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Teaching students the Black Magic of Electromagnetic Compatibility

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Abstract—Introducing Electromagnetic Interference and Electromagnetic Compatibility, or "The Art of Black Magic", for engineering students might be a terrifying experience both for students and tutors. Removing the obstacle of large, expensive facilities like a fully fitted EMC laboratory and hours of complex theory, this paper demonstrates a design of a laboratory setup for student exercises, giving students experience in the basics of EMC/EMI problems that may challenge the functionality and stability of embedded system designs. This is done using a simple laboratory installation and basic measurement equipment such as a medium cost digital storage oscilloscope, at the cost of not knowing the exact magnitude of the noise components, but rather if the noise is significant or not, as well as the source of the noise. A group of students have performed a trial exercise with good results and feedback.

Keywords—EMC, EMI, Engineering Project, Student Laboratory.

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I. Introduction

ELECTROMAGNETIC compatibility (EMC) and Electromagnetic Interference (EMI) may for good reasons be regarded as the "Black Magic" of electronics engineering. Giving engineering students training in this topic can be a frustrating matter for the students as well as the tutors. Without the practical experience of both the effect of EMI and the observed effectiveness of shielding, filtering and reduction of noise at the source, a complex theoretical background has limited value for the students. Exercises, on the other hand, require much effort from staff members, expensive equipment and tedious experimentation with complex installation.

The topic of EMC/EMI is a highly complex area of electrical engineering, and engineers with special education and training in this area should be used for ensuring compliance at least towards the end of the design process [1]. The final approval of EMC for new designs, a certified EMC laboratory is normally used. Laboratories such as in [2], are expensive, and might not be available for students at all times. Correcting errors at this stage however, often require significant redesign if EMC have not been taken into account at earlier stages in the design process. Significant redesign at this stage is extremely expensive as opposed to measures taken at the start of the design process. In this context, having design engineers with at least basic competence and practical experience in EMC/EMI would make the design process far more efficient, which is the main motivation for the laboratory project described in this paper. The idea of arranging modules with EMC/EMI as part of the learning objectives is not new. In [3] a module is dedicated to EMC and design of PCBs, and careful measurements of the EMI is conducted using special equipment for EMC/EMI measurements, while in [4] this has been introduced as a part of the graduation project module. In [5] an introductory module is set for teaching computer engineering students enough to attend a "full" EMC module for electronics engineering students, while in [6] a module has been dedicated to a project with focus on EMC challenges. In [7] the focus is set on the coupling mechanisms of EMI, and in [8] the teaching of EMC has been spread out on several different modules. There is still, however a need for a full EMC laboratory.

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A. Running laboratory exercises

There is a desire among staff members at the authors' university to give the students a suitable distribution between theory and practice. The practical part has become increasingly limited, while the industry partners of the university are in meetings asking for more practical skills from the students. For this purpose, a cost-effective way of administering the hands-on laboratory is becoming more important. Running the hands-on laboratory can be done in a number of different ways. One common arrangement, as in [9] and even as a remote laboratory in [10], where the hands-on laboratory exercises are performed as part of a module, and a ready-made description of the steps necessary to complete the laboratory is given to the students before the laboratory. The students are then supposed to follow exactly the described steps in order to get the expected results. The main reason for running laboratory exercises in this way is the need for having control of the range of expected outcomes of the experiments, in order to limit the time needed for tutoring the students. The main drawback of this arrangement is the students being taught or at least getting the experience that engineering is a more precise science than what is actually the case. The results achieved in an experiment are in reality not always within the expected range, due to phenomena that are either ignored or simply unknown.

A more "high-risk" arrangement is where students are explained the goal of the exercise, and then set off to find the path between their own starting point and the goal on their own. Close guidance is of course crucial to the success of such a laboratory assignment, and as the path is not clear to anyone - neither the students nor the tutors, surprising results and challenges might show up as the project evolves. Surprises for the tutors will occur from time to time as students find creative solutions that introduce new problems not thought of before. In the case of the project used as basis for this paper, the EMC/EMI problems that appeared became huge obstacles for the students, but showed to be an important experience for them. This is consistent with the student feedback in [11] where students asked for more hands-on class projects.

