An Engineering Team Approach to Mentoring Graduate Students through Projects

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Abstract

This paper describes a new approach to the mentoring of graduate students through their master's projects recently developed at California State University, Sacramento in the area of integrated circuit (IC) design. Student engineering teams were formed to design, layout and test two separate pipelined analog-to-digital converter chips and a specialized biomedical chip. The goal of each team was to build a complex mixed-signal system on a chip comprising several diverse circuit blocks, with each student taking responsibility for a particular block. The students were guided through a complete industrial style IC design flow, including architecture, design and layout reviews. The unique challenge of this approach for the instructor is to guide the students to design their individual blocks while insuring that the overall system requirements are met. For the students, the advantages of this approach include the experience of working together as a team, the ability to work on larger designs than a single student could do alone, and the understanding gained of several different circuit blocks. The methodology and pedagogical techniques developed for this approach as well as a number of challenges which were overcome along the way will be described. An overall assessment will be presented based on technical results achieved, student exit interviews and feedback from industry experts.

I. Introduction

Over the last decade, pressures to decrease time-to-market for new products have forced the semiconductor industry to adapt, moving to the formation of ever-larger design teams to develop integrated circuits (ICs). For example, in a recent development effort, a team of 20 engineers worked on the analog portion of an IC. Of that team, 5 engineers (including the authors) designed the analog-to-digital converter (ADC) portion of the IC. This is in sharp contrast to the development of a very similar IC immediately preceding this one, in which a total of 5 engineers worked on the entire analog portion and only a single engineer designed the ADC.

This trend has increased the importance of teamwork and communication skills for new engineering graduates, and has received attention from bodies such as the Accreditation Board for Engineering and Technology (ABET)[1]. Employers value prospective employees with teamwork experience[2].

The authors believe that integrating these skills with the master's project will help the institution meet the needs of the community that it serves. California State University, Sacramento (CSUS) is located in a region with many employment opportunities in the semiconductor industry. "Silicon Valley" is nearby, and the greater Sacramento area itself is a growing technology center. The College of Engineering at CSUS offers Master of Science degree programs in Electrical and Electronic Engineering (EEE), Civil Engineering, Mechanical Engineering, Computer Science, and Computer Engineering. The institution does not offer doctoral degrees. It should be noted that CSUS requires that master's project teams be no larger than two students. Each student on a larger design team must therefore be assigned responsibility for a well-defined part of the project. This part serves as the students own master's project, and must meet all relevant requirements. Each student having a defined area of responsibility is consistent with the team model described below.

A team approach to the master's project in EEE will benefit the students in a number of ways. A primary benefit is that graduate students will gain valuable experience working in the same type of environment and using the same methods that they will encounter in industry after graduation. Other advantages arise from the fact that the students will have the opportunity to be part of a project with a much larger size and scope than an individual project could have. This includes the understanding gained of other team member's circuit blocks, particularly other blocks with which the student's own block must interface. The team approach also helps to increase efficiency of instruction. At group meetings, the information shared by the faculty advisors is frequently of interest to the entire team.

A detailed description of the design team methodology is given in Section II below. This is followed in Section III by a discussion of the first design team efforts employed at CSUS and an assessment of the benefits and issues encountered. Section IV describes both the educational and technical results achieved, followed by conclusions in Section V including a summary of what the authors believe are the keys to a successful design team effort.

II. The Design Team Methodology

The design team methodology adopted here closely parallels that used successfully by the authors while working at several different semiconductor companies, and has been adapted to the university environment. It involves a multiple phase process, with reviews by peers and advisors at strategic points during the IC development to insure success by identifying issues and correcting potential problems as they occur. This is particularly important for student design teams, which lack the experience of professional engineering teams and are therefore more prone to errors. Presentations are given by each student for their individual circuit block, with the entire team as well as faculty and industry advisors in attendance. These reviews typically occur at the end of each phase of the project. This not only gives the students valuable experience in preparing and presenting professional style engineering reviews, but also allows them to work together as a team to identify and solve real world engineering problems. In addition, weekly team meetings are held to track progress and address issues between reviews. Each phase of the development process will be described in detail in the remainder of this section.

