic ones is not a trivial task and a multilevel study is necessary. Besides, experimental tests must be designed to identify and measure the critical points.

3.5 | Step 5. Match physical interfaces with electromagnetic interfaces

Review the N SQUARE charts or context diagrams from an EMC perspective to match the physical interfaces with the electromagnetic interfaces (EMC critical points) as much as possible. In the cases that this is not feasible, detail the problem and search for solutions. See the book of Fernandez et al.[66] for more details.

3.6 | Step 6. Detail the type of electromagnetic interactions and complete them with their associated requirements and EMC margins

For example, detail radiated or conducted emissions, and so forth. A complete classification scheme will be shown in the next section for easy reference. Complete every electromagnetic interaction with its associated requirements and EMC margins.

3.7 | Step 7. Simulate every electromagnetic interaction

Study the kind of modeling and simulation tools best suited to the analysis of EMC in different system scales. Each kind of electromagnetic interaction demands a different simulation approach. Ideally, it could be possible to perform a one-to-one mapping between the most detailed system context diagrams or charts and the electromagnetic model of the system. For example, a circuit model of the MEMS seems adequate, because it is electrically short compared with the incident radiation, but the high frequencies involved demand a more careful analysis of non-ideal behavior of electronic components. Later, some practical advice for EMC modeling will be provided. It must be remembered that it is always necessary to be able to build a model of the architecture envisaged. If a clear EMC model of the system is not achieved, it should not be expected that further testing and development will be able to solve the problems. Always try to imagine the worst scenario.

3.8 | Step 8. Perform trade-off studies of the candidate EMC solutions

Iterate until a satisfactory physical architecture is found.

3.9 | Step 9. Define testing procedures and build prototypes

Design testing procedures for the identified critical point at all relevant scales. Build prototypes and measure all relevant EMC variables at all relevant scales and points. Use dimensional analysis, similitude and analogies to relate the tests with the final system in the most realistic scenarios, because many modern systems are so large and complex that testing the complete system can be impossible. Besides, some EMC testing procedures can be potentially very destructive, so that, if the final system fails, the consequences can be disastrous. If new problems are detected during the testing step, return to point 6. If the present physical architecture cannot solve the problem, propose new solutions and perform a new iteration cycle from the beginning at the affected scale. Ideally, a complete system redesign should not be necessary, but in the case of MEMS, this cannot be discarded, due to their small dimensions.

4 | BASIC TYPES OF ELECTROMAGNETIC INTERACTIONS INVOLVED IN EMI—EMC

In this section, a summary of the main types of EMI—EMC phenomena will be shown for easy reference for systems engineers. It is not intended as a comprehensive reference or a solution cookbook for specialists, but as a useful guide to conduct the first EMI—EMC analysis. For detailed descriptions and possible solutions see the suggested references in the Introduction. A very important rule in EMC is: "Identify the source, coupling path and receiver of electromagnetic energy. Try first to solve the problem at the source level. If this is not possible, minimize the coupling path and finally improve the receiver immunity if everything else fails." Generally, all three approaches must be used, because complete control of any one of them is impossible, but the rule has universal validity.

The first consideration is to determine and compare the electrical dimensions of the system, subsystems and parts. Electrical dimensions are measured in wavelengths and are the representative ones from an EMC perspective. A system, subsystem or part are electrically small when their largest dimension is smaller than one-tenth of the wavelength of the exciting electromagnetic waves. For example, almost any system can be considered electrically small compared with the wavelength of the mains supply at 50 or 60 Hz. Electrical dimensions are very important because they determine if a lumped circuit approximation can be used, or a distributed approximation is needed. If a system, subsystem or part is electrically small, then a lumped parameter or circuit approach is convenient, greatly simplifying the EMC analysis. In the case of MEMS, this approximation of lumped circuits is generally granted, although other problems, as previously commented, may appear. If the system is electrically small, its circuit parts can be considered ideal to a very good approximation. But, if this is not the case, non-ideal phenomena appear, so that electrical and electronic components must be considered as complex circuits in themselves. For example, a simple resistor for an electrically small circuit, has non-trivial capacitive and inductive behavior at higher frequencies. This is crucial for the systems engineer and the EMC analyst alike, because a simple electronic part can show very different behaviors at different frequencies, hiding a high level of complexity. In other words, a single part can turn out into a complex subsystem at higher operating or exciting frequencies.