B. Embedded systems

In a normal PC, a generic processor is used to run a variety of different software. This generalisation is used for making the PC as versatile as possible. Processing power in general however, is utilised in virtually all appliances found in modern households of today. In order to make the processing power cost effective, hardware is specialised as much as possible, leaving out all unnecessary functions, while keeping the few functions that are actually needed. Such a system is often referred to as an embedded system. An embedded system often consists of a single processor or a micro controller, a small amount of digital and analogue electronics, power supplies, and sensor and actuator devices needed to interact with the physical world around the appliance. The software running in the processor is normally written specifically for the appliance the embedded system is residing in.

Embedded systems has become more and more important for engineers in the area of electronics and computer science, and giving engineering students adequate training in this discipline is important for the students in their future professional career. The design of embedded systems impose multiple challenges on engineers, one of which is the concept of software/hardware co-design, another the topic of EMC/EMI where the latter is known to have the potential to create unmanageable problems for the engineers in a project, if not dealt with at a sufficiently early stage of the design process. Giving students real life experience with the effects of EMI and how to achieve EMC are in the authors' opinion as important as mastering the design process itself. Hence, the topic of EMC/EMI challenges is considered an important part of the "adequate training", and is the topic of the project presented in this paper.

II. Project description

The task given to the students is to set up the hardware and software for controlling a model of a house. In the house model, the heating and lighting should be controlled by an embedded control system designed by the students. The students are supposed to design and implement both the hardware and the software, which have a reasonable complexity, within what the students are expected to handle. The idea here is that the students will be sufficiently occupied with the hardware/software co-design to be able to handle the EMI problems simultaneously, if given tutoring during the project period.

The house consists of four rooms, and the heating is made up of two fans, controlled by a supply voltage between 5V and 14V, blowing a variable amount of air, each through two of the rooms and out of the building. In front of the fan outlet there is a 230V heater element, where the current is controlled

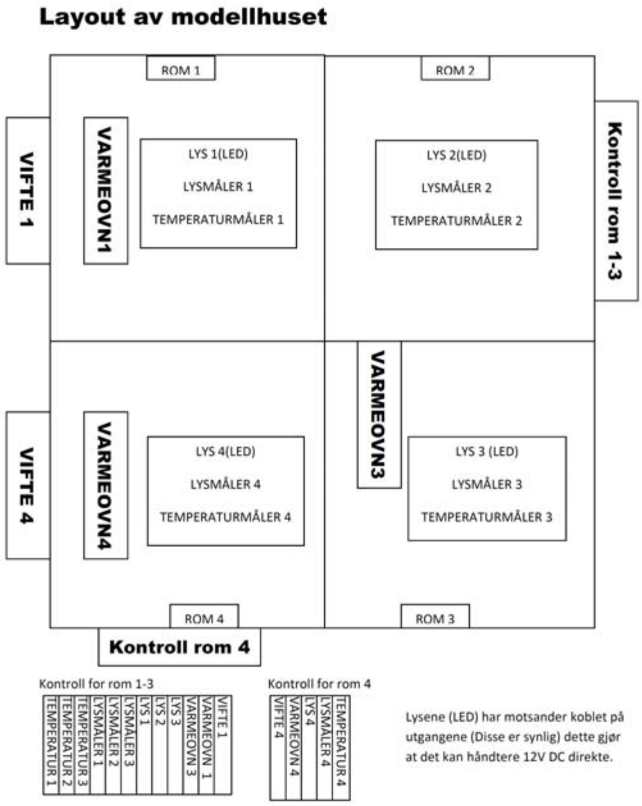

Fig. 1. Layout of the house in the project as presented for the students.

by a simple relay with 12V nominal coil voltage. This means that the actual air temperature after the heater is inversely proportional to the speed of the fans. The lighting in the rooms is made from one power LED in each room. The total amount of light in each room is made up from a combination of light from the LED and light from the outside of the house. A light detector in each room, used to measure the total amount of light in the room, is made available to the control system. The layout of the house was presented to the students as shown in figure 1. Unfortunately the text is only given in Norwegian.

A. Hardware interfaces

The hardware interface to be made of the students includes everything from the power supplies to the devices. The power supplies are chosen from a number of different readymade units, available to the students. For the purpose of better explaining the role of the hardware setup in the EMC/EMI discussion in the next section, a short description of the hardware interface for the different devices follows.

1) Fan control: The voltage set for the fans control the speed and, hence, the flow of air. Normally, a switching transistor is used in combination with a pulse-width-modulated (PWM) signal to set the average voltage for the fan motors. This will cause some EMI noise in the power supplies as well as through the air. As an alternative, an analogue voltage can be used by utilising an operational amplifier with a high-current output. This removes most of the EMI, at the cost of wasted heat in the operational amplifier output stage.