Assembling the Team

The first step is to assemble the student design team. While the opportunity to join a team is provided to all interested students, it must be recognized that not all students have attained the required skills to succeed in an effort of this complexity. It is therefore necessary that the students go through an interview and selection process. During the interviews, the faculty advisors ask questions to determine both the technical ability and communication skills of each student. Whenever possible the student who will act as the team leader is selected first and participates in the selection of the remaining team members. The team members are chosen based on the results of the interviews and the skill sets required for the project. While this selection process means that not all interested students are able to participate in the project, even those students who are not selected see tangible benefits. They are able to identify areas for improvement as well as being exposed to a technical interview similar to those they will experience when applying for their first job in industry.

The resulting team is then convened and each student is given the opportunity to provide input as to the circuits they prefer to design. Based on these requests as well as the skill assessments obtained during the interviews, the faculty advisors and team lead then assign each team member a circuit block that will be their responsibility to design, layout and test.

The Architecture Phase

After the team has been selected and block assignments made, the project begins in earnest. The first step in the IC development process is the architecture phase. The purpose of the architecture phase is to determine exactly what circuits need to be built to perform the required functions. This is accomplished by studying how similar problems have been solved in the past and by examining tradeoffs between competing solutions. The goals of this phase are to resolve any open issues that could affect the block design and decide exactly what to build in the design phase. Note that completing the design is not the goal of this phase.

The architecture phase begins with a through literature review in order to understand what proven circuit topologies have been used to successfully solve similar problems. The students learn both the state-of-the-art for their circuit and the level of performance that is possible in the process technology being used for the project. Key specifications and tradeoffs are also identified. It is also important at this point to determine where innovation is required and consider opportunities for reuse of circuit blocks. For example, can a single operational amplifier (“op amp”) be used in several places in the circuit, or must several different op amps be built? Note that taking advantage of opportunities for reuse of circuits is particularly important given the limited time and resources available to the students.

Once the questions outlined above have been answered, an architecture review is held to allow other team members and advisors to review the conclusions reached. This presentation should include a summary of all the required specifications for the circuit block and a comparison of the architectures considered. An explanation is given of which architecture was chosen and why. The results of any simulations that confirm the choice of architecture should be included to support the conclusions reached. An overview of the circuit planned for design should be

presented, including block diagrams or preliminary schematics, as appropriate. Details of all specifications needed to begin the design should be discussed, including a summary of any test modes or other special modes planned, interface information needed by other blocks, any clocks and power supplies required, etc. The main goal of this review is to show that the architecture selected can meet all requirements, however this also provides other team members the opportunity to learn about each other's circuits and how they fit into the overall system.

The Preliminary Design Phase

The next stage of the IC development process is the preliminary design phase. The purpose of this phase is to design all circuits required for the block to meet its specifications. All known issues should be resolved during this phase and the circuits exercised sufficiently to uncover any new issues which may exist. The circuits should be shown to meet all specifications, including additional margin to account for expected layout parasitics such as wiring capacitance. Note that the goal of the preliminary design phase is to complete the design to the point where it is ready to enter layout, but not to completely polish and finish the design.

The tasks for this phase include designing any new circuits down to the transistor level and verifying the performance of any borrowed circuits being reused in this new application. All test benches needed for simulations should be developed, including detailed models for sources and loads. Simulations should be run to show that all specifications are met, with extra margin for expected layout parasitics. This includes simulating the circuit over all standard corner cases defined for the chip (i.e., process, temperature and supply voltage variations), plus any additional corners which could cause problems for this specific circuit. It is also important that the students completely understand any circuits being reused, and take responsibility for these circuits in their application. All interfaces to other blocks should be verified, plus any control signals and unusual modes of operation being used. A floorplan for the block layout should be developed, including items such as the aspect ratio and orientation for the block, and routing plans for all signals and power supplies. Plans for device placement, especially critical portions such as high speed devices, capacitor and resistor arrays, etc. should be developed.

Once the tasks outlined above have been completed, a preliminary design review is held to allow other team members and advisors to review the design and make suggestions. This presentation should start with an overview of the circuit block so that everyone in the audience understands what the block is expected to accomplish and how the design is intended to meet those goals. It should describe the circuit's function and how it fits into the overall chip and include a block diagram of the circuit to show how all the major pieces of the design work together. A list of target specifications for the circuit should be compared to the results achieved in simulation. Any important issues faced during the design should be reviewed, particularly with regard to any specifications that were difficult to meet and any tradeoffs that drove key decisions. A complete set of schematics for the design should be included. Simulation results should be shown to prove the design meets all specifications over all standard corners and any special corners or tests required for this block. The proposed layout floorplan for the block should be presented, including the location of all major sub-blocks such as op amps and capacitor or resistor arrays, as well as how the block fits into the overall IC. The goal of this review is to show that the design meets all design requirements and is ready for layout to begin.