Sources must be studied as natural or manmade, because natural sources are generally very difficult or impossible to avoid and control. Manmade sources can be divided in intentional and non-intentional, depending on if there is a deliberate intent to disrupt the system or not. Obviously, a non-intentional source can be dealt with in a very different way than an intentional one. For example, the effects of a solar storm and a high-altitude electromagnetic pulse can be similar, but it is evident that the first cannot be avoided, because it is natural and only predictable with a very short notice, while the second is manmade and clearly malicious. Although geomagnetic storms are an enormous threat to current electronic technology[69] and must be considered for large electrical infrastructures, military equipment and spacecrafts, they are fortunately rare, so other natural sources of EMC problems are of more immediate concern like lightning and electrostatic discharges (ESD). However, ESD devices exist that can be used intentionally. Actually, ESD tests for EMC are performed with ESD producing devices. From the point of view of the coupling path a new classification can be made:

- Conducted emissions, if they follow the path of minimum impedance of the system circuits. They can be approximated as currents in conductors. Generally, a lumped circuit or transmission line approximation is sufficient to describe system EMI. Conducted emissions can be of two types:
  - Common mode currents. They have the same magnitude and same direction. These are undesired currents in the system.
  - Differential mode currents. They have the same magnitude and opposite directions. These are the desired currents on a circuit.
- Radiated emissions, if they propagate as electromagnetic waves between the system circuits and even to the environment. A full electromagnetic field simulation is required in most cases. Conducted emissions can produce radiated emissions when certain system parts behave as antennas, for example, wires and path corners in printed circuits.

Two important intermediate phenomena can also appear, near-field coupling and crosstalk, depending on the relative electrical dimensions of the system parts. Near-field coupling must be considered when the electromagnetic energy source and the receiver are less than one wavelength apart. These effects are increasingly important in many WPT applications. Crosstalk is one of the oldest and most pervasive problems in EMC. It originated in the coupling of signals in telephone lines, producing sound interferences, when several different conversations could be heard at the same time. This is the origin of the term "crosstalk," which has been kept in spite of its application far beyond sound interferences in old telephones. Crosstalk is produced when at least three conductors or two conductors and an earth plane are involved. Shielding is traditionally studied as a separate phenomenon due to its importance in EMC. Although shielding is commonly used and many times it is an unavoidable solution, it should be considered as the last option, because it introduces new problems, like the possibility of cavity resonances and notable increases in mass and volume. The ideal solution is the use of system mechanical and thermal interfaces as electromagnetic shields when possible. Finally, due to the pervasive use of digital signals, the effects of their form in the time domain are very important, because they determine their spectral content and their ability to produce EMI. For example, most digital pulses have trapezoidal forms to reduce their high frequency emissions.

5 | RECOMMENDED EMC MODELING TECHNIQUES AND SIMULATION TOOLS

A brief guideline for useful modeling and simulation of EMC will be presented. At present there are several excellent electromagnetic simulation software packages, but these will not be discussed, only general techniques will be described.

