A *D&T* ROUNDTABLE

ONLINE TEST

Online testing has been a known field for sometime now. However, today's situation with online testing may be a little bit different than it was in the past. With the nanometer technologies, we may see more soft errors that cause problems. The goal of this roundtable is to analyze where online test was and where future technologies are going.

D&T thanks participants Jacob A. Abraham (Univ. of Texas at Austin), Miron Abramovici (Bell Labs), Silvano Motto (CAEN Microeletronica), Isaac Levendel (Motorola), and Michael Nicolaidis (TIMA). Our moderator was Yervant Zorian (LogicVision). Also attending were Lorena Anghel (TIMA) and Fabian Vargas (Puers, Brazil). *D&T* Roundtable Editor Kaushik Roy (Purdue Univ.) organized the event.

The roundtable was held at the Fourth IEEE International On-Line Testing Workshop in July 1998. *D&T* thanks the workshop for hosting it.

D&T: How would you assess current online testing technology and where might it go in the future? What trends do you foresee?

Levendel: I've noticed that today's online testing community sees the field too narrowly as bit-level oriented; it needs to be elevated. Paradoxically, system-level online testing has been around as long as we have worked with computerized components, for example, telecommunications in the 1960s. A lot of work has been done pragmatically on system integrity. To ensure system integrity, we need online testing. Economically, there is an enormous value in elevating this science to span all levels of systems from the bottom to the top, and not just concentrate at the bottom.

Nicolaidis: From another viewpoint, online testing is important for improving a product's reliability. We have to see where we need to improve reliability, which is strongly related to two things: what is the reliability level corresponding to a given technology or process, and what are the reliability levels required by the various application domains. This means that we can use online testing when the reliability level achieved by a given process is not enough for the majority of applications or for applications that have very high reliability requirements.

In the very early age of computers, unreliable electronic components made online testing approaches mandatory. In the VLSI era, component reliability improved dramatically. This restricted the use of online testing techniques in specific application domains that require high-reliability levels or in specific environments such as space where the environment caused lower reliability. To understand the future trends, we need to understand the reliability levels achieved by the future VLSI processes and the needs on the application side.

Levendel: Online testing has a bigger role than increasing reliability in assuring system dependability. In the case of unreliable or partially unreliable components, online testing should take care of that in the tolerance of failures.

Abraham: I'm not clear whether online testing includes both checking the hardware and checking the results of the computations. I assume it involves both. Long ago, Babbage suggested computing a result two different ways to make sure that the results were right. So the need goes beyond even our century.

It is also true that the dependability of

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components goes in cycles. A new technology has more failures and errors, so we need checking. As it matures, however, it becomes more reliable, and people don't want to pay the price for checking. My guess is that as we go into deep-submicron levels, we may see more soft error rates and defects that cause problems, and it follows that we will require some sort of online correction. We do this for memories already, and we may have to do it for computational units.

D&T: Do you agree that the technology's become more mature at the low level?

Abraham: Yes; people have understood the theory and the mathematics to develop all kinds of circuits. Ultimately, we made all this technology so users can get correct results in their applications. Now, we have to move up to the application level, including not just digital components but also embedded analog components, sensors, actuators, and software. Perhaps we should also look at design faults, both in hardware and software, because ultimately we have to make the system dependable for all of those applications.

Abramovici: I'd like to get your opinions about the direction of the field. Is there a growing field or not? Aren't applications a constant and not really an increasing field? Telecommunications and space missions have always required reliable computing. New areas, such as automotive and medical electronics, have high reliability requirements. We need to get a measure of how most other fields that meet online testing needs are growing.

Motto: In my company, we had to think about online testing not more than one year ago. I can say that it was a precise leap above our customer's experience in very important biomedical, space, and nuclear physics applications. Most of the time, we have been approached on problems related with online testing, but really our testing was more than an online testing problem. Especially for biomedical applications, it's a problem of improving reliability. We have found that much of the technology available today doesn't guarantee the products even though they know that they're going to be applied to the human body. I'm speaking, for example, of pacemakers.