The Layout Phase

The next stage of the IC development process is the layout phase. The purpose of this phase is to draw the physical transistor designs for the circuits under development. The goal is to create a layout which meets all requirements for the circuit, both in terms of how it fits into the overall chip layout and in terms of performance. The importance of the layout should be emphasized to the students, stressing that for analog and mixed-signal circuits engineering the layout is just as important as the circuit design. In sharp contrast to many digital circuits, some iteration is virtually always required to create a good analog layout in order to account for the effects of parasitics such as the capacitance associated with metal wiring. Unfortunately, very little software currently exists to automate the layout of precision analog circuits, resulting in the need for extensive guidance for the students.

The tasks for this phase include drawing the layouts for any new circuits plus placing and connecting any existing blocks being reused. Any critical transistors such as op amp input differential pairs and current mirrors should be identified, and close attention paid to good analog layout techniques during their design (e.g., symmetry and matching). Once the block passes all automated rule checks for the process including Design Rule Check (DRC) and Layout versus Schematic (LVS) checks, plus visual inspection of critical devices and signal routing for matching, symmetry, etc., then the block is ready to be reviewed by the team.

The goal of the layout review is to carefully inspect the block's layout for any problems or issues that can be detected visually. Examples include non-symmetrical routing of differential signals, unintended coupling between wires, poor power bus routing, lack of symmetry in device arrays, etc. Note that this review is critical, since these types of issues are not detected by automated checks such as DRC and LVS. It's important to have a complete set of schematics on hand for use by those reviewing the plot(s), to be sure that they can understand the circuits involved.

The Final Design Phase

The last stage of the IC development process before a circuit block is considered ready to be taped out for fabrication is the final design phase. The purpose of this phase is to incorporate the effects of the physical layout into the block's circuit design and address any performance issues found. The goals of the final design phase are to complete the circuit design and layout and ensure that the final design including layout parasitics meets all specifications. Note that some iteration is virtually always required between the layout and final design phases.

During this phase the parasitic capacitances associated with the layout are extracted and all simulations run during the preliminary design phase repeated including these parasitics. The results of the simulations are checked to make sure the block still meets its specifications. While this step is particularly important for high-speed circuits, it should not be overlooked even for low-speed circuits as unwanted parasitics can still cause problems due to mismatches and power supply rejection ratio (PSRR) issues.

The review for this phase will be very similar to that for the preliminary design phase. A brief overview of the block should be included to refresh the audience as to the block's function and circuit design. Typically this overview can be taken as a sub-set of material from the preliminary design review. Simulation results should be shown to prove that the circuit meets all specifications including layout parasitics. This review should also cover any changes made to the circuit block since the last review.

III. Experiences and Assessment

The first design teams began work in January 2004. As of December 2004, all teams have had their designs fabricated, and have begun testing their ICs. Test results obtained to date will be presented later. The authors have started a second design team effort, incorporating improvements based the first team effort. This section will describe experiences with the first design teams, provide assessment, and make recommendations.

Team formation

In November 2003, the authors began planning the first design team projects. Two teams were envisioned, and it was decided that both teams would design 8-bit pipelined analog-to-digital converters (ADCs). The decision to pursue two projects with the same goal was made so that test equipment and procedures could be shared between the two groups. Other factors in this decision were that the architecture for this type of ADC is well defined[3], and that both authors had recently been involved in a similar industrial design effort. Having two redundant teams turned out to be an advantage when one team member left the project, and the corresponding block from the other team was used in both projects.

The projects were publicized and interviews were conducted with all prospective design team members. For future design team efforts, in order to facilitate a more organized and accurate exchange of information, students will complete a questionnaire before the interview. The questionnaire explains the project expectations and timeline, and asks for the student's acceptance. It also gathers relevant student data.

From among the qualified applicants, two team leaders were selected by the faculty advisors. The role of the team lead is to coordinate the efforts of the team members and to be responsible for the system-level design. For example, the team lead develops specifications that each circuit block must meet based on an analysis of the overall system performance. The team lead is also responsible for connecting all of the blocks for the purpose of top-level circuit simulations, and for assembling and connecting all of the block layouts into a top-level layout for fabrication. The team lead convenes team meetings and makes group announcements.