- If the system or subsystems are electrically small, the lumped circuit (0D) approximation can be applied.
- If the frequency of the electromagnetic energy is very low, for example, 50 or 60 Hz, a lumped circuit (0D) approach is generally justified, because the circuit elements have a fairly ideal behavior.
- If EMC emissions are conductive, but the system or subsystems are not electrically small, the transmission line approximation (1D) is generally sufficient. However, in many problems, transmission line models cannot simulate common mode currents adequately. Thus, a 2D electromagnetic model can be necessary if circuit geometry is planar.
- If EMC emissions are radiative, a full 3D electromagnetic field model may be required, although many simplifications must be applied in practice to reduce the problem complexity and make it tractable. Sometimes, a too complex simulation, involving high computing resources can produce unreliable results, while a simpler, conceptually controlled model, permits the solution of the EMC difficulties with realistic modifications. One of the worst problems of full 3D electromagnetic field simulations is a false impression of accuracy, which actually hinders the interpretation of the results, resulting in the practical impossibility to isolate the culprits of the EMC malfunction.
- Generally, many different frequencies and electrical dimensions are involved at a system level, demanding the coupling of different approximations and simplifications. For example, conducted emissions at low frequencies can be described by 0D tools, but the same circuit radiates at microwave frequencies, demanding a 3D electromagnetic field model. The seamless coupling of 0D + 1D + 2D + 3D models is not a trivial task, and much research has yet to be done in this area.
- Each full 3D electromagnetic field numerical simulation approach has its strengths and weaknesses. Even commercial constraints must be considered by the systems and EMC engineers, like integration with other design software tools and cost. Some multiphysics software packages try to integrate all necessary simulation tools, which obviously simplify the integral study of the system behavior. However, these packages are fairly rigid in their selection of numerical algorithms and the programming of new equations or boundary conditions. Sometimes, the provided tools are not the best for the problem at hand. For example, some packages can use finite element algorithms for the simulation of mechanical, thermal, fluid, and electromagnetic systems, but finite element analysis is not the best approach for most electromagnetic problems, where other numerical tools, like FDTD, TLM, or MoM, are clearly better.

However, a detailed knowledge of the peculiarities of all these numerical approaches is generally the task of specialist EMC engineers. Therefore, a more detailed description for systems engineers is not deemed necessary. They must only be aware of the difficulties involving the system-level simulation of EMC. In any case, in the previously cited EMC references a fairly complete information can be found. The limitations of present and presumably future simulation tools demand a careful testing design, which, in the case of EMC, must comply additionally with plenty of legal requirements and norms, many of them changing at a quick pace, because regulatory agencies and governments demand continuously better and safer systems in an increasingly complex electromagnetic environment. Therefore, simulation can never be a substitute of testing in an EMC context, so that the cost of testing must considered from the beginning because it can be high and a considerable part of the overall EMC study budget.

6 | DESCRIPTION OF THE EXAMPLE PROBLEM

Exploring high torque density micromotors for micro-robotic joints is one of the main objectives of H2020 UWIPOM2 project. See the papers of Villalba-Alumbreros et al.[70] and Diez-Jimenez et al.[71] This project seeks to develop a micrometric-size wireless powered micromotor. The micromotor will be wireless powered through gigahertz electromagnetic waves, thus providing infinite autonomy to any tool. The dimension targeted for this new robotic joint is diameter smaller than 3 Frenches, that is, diameter smaller than 1 mm and total lengths not larger than its diameter. This would allow the integration of the micromotor in catheters end tips. For these new tools, high torque electromagnetic micromotors are critical components that require specific development. The medical grade micromotor with dimensions of de order of 1 mm3 must be powered by a WPT receiving microwave radiation in the far field from an external source working ideally at or as near as possible to the 2.45 GHz ISM band. However, this can be accomplished using only a larger antenna than originally desired. Thus, two alternative designs are proposed, a helical antenna similar to the one purposed in the paper of Fernandez-Munoz et al.,[72] but in the 2.45 GHz range, and a smaller planar spiral antenna working near 4.5 GHz.

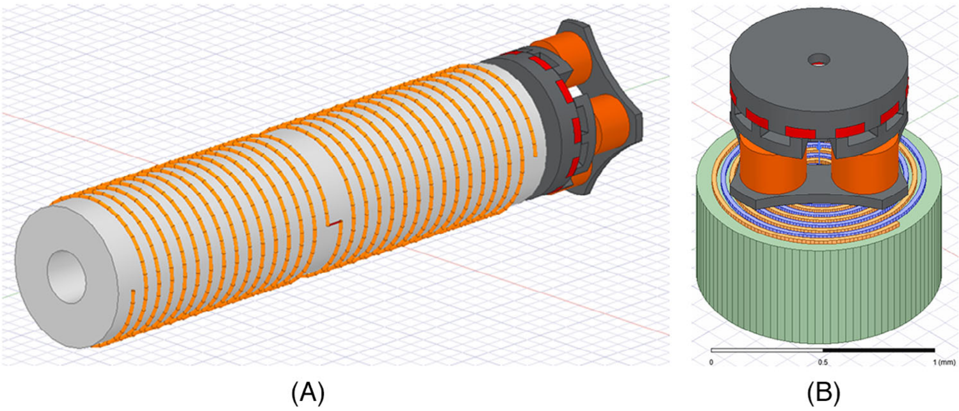

FIGURE 2 (A) 3D view of the micromotor + helical antenna. (B) 3D view of the micromotor + spiral antenna.