2) Heater: The heaters are fitted with relays switching in or out the 230V supply to the heater elements. The coil voltage is 12V, and a transistor is normally required between the micro processor/controller output to drive the relay. A snubber circuit should be used, both to protect the transistor and to reduce the EMI from switching the relay.

3) LED lights: The led lights are controlled in the same manner as the fans, either by use of PWM-control signal, or an analogue voltage.

4) Lux measurement: The lux is measured by connecting the sensors in series with a resistor, and measure the voltage drop over the resistor, as the current is proportional to the lux. Typically a 10kΩ resistor is used, making this a high-impedance output susceptible to noise pickup from other sources.

5) Temperature measurement: Temperature is measured by a PTC element in series with a resistor. Also this is of high impedance type, and the voltage is measured with a fixed resistor in series with the PTC.

III. EMC/EMI - THE SHORT VERSION

Electromagnetic Interference covers every undesired signal coupling between different systems, or different parts of a system, that causes malfunction in the receiving system. The latter part is important as it states that a signal coupling, where the product of the energy emitted from the source and the coupling factor, results in received energy below some level at the receiver, is not considered interference, as the receiver is able to handle a certain amount of noise. In other words, avoiding interference and by that achieving EMC, can be split into two parts: Reduction of signal energy at the source, and reduction of the coupling factor between the source and the receiver. Thus, EMI is the phenomenon of interference, while EMC is a property of a system, saying that the system does not emit electromagnetic noise above some level, and that the system is able to receive a certain level of electromagnetic noise, without malfunctioning.

A. Coupling mechanisms of EMI

The challenges the students face in this project are directly related to the coupling mechanism of EMI, and in order to reduce the EMI, an understanding of these mechanisms are necessary. A short description of four basic mechanisms is given with reference to figure 2[1].

1) conductive or galvanic coupling: Interference can be transferred through wires as any other type of signal. This includes both normal signal cables as well as power supplies. Power supplies must be carefully designed in order for EMI not to propagate from one device to another.

2) capacitive: When wires are placed close to each other, signals can be transferred through the stray-capacitances that are created between these parts. Voltage levels are in this context more important than current flow.

[1]Design by Guy Inchbald, distributed under creative commons license: http://creativecommons.org/licenses/by-sa/3.0/

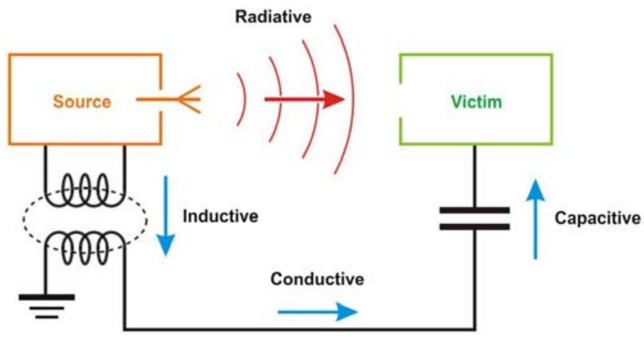

Fig. 2. EMI coupling mechanisms[1]

3) magnetic or inductive: Magnetic or inductive couplings are made either from wires close to each other, or from components that contains coils or wires/tracks that have the form of a coil. Either way, the noise energy is transmitted through the air by magnetic fields, and any structure shaped as a coil in the vicinity of the source, will receive the noise.

4) radiative: Radiative coupling will have much of the same behaviour as radios, where signals are transmitted through air over larger distances. This includes most circuit structures, but especially mechanical switches have a high noise factor.

B. Sources of the EMC problems in the project

An effort has been put into letting the EMC challenges be as realistic and true to reality as possible. The house contains both motors that can be run with pulse-width-modulated (PWM) signals, and relays with mechanical switches. Both of these introduce EMI problems that will be clearly visible when building prototype circuits.

Both the light intensity sensors and the temperature sensors have high impedance, causing any source of noise to have a significant impact on the values retrieved. This means that it is fairly easy the show the effect of EMI when students are setting up their self-designed equipment connected to the house.