At the initial team meeting, each team member expressed preferences regarding his or her block assignment (first, second, and third choices were solicited from each student). Faculty members, in consultation with the two team leads, considered the students preferences as well as their individual capabilities and determined the block assignments.

The Design Process

The team lead plays an important role during the design and layout phases of the project. The team lead consults with the block designers and sets specifications to ensure that the blocks work together (e.g., for signal amplitudes and bias voltages). It is essential that the layouts conform to dimensional requirements, and these are established by the team lead based on each designer's estimated area and on a floorplan for the entire chip.

The team lead also considers appropriate test modes for the IC. Test modes provide alternative input and/or output connections that will allow the performance of an individual block to be evaluated. Hence if a vital block fails and prevents the entire system from working, some information may still be gathered about other blocks.

For the ADC teams, the architecture of the overall system was already defined, but each student had to select an architecture for their own block. During their literature searches, students typically needed advice on how to decide if a particular article is relevant to their block, and on how to infer the performance of a particular circuit from information given in the article. They also needed guidance on different types of internet searches. For example, students are often naturally inclined to use general purpose internet search engines as opposed to searching the IEEE database.

The architecture phase contains some of the very first design decisions made by the students. Most of the students were unsure of their ability to come to the correct decision and needed to be mentored through the process. Two techniques have been found useful. First, the faculty advisors ask the students the right questions. In most cases, the students develop the ability to ask these questions themselves as they conduct their literature searches. Second, the students may be asked to make a choice and defend it. The resulting discussion should help clarify the factors involved in making such a decision.

During the design phase, the weekly team meetings began to devote more and more time to specific discussions on circuit design issues. The discussions began to resemble brief lectures from the faculty. To address this problem, one-hour help sessions were scheduled in a computer lab before the start of the scheduled meetings. During these sessions, the students and faculty advisors could together view relevant schematics and simulation results. Although the help sessions were informal and unstructured, questions and answers frequently involved groups of students, resulting in efficient dissemination of information. This allowed the meeting time to be used for its true purpose: a time for status reports, communication with the team and team leader, and for planning.

Throughout the design process, students rely heavily on circuit simulation programs (e.g., SPICE) in order to verify the performance of their designs. It is vitally important, however, that students understand the proper role of circuit simulators in the design process. Simulation results do not replace sound engineering judgement and typically will not show the effects of many practical concerns (e.g., random mismatch and signal coupling). A number of carefully-crafted simulations can, however, be a factor in the verification of a well-designed circuit.

During this project most students used circuit simulation software more intensely than they ever had before. Also, most students had had minimal exposure to IC layout programs. Such computer-aided design (CAD) software packages are complicated, and students will require a significant amount of time to learn the mechanics of their use. To address that problem, seminars on the use of the CAD tools were held in a facility with computer workstations and a video projection system. Recordings of the presentations were made for the students' later reference, as well as for use by future design teams.

The layout of analog circuitry is especially challenging for students. There are a number of process-dependent design rules (e.g., specifications for minimum spacing and distances) to which the student's design must adhere. Students have difficulty adjusting to the fact that when doing analog layout, nearly every decision involves a design trade-off. It was noted that students from different groups began to work together to share information regarding layout techniques and use of the CAD tools. This interaction was facilitated by the fact that most of the layout took place during the summer of 2004, at which time it was possible to dedicate a laboratory space to the design teams. Students were also encouraged to share problems and solutions through a special web page. The authors strongly recommend that for any effort involving IC design, a laboratory space equipped with the relevant CAD tools be set aside for student interaction.

Reviews

The authors found that it was necessary to go over the general format and purpose of design reviews before the students' first presentations. One of the primary purposes for the reviews is to allow the assembled team and other experts to assess design decisions made and to spot potential problems with implementation details. Hence the reviews should be highly organized, and visual aids should have a high degree of detail content. The schematic diagram presented should be taken from the same source as the one used for design and simulation; that way, reviewers will see complete and accurate information. CAD tools often place text (e.g., transistor dimensions) in a very small font, so hardcopy handouts should be distributed or the text attributes should be altered to increase the size. The same is true for the graphical presentation of simulation results; scale factors should be clearly shown and care should be taken that multiple traces do not obscure the important results of a graph. The layout review is often best held as a poster session, with each student explaining their layout and taking careful notes regarding improvements suggested.

The architecture review was the first one presented by the students. Originally, the authors planned to arrange for the reviews as each student was ready. It turned out to be much better to schedule a session in advance comprising many reviews. This is preferable as outside experts can be invited for the entire session. The scheduled dates also give students a target for the completion of each phase.