The motor design and all their powering alternatives is presented on the patent application document "MINIATURIZED ELECTROMAGNETIC ROTARY ACTUATOR" which is under European patent evaluation process (EP21382782.7). The micromotor main characteristics are described below:

- Dimensions: 1 mm diameter × 0.7 mm.
- Output: 1 μNm and 500 rpm.
- Stator made by 4 coils (2 phases) wound around a ferromagnetic core.
- Ferromagnetic flux modulator to multiply output torque.
- Ferromagnetic material: Hyperco50 Fe-CO soft magnetic alloy.
- Rotor made by permanent magnets and ferromagnetic backyoke.
- Permanent magnet made in SmCo quality R35, (1.2 T Br).
- Bearings made with balls and high hardness coated tracks.
- Non-magnetic parts made in titanium grade 5 alloy.

Therefore, it is clear that it will be highly susceptible to electromagnetic radiation and magnetic coupling. In our problem, multiple, very different scales, must be considered (from smallest to largest):

- Parts of the micromotor, like the copper coils, or of the WPT subsystem, like the microantenna.
- The matching circuit to couple the WPT subsystem and micromotor.
- The packaging of each subsystem or a common packaging (one of the earliest problems to solve).
- The near environment of the internal system (blood, human artery, and catheter).
- Parts of the patient's body exposed to microwave radiation.
- The whole patient's body (if some undesirable reaction is produced).
- The external microwave source and control system for the WPT.
- Other systems involved.
- The electromagnetic room environment.
- Issues and safety related with the complete system operation, both automatic and by surgeons, making human factors also relevant for EMC.
- Protection against external attacks, power surges or shutdowns, lightning, and so forth.

The micromotor is electrically short compared with the microwave wavelength, so that a circuital approximation, with corrections due to the microwave frequencies involved, would be sufficient to model it, but the patient's body or the room environment are clearly much larger than the radiation wavelength, demanding a full electromagnetic wave simulation. Coupling this very different scales is not a trivial task by any means, making this one of the most important topics in systems-level modeling research. Even modern MOR (model order reduction techniques) are not up to this task yet as detailed in the works of Feng[73] and Baur et al.[74] The main parts of the WPT internal subsystem are: a microantenna of a helical (Figure 2A) or spiral (Figure 2B) type, a rectifier, a voltage regulator, a matching circuit to connect to the micromotor and a circuit to produce sinusoidal outputs to power the motor. A microwave signal generator and an array of antennas constitute the external microwave emitter.

This is a very complete example which illustrates many EMC difficulties from a complete system, subsystem and parts perspective. The contribution of many different scales makes a simulation of the complete system very challenging and difficult to interpret from a conceptual point of view in order to apply rational and incremental solutions. From a system engineering perspective, the definition of interfaces is also complex, because the complete system is very small (i.e., electrically short) compared with the microwave wavelength, blurring the conceptual definition of interface at this level, even when the analysis of the system parts and circuits in larger dimensions would produce a clear interface picture. An important question in the analysis of EMC in MEMS is: Are physical interfaces and EMC interfaces coincident? If not, how to define them? In other words, from a practical point of view, can be achieved a reasonable electromagnetic isolation between the motor and the rectenna, when both and its interface are inside a volume of dimensions far smaller than the microwave radiation that powers them? In fact, it is not unreasonable to think that the micromotor coils can act as an antenna themselves, creating many problems and conflicting with the purpose of the rectenna in the first place.