1) Motors: The motors in the house is found in the fans blowing air into the rooms. These are brushless DC-motors, which themselves are EMC approved, meaning that they have a low enough EMI noise output to be used in any installation. This is however dependent on the type and quality of circuit used for controlling the motors. The motors can be used with speed control within limits, by varying the supply voltage to the motors between 5V and 14V. This can be done generally in two ways, as introduced in section II-A: PWM control of transistors to set an average voltage over time to the motors, or by using a high current output operational amplifier. The PWM-type control will introduce noise from the switching elements, i.e. the transistors. The commutation of the transistors will cause a change in the current through the motors, if this is not damped by a capacitor or inductor. If an operational amplifier with a high-current output is used, much of the noise will be removed, but this is rarely a recommended solution as the heat dissipation from the transistors will be significant. This solution will never be used for larger motors, hence, the switching problems must be solved.

2) Relays: The relays have several sources of noise with relevance to EMI, which makes them a good choice for this project. First, there is the inductance in the coil of the relay, which causes galvanic coupled noise to enter the power supply connectors, and from there spreads out to the other components, if not filtered at the source and at the other components.

Second, there is the inductive coupled noise emitting from the coil itself, interfering with components in the vicinity of the relay. This will to a large degree affect especially sensors, or their signal cables placed near the relay, but could also interfere with other circuits if placed sufficiently near the relay.

The third source will be the 230V connectors in the relay, having several sources of its own. When switching such a large voltage, this will have a significant capacitive coupling to electric components around the 230V cables both before and after the relay, and as wires both power supply, signal and others tend to be collected within the same area, this is likely to actually cause problems in the setup presented. The 230V cables will also introduce inductive coupling as the current will show a sharp increase or decrease as the relay is turned on or off, although the current in this setup is quite low. A third effect will be the unavoidable sparking effect between the contact surfaces of the relay connectors. This will cause broadband radiated noise, also affecting components around the relays. The fourth component of inductive coupled noise through the 230V cables could also have an effect.

C. Identification of EMI sources

The question for the students would then be: How to identify the sources of noise without using a fully fitted EMC laboratory? The answer to this question is simple: A four input digital storage oscilloscope will get the students well on the way. The argument for this is as follows: At this stage of the design process there is no need for very accurate measurement of the noise levels. As a start, the source may be identified by measuring control voltages for switching elements, power supply voltages and sensor outputs. When using the oscilloscope trigger correct, the noise "image" might be captured, revealing the main source of the noise, based on timing relative to the control signals, magnitude of the noise components, etc.

The signal frequency of interest is mainly the medium frequency. The argument for this is that low frequency signals normally have a low coupling factor between the source and the receiver, and the received noise therefore is low. On the other hand, high frequency signals are easily damped by other parts of the circuit, and neither these signals do normally have any large impact on the receiving circuit.

In effect, to investigate whether the noise could have an impact on the circuits behavior, the digital storage oscilloscope can be used to monitor specific points of a circuit. By clever use of the trigger, this can be synchronised with the suspected source of the noise to identify the likelihood of a specific problem.

1) Power supplies: The power supplies is the main problem of galvanic coupled noise, as all circuits need some sort of power supply. There is always a desire to limit the number of isolated power supplies in a system, and because of this, several circuits may share the same power supply. Incorrect filtering of noise either at the source or the receiver can in most cases easily be monitored with the oscilloscope connected to both the positive/negative supply as well as the ground connection of a specific circuit.

2) Signal inputs or outputs: Signal pins of analogue or digital circuits can be monitored to reveal any noise present at the pins. This type of noise can either be galvanic coupled or transmitted through the air and picked up by wires or the tracks on the PCB. The voltage can be monitored similar to the power supply nets to reveal potential problems.

3) Magnetic transmitted noise: This type of noise can effect internal parts of a circuit in ways that is not easily discovered by the methods described above. A much used trick is to connect the grounding loop of the oscilloscope probe to the probe tip, creating a loop for picking up inductive noise emitted from a suspected source, or magnetic noise present in the vicinity of a circuit with problems where EMI is suspected as the source of the problems. This will in no way give any accurate measurement, but is only used for identification of sources of inductive noise. This can also be used to get a simple measure of the effect of simple shielding or other measures to reduce the EMI locally.

D. Suggested measures to reduce the EMI couplings, or filter the signals

In order to reduce any EMI problems that might occur, the normal strategies are used. Decoupling capacitors are placed between the power supply pins of integrated circuits. These will reduce the transient EMI noise from the circuit that may occur when the current in or out of the power supply pins experience sudden changes. Without the capacitor, this might propagate to other circuits sharing the same power supply.