D&T: Would you expand on that a bit?

Motto: Our company had been developing products at the starting level. Then we were advised to stop development because the technology that we were going to use wouldn't guarantee the high reliability we needed. We started to think about adding hardware to improve that reliability that the technology couldn't guarantee. In the biomedical and nuclear physics fields, a lot can be done to achieve the required high reliability. But in my opinion, these are not markets we can rely on to foresee a trend.

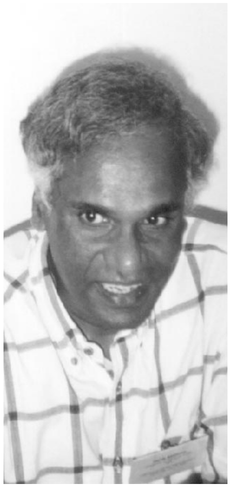
Levendel:

"Economically, there is an enormous value in elevating this science to span all levels of systems from the bottom to the top, and not just scan at the bottom."

Levendel: Jacob mentioned the failure model of software. But the failure model is not sufficient in restoring proper functioning of real-time systems. In fact, many times we not only can see at the application level the effects of a failure at a lower level, but we can correct the resulting data corruption at the application level. For instance, when processing calls in a telecommunications system, the data for a given call in progress may be modified dynamically. The data is corrupted or changes state illegally. The only logical action at that level is to decide whether to correct that data—if we can—or throw it away. We need to understand that we're throwing away the call, and not the entire system. So the correction and the detection must be at the level of the application.

D&T: Would you hazard a guess as to where you feel the online testing field is going?

Levendel: I don't know where it's going, but I know where it should go. Online testing is really what I would call a functional boundary technology. We need to observe what's happening in a function, wherever the level is, and to analyze what we see. We also need to take an action, which means that we need to control the observed element. We are really talking about testability (observability and controllability), which is a boundary condition technology. If we elevate the testability and controllability of the components, we will be able to reuse many functions and integrate them in a system at lesser cost. I believe in economics, and this will lead to better online testing.



Abraham:

"… as we go into deep-submicron levels, we may see more soft error rates and defects that cause problems, and it follows that we will require some sort of online correction."

Nicolaidis: It is very important to consider online testing at both the system level and the low level. We still need to do a lot of work at the lower level because we have new problems and new constraints there. For a certain period, we need online testing and eventually fault tolerance in specific applications where most usually we have a low-volume production. In such cases we don't want to pay a very high development cost because this cost will increase the per-product-unit cost. Then, it is not interesting from the cost point of view that we develop new VLSI components that integrate online test solutions. For instance, massive replication using off-the-shelf components may be more cost effective.

The other problem is that for all this period we don't have tools developed for designing online testable VLSI circuits. This problem also affects both the development cost and cycle. We need commercial tools to resolve this problem. However since these tools concern specific applications, the market is small and CAD vendors are not really interested in investing in this domain.

D&T: Michael, you mentioned earlier that in the deeper submicron technologies we could see different manifestations. How do you see that happening? What's the reason behind it?

Nicolaidis: We are starting to see an increase in the number of applications that will require online testing. In addition to traditional domains, we have other domains that involve mass-volume production, such as in providing millions of systems for cars. It is becoming interesting to pay a certain amount of cost to develop new VLSI components and reduce the production cost corresponding to the use of off-the-shelf components. This is one of the reasons that VLSI-level fault tolerance or online testing will be developed in the future.

In addition, there is another much more important reason. The trend today is that from one process to another, we are reducing device size to put more transistors on a single chip. This is very important for the industry. Because we can produce products that are cheaper and faster, consume less power, and offer more functionalities, we can expand the electronic application domains. We have an absolute interest in maintaining this progress. When we go from one process generation to another, we reduce device size and power supply levels and increase circuit speed.

D&T: How does this affect chip noise?

Nicolaidis: We are becoming increasingly sensitive to noise, and it is obvious that we cannot continue in this direction infinitely. Our products will become very, very sensitive to soft errors. Analyses show that we are very close to this point. Soft errors will be caused by internal and external sources of noise.