Another interesting problem in EMC is the fact that non electronic interfaces (e.g., mechanical, thermal, or optical) can modify the electromagnetic behavior of the system, for example, the titanium parts of the micromotor, because of partial shielding and metal—metal mechanical contacts which can influence the formation of intermodulation products. Because the human internal environment is very aggressive, these phenomena can be worse due to the need of extra protection layers, biofouling and rusting. Therefore, a complete life cycle of the MEMS must be taken into account for a comprehensive EMC analysis. A very important feature of MEMS, as in this case, is that their reduced size makes very difficult or directly precludes the implementation of important safety and reliability measures, like redundancy. In a medical context this possess a very challenging problem and alternative solutions must be used. Besides, testing equipment and probes are not designed, in general, for such small devices. New testing procedures and equipment must be developed.

For this example, the Systems Engineering process steps are:

6.1 | Step 1. Identify relevant EMC scales

First level of analysis:

Two main subsystems: external microwave emitter + internal WPT/micromotor.

- The external microwave emitter is electrically large, so a full 3D electromagnetic model could be necessary.
- The internal WPT/micromotor is electrically small. It is not evident that a 0D lumped circuit model is enough due to the high frequencies involved. Non ideal behavior of components must be studied.

Interfaces between the WPT and the micromotor: Microwave radiation near 4.5 GHz.

Possible environments of the external subsystem: Surgery room.

Possible environments of the internal WPT/micromotor subsystem:

- Protective case.
- Air.
- Surgeon gloves.
- Catheter.
- Catheter + artery + blood.
- Other human tissues.

Second level of analysis:

Centered on the internal WPT/micromotor subsystem for brevity.

- The WPT is electrically small, but it is not evident that a 0D lumped circuit model is enough due to the high frequencies involved. Non ideal behavior of components must be studied.
- The micromotor is also electrically small. Same precautions as the WPT about non ideal behavior.

Interfaces between both main subsystems:

- Coupling circuit.
- Mechanical attachment.
- Thermal isolation.
- Common packaging.

Possible environments of the WPT: Individual packaging.

Possible environments of the micromotor: Individual EMC shielding, individual packaging.

Third level of analysis:

Centered on the WPT subsystem for brevity. Subsystem parts:

- Spiral antenna: Electrically small.
- Rectifier (diode bridge): Electrically small.
- Very small supercapacitor or microbattery: Electrically small.
- Voltage multiplier: Electrically small.
- Sinusoidal modulator: Electrically small.

Interfaces between parts:

- Spiral antenna—rectifier: Conductor.
- Rectifier—microbattery: Matched circuit.
- Microbattery—voltage multiplier: Conductor.
- Voltage multiplier—modulator: Conductor.

WPT parts environment: Air inside a common packaging.

Further levels of detail can be made until individual electronic components are described, but at this level the modeling should be done by an electronic engineer or EMC specialist using their own modeling tools.

6.2 | Step 2. Use ISE&PPOOA to develop the modular architecture

In Figure 3A the system context diagram is shown. In Figure 3B,C the IBDs of the system are represented for two different operational scenarios that are operation and storage.

6.3 | Steps 3–5. Optimization of the context diagrams

In this case, they are represented in a high level of abstraction, so further optimization is not necessary.

6.4 | Step 6. Electromagnetic interactions among WPT parts for brevity

- Complete WPT: ESD susceptibility.
- Spiral and helical antennas: Radiated emissions, radiated susceptibility.
- Rectifier (diode bridge): Differential mode conducted emissions.
- Very small supercapacitor or microbattery: Differential and common mode conducted emissions and susceptibility.