The input of industry experts attending the reviews was valuable in helping students avoid mistakes, and the experts were also grateful that they were involved in the process early enough to have an impact on the design. The presence of the industry experts made an impression on the students. It was clear to the students that they were receiving very practical training, and they were appreciative.

A Biomedical Design Team

There were enough qualified applicants to form a third design team. Another faculty member was available to advise this team on a specialized biomedical application. Previous work in this area[4] had been done with circuitry not well suited for integration, so this team's first task was to develop an entirely new system architecture. A team leader was not selected for this team and one did not emerge for some time.

The goal of the biomedical team was to miniaturize circuitry needed for a telemetry system that could be implanted in a knee joint after surgery. This first-cut design was only for gaining experience; it was never intended to be implanted. Because of the major change in approach compared to the previous work, the team did not have a system architecture from which to begin. This made the search for information more difficult. Each of the possible system architectures needed to be developed to a point where its performance could be evaluated. The team as a whole found it difficult to be decisive and this process took much longer than expected.

The major impediment to the design effort in this case was the number of unknowns. The input signal was not well-defined, and a number of inter-dependent systems had to be developed. Eventually, some reasonable starting points were assumed and an IC with a number of diverse circuit blocks was fabricated. The circuitry included a dual-slope ADC, a parallel-to-serial converter, and power management circuitry.

IV. Results Achieved

The ADC design teams had set a goal of finishing their design in time for a mid-July 2004 tapeout. The students made an effort to be ready, but finally submitted their designs in August. Even if major design issues are resolved, smaller details related to layout and perhaps to circuit design usually remain as the tapeout date approaches. Although these tasks are small, there may be a very large number of them. Typically, students underestimate the time it will take to complete all unfinished tasks and have the design ready for fabrication. Faculty advisors should attempt to help students to make realistic projections, and to realize that the team must "pull together" prior to tapeout. That is, team members who are finished with their own blocks may be reassigned to help others. Still, faculty members should have a backup date for tapeout in mind.

Due to the late tapeout, the parts arrived for testing in mid-November and complete test results are not yet available. At the time of this writing, one of the ADC chips is fully functional, although a good measurement of its specifications has not yet been completed. The other ADC appears to function, but due to issues with the test setup this cannot yet be confirmed. The biomedical team has verified that the dual-slope ADC on their chip is functional, and their testing continues. Another student designed a separate bandgap voltage reference chip that was used on the same printed circuit board as the ADC to supply the ADC reference voltage.

Besides the technical results achieved, other indicators show that this effort was successful. In all three teams, a true team spirit was developed as the project progressed. In one group, a team member had to leave before tapeout (to return later). The rest of the team completed the layout

of the absent member's block. The teams have been given a relatively complete industrial experience, and have functioned efficiently.

Comments from prospective employers (including but not limited to the individuals attending our reviews) have also been positive. They acknowledge that the students team experience is a valuable asset. Involvement in the development of a successful IC is also highly valued.

V. Conclusions

Overall the first design team effort at CSUS has been quite successful. Feedback from both students and industry advisors has been very positive, with both groups expressing a strong desire to participate in future team efforts. While this first team effort was not free of problems, the students involved learned far more than would have been possible through an individual project and are therefore better prepared to begin their careers.

The faculty advisors also learned some of the obstacles to adapting a professional engineering team approach to the university environment, and have developed several keys to a successful team effort. The first key is to have a solid foundation upon which the team can begin their work. The project should be well defined to provide the students with clear directions to pursue and prevent them from losing focus and wasting valuable time. Regular team meetings with all members attending are a must, as is a clearly stated timeline with milestones. The second key is to have a strong team leader who can keep the team focused and moving forward. The lead should also understand the system being designed and be able to answer team member's questions when faculty advisors are not present. Experience working as a professional engineer is a major plus for the student acting as the team lead, as is a great deal of enthusiasm for the project. The third key is to have advisors with strong industry experience involved throughout the entire IC development. The faculty advisors may have extensive experience of their own, but having outside industry experts provide input and attend reviews lends a fresh perspective which the students appreciate. This both encourages the students and validates the guidance they receive from their faculty advisors.

This first successful effort has provided a strong basis for future student design teams at CSUS. Future design team efforts will undoubtedly lead to further refinements of the methodology and pedagogical techniques described here.

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