Power supply wires and tracks are kept as short as possible to reduce the inductance, which together with a changing current produce alternating magnetic fields, inducing noise in other parts of the system. Keeping the tracks short will in effect reduce the area over which the magnetic field is produced.

Long signal wires should be twisted and configured as current loops, in order to reduce the susceptibility of external magnetic fields. Twisting ensures that any magnetic field is not oriented perpendicular to the wire for longer lengths of the wire. Current loops dictate that any voltage gained (induced) by external noise in the wire, does not contribute to the signal transmitted through the wire.

Optical couplers produce galvanic isolation between separate parts of the circuit, and are normally used to ensure safety for the user or the circuit, but can also be used to stop galvanic coupled noise from propagating through signal paths from one part of the circuit to another.

When designing printed circuit boards, correct use of ground and power planes will limit the circuits' susceptibility to EMI. Shielding by use of solid boxes around critical parts of the circuit can also be used.

These are just some of the many techniques that exist to reduce EMI problems in circuits.

IV. Experiences from running the project

The laboratory project is set as the main challenge in an elective module, electable for final year bachelor students in both electrical and computer engineering. The students are divided into groups of students where the aim is for the groups to consist of two electrical engineering students and one computer student. The task given to the students is to control the light levels and the temperature in the four rooms of the house, both locally and remotely across the internet. The project contains challenges that are designed to be solved by a joint and coordinated effort from both electrical and computing engineering students.

The task is in short that house should be controlled using a combination of a local PC as well as offering a remote access using this local PC as a web server. The groups was free to implement this as one or multiple setups, most often for a single setup, the application produced acted as a controller of the physical infrastructure as well as offering access from a remote location. Security in the form of access control is not part of the challenge.

A. Outcome of the students work

The main part of the challenge, simple direct control of the house and remote control was completed by all the student groups without unforeseen problems. The challenge is not trivial, but is well within what a joint group of electrical and computer engineering students are expected to be able to complete. The meaning of direct control is that lights, heaters, and fans can be switched on and off, that lights and fans can be partly on, in addition the temperature and light levels can be viewed. All groups of students attempted to refine this basic system in order to offer automated control of both light levels and temperature in the four rooms independently.

As part of how the challenge was designed, the students was fairly free to select the types of hardware and software support they elected to use. Two of the groups elected to use a recommended NI USB-6008 [12] interface between the PC and the "physical world" the two other groups elected to use a Arduino [13] setup. Arduino is an open-source electronics prototyping platform, the micro controller on the Arduino board is programmed using the Arduino development environment.

The EMC problems started to appear for the groups in the starting phase of the project, initially all groups decided to just ignore them and kept going, after getting the initial system up and running two groups tried to get to grips with the EMC problems. Of the two groups that made an real effort to work on the EMC problems, one utilised the NI USB-6008 and the other the Arduino setup.

The two groups had severe EMC problems. One group struggled with power supply instability when the relays for the heaters turned on or off, causing large offsets in the operational amplifiers that resulted in an oscillator circuit malfunctioning. They also struggled with signal noise in the light and temperature measurements, and even filtering in software did not remove all the problems related to the EMI. After changing the circuit according to the measures described in subsection III-D, most of the problems were removed. Time was however a limiting factor as the students waited too long before asking for guidance. The system utilising the Arduino controller managed to randomly put the controller board into a safety state, where a manual reset was required. This group never managed to solved their ENC problems, also due to the limited time available.

B. Experiences

The main experiences from the trial run, was twofold: First, that tutoring must be improved in the sense that the students must be followed more closely during the initial project period, in order for the time to be used more efficiently. This is mostly due the the students lack of ability to do effective troubleshooting, as their theoretical background is somewhat limited. Second, the project achieved to demonstrate for the students that EMI/EMC is a matter to be taken seriously, and that there is a very clear cause-and-effect relation between the measures that is taken to avoid EMI problems, an the amount of problems that arise when assembling a larger system.

V. Conclusion

In this paper it has been presented a laboratory project for giving students experience in EMI/EMC challenges. The laboratory focus on learning students the basics of EMI coupling mechanisms and standard measures to achieve EMC. This is done without introducing complex and expensive laboratory equipment for EMI measurements. Instead the standard digital storage oscilloscope is used for identification of the presence of EMI, without quantifying the noise any more than "large" or "small". Feedback from the students were good, with emphasis on the advantages of doing this as a project where they could experience on their own how EMI can adversely affect the functionality of electronic equipment.

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