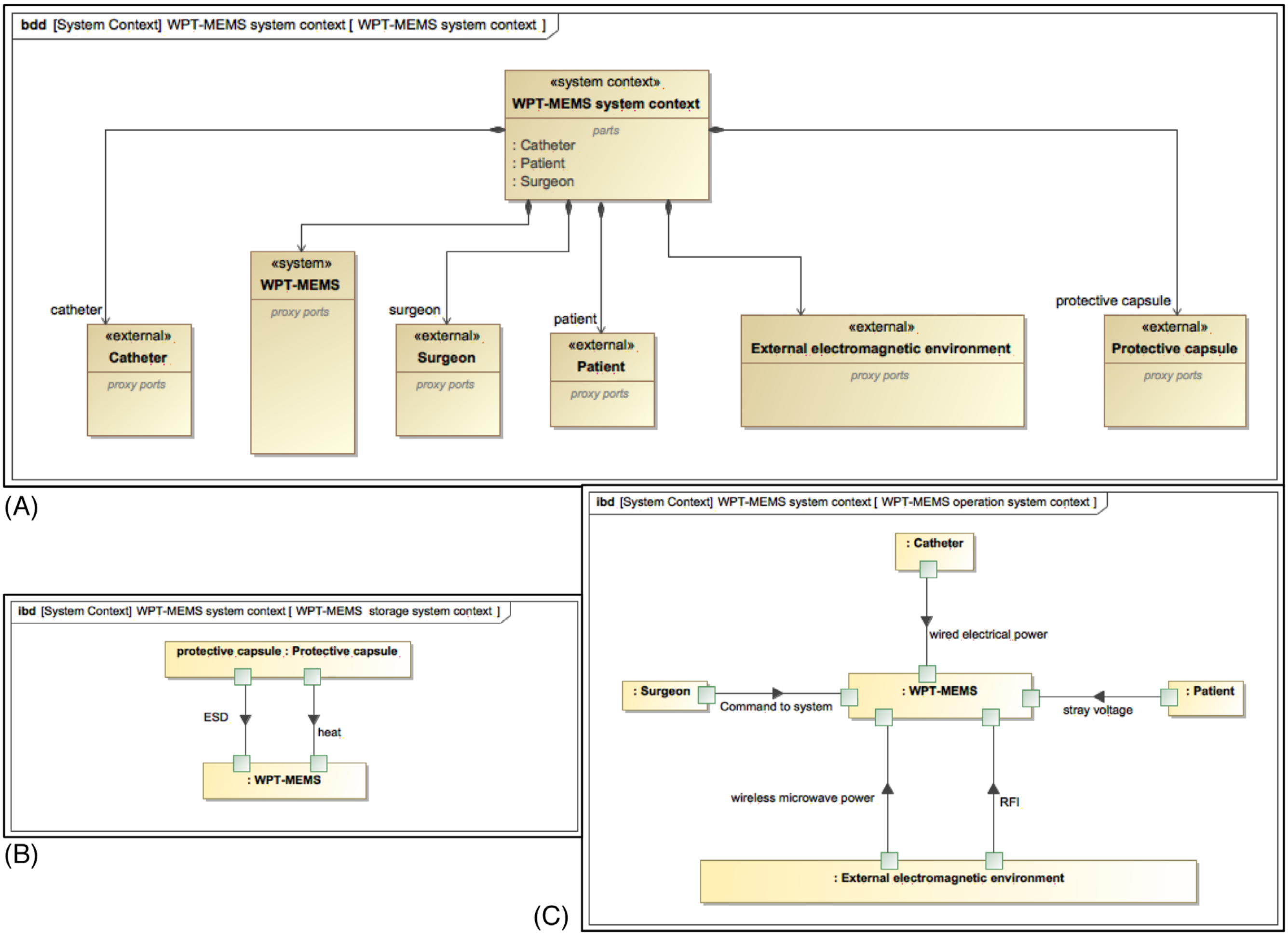

FIGURE 3 (A) BDD of the context diagram of the system. (B) IBD of the context diagram of the system for the storage scenario. (C) IBD of the context diagram of the system for the operation scenario.

- Voltage multiplier: Differential and common mode conducted emissions and susceptibility.
- Sinusoidal modulator: Differential and common mode conducted emissions, radiated emissions, and susceptibility.

Further details would be too much verbose for this example. The most important part is to comply with safety regulations. Then, tolerances and specifications can be defined. At this level, electronic engineers and EMC specialists should complete the electromagnetic modeling of the system.