As an important example, consider the case of single-event upsets caused by the neutrons produced by sun activity. At the ground level, the flow and energy of these particles are not enough to drastically affect the operation of today's ICs. But as the technology moves toward 0.1 micron, the error rates induced by the cosmic neutrons will become unacceptable. The impact is that we would need tolerance of transient faults for any kind of application, not only in very specific applications. This will be a very important evolution for online testing.

Abraham: Are you saying that even our commodity products would need online error detection?

Nicolaidis: Yes.

Abraham: Even for logic, not just for SRAM?

Nicolaidis: Exactly. Analysis shows that not only will memory parts be impacted by such errors but logic will also. This will happen increasingly. At around 0.1, it will be very important. When we go ever deeper into submicron, say 50 nanometers, the error rates will become very, very important. So we have to change our design methodologies—how we design circuits.

In commodity applications, we cannot afford the cost of massive redundancy. System-level solutions are not more adequate, since error handling at this level is much more complicated than at the IC level, resulting in high product cost. It will require a development effort for each application in which an IC may be used. What we need are ICs that can tolerate this kind of failure, providing a universal transparent solution for the IC user.

Levendel: The technology, in terms of design technique, is far behind in developing online testable processor chips with all of the available complex capabilities. We have the capability to design functional modules, like comparators, adders, or whatever, but not the full hardware system.

D&T: Let's go back to what Haim was saying about reliability in the field. Were you considering only the telecommunications viewpoint?

Levendel: Not at all. What I said is certainly correct in the telecommunications arena. In the last 20 to 25 years, we have seen large changes in elevating the level of commodity components. Think about how many times you have relied, indirectly or directly, on a processor to do something you were doing. Try to count the number of times that you relied on some electronics that are at least at the processor level. I have no doubt that in automotive, as well as in any other segment, the elevation did not stop there. Today's automotive industry uses systems inside and outside the vehicle. My point is that online testing and online testability have to accompany the level of commodity product, not just the application, which really includes software, online testability. We also need to go to the elevation of the commodity units.

I disagree that computers in a car must be more reliable than in telecommunications. The degree of rigorousness in the security of a system depends on the number of people affected. If we lose 5,000 people or an entire city, it becomes even more critical than when we lose one person. A gas tank that blows up will affect perhaps two people out of two million.

Nicolaidis: We have different requirements, different levels of dependability in different systems.

Levendel: One of the dimensions of dependability is the ability to avoid catastrophes. And the degree to which you want to avoid catastrophe depends on who's affected. In telecom, people don't care as much if one person loses one phone call.

Nicolaidis: When we're talking about human lives, it's different.

Levendel: They do care. What about that gas tank GM installed and Ford put in the Pinto? They were known to blow up once in a while, yet the company spokespeople said "Well, it will cost so much in insurance costs, and given the low probability of adverse publicity, we don't care. The insurance costs will be less than redesign."

Abramovici: We must consider two types of cost. One is easily measured in dollars. But if some problem in a car results in a loss of life, there is another dimension to "cost."

Motto:

"From an economical point of view, I care about the standards, and I care about the competition."

Levendel: There is what is called a decibel of incidence: how many incidents are involved. There is a decibel factor that is multiplying the severity of the problem and has an influence on the reaction.

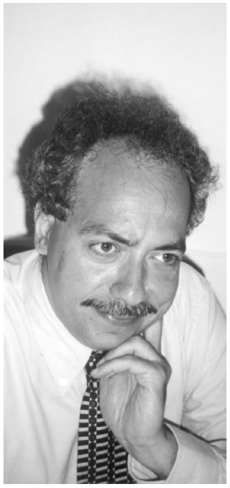
Motto: I don't believe people in a company would consciously endanger the lives of their customers, taking only the numerics into account. Not only from the human aspect, but also commercially, this becomes really important.

Levendel: You can't pay an infinite cost for everything. Companies have no morals; they have balance sheets. I was in charge of system test, and at some point we learned that our customers do not want problems in software that support telephone attendants. (The attendant directs phone