6.5 | Step 7. Simulate every electromagnetic interaction

In the microwave range it is expected that non ideal behaviors of electronic components and conductors arise. Thus, a simple circuital approach should be complemented with models that permit the calculation of the full electromagnetic fields. Besides, radiated emissions and even near field couplings between the WPT and the micromotor are expected. All these EMC phenomena demand a complete 3D field simulation. Even the very good professional simulation tool used for this example (electromagnetic tool HFSS from Ansys Electronics Desktop 2020[75]) has difficulties with complex effects like certain boundary conditions or fractional derivatives, among others, so that, in general, a previous theoretical analysis is always advisable to check the accuracy of simulation tools, as was conducted in references.[76,77] However, for this case, the complexity of the geometry and the number of different materials make simulation a more practical tool than theoretical analysis. Simulations of both WPT candidate antennas behavior, without and with the motor attached, are shown in Figures 4 and 5, and their comparison with real behavior should be performed in later tests. S_{11} is the scattering parameter that measures the reflection coefficient of the antenna considered as a two-port network. Therefore, Figure 4 indicates the shape of the antenna resonance. The deeper and thinner the S11 curve is, the resonance quality factor of the antenna is higher at its resonant frequency. In this case, there are two resonant frequencies near 2.45 and 4.5 GHz.

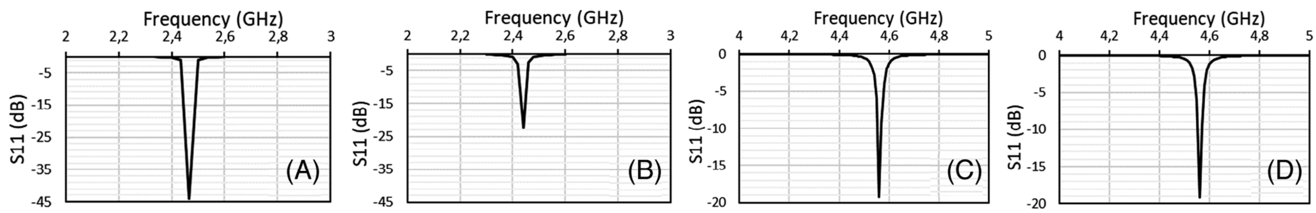

FIGURE 4 (A) S11 behavior of the helical antenna without micromotor. (B) S11 behavior of the helical antenna with the micromotor. (C) S11 behavior of the planar spiral antenna without micromotor. (D) S11 behavior of the planar spiral antenna with the micromotor.

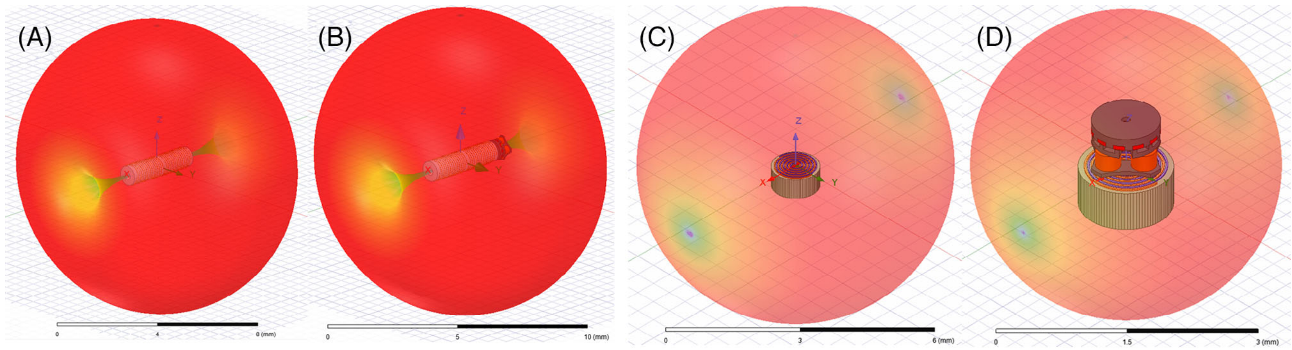

FIGURE 5 (A) Radiation pattern of the helical antenna without micromotor. (B) Radiation pattern of the helical antenna with the micromotor. (C) Radiation pattern of the planar spiral antenna without micromotor. (D) Radiation pattern of the planar spiral antenna with the micromotor.

6.6 | Step 8. Perform trade-off studies of the candidate EMC solutions

For a complete example of trade-off analysis related to this example, see the papers of Martínez Rojas et al.[78] and Duncan et al.[79] In this case we have two alternative antenna designs. The first one is a helical antenna with dimensions larger than the specified volume which act as an external part. The second one is a miniature planar spiral antenna which can be integrated next to the micromotor. Simulation and tests must be done before a quantitative trade-off analysis can be done. This is a very costly step and proves that the proposed phases cannot be strictly serial. In this case, testing must be done before a final physical architecture can be selected. A refined physical architecture must consider the results of the trade-off analysis and simulations, but prototype testing will determine if this physical architecture comply with the EMC requirements of further modifications are needed.

6.7 | Step 9. Define testing procedures and build prototypes

The MEMS dimensions make difficult to measure electromagnetic values with accuracy. For example, probe dimensions are far larger than the MEMS itself. Actually, the cost of developing new EMC testing tools for MEMS can be even higher than the building costs of the MEMS, as this example clearly shows. This problem was not anticipated in the first phases of the project, and it has been a serious one. In fact, a satisfactory solution has not been found yet. This case shows the limitations of both simulation and testing in order to analyze the system, highlighting the importance of design heuristics and the experience of the EMC specialist. As can be seen in Figures 4 and 5, simulations of the electromagnetic behavior of both antenna candidates would indicate that they do not affect the motor performance significatively. Or from an EMC perspective, that there are not serious interferences between the antennas and the micromotor. However, this result is suspicious, as it conflicts with our EMC heuristic intuition about a heavy electromagnetic coupling between the antenna and the micromotor, because the radiation wavelength is many more times larger than de dimensions of the system and the micromotor has copper coils and metal surfaces that must change the system electromagnetic response significatively. This points to severe limitations of the simulation tools to accurately describe the kind of EMC coupling that it is expected in MEMS.

Due to the inconclusive results of the simulation approaches, a complete testing procedure should be performed. However, as previously commented, the microscopic features of the system make this a real challenge. For example, it is impossible to measure the planar spiral antenna parameters using our standard equipment. However, to design, build and calibrate custom made microwave testing equipment would be even more difficult and costly than the system under study. This problem was not clearly anticipated during the initial phases of the project, adding so a serious cost increment, which could put this part of the entire project at risk. At first, based on previous experience with macroscopic projects, it was considered that simulations could be enough to understand and predict the system behavior, so that testing could be reduced to study the electromagnetic response of the antennas inside different human tissue simulants. As the results clearly show, this is not the case and unexpected problems have arisen, proving the importance of an early integration of systems engineering and EMC engineering from the beginning.

7 | CONCLUSION AND FUTURE WORK

An integration of EMC studies with Model-Based Systems Engineering, using the ISE&PPOOA + EMC methodology, is proposed in order to facilitate the design of modern MEMS devices, although the guidelines are general enough to apply to other larger systems as well. MEMS devices are very susceptible to catastrophic ESD damage, conducted and radiated emissions and other problems that are not so evident in larger systems. They are very low tolerant to overvoltages and current surges, because they cannot dissipate too much energy, so that thermal runaways are a constant problem. These limitations demand new approaches to build successful products, able to operate in increasingly contaminated electromagnetic environments. Therefore, EMC constraints must be considered from the beginning in most MEMS design, considering their integration into larger systems and their environments as essential as the MEMS themselves. Besides, EMC engineering is a heavily regulated engineering discipline, which demands a detailed knowledge of local and international norms. Finally, EMC testing of MEMS performance is not trivial and new research is needed. The most important aspects of this approach are illustrated with a real example which highlights the problems that a system engineer must face designing MEMS products with good EMC behavior.

Future lines of research related to this work are: Integration of biocompatible MEMS packaging design from an EMC perspective, development of new EMC testing instruments and procedures for biomedical MEMS, better cost estimation of EMC related issues in early design steps, compilation of EMC heuristics in a system engineering framework and to extend the study to non functional EMC requirements.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article, as no datasets were generated or analyzed during the current study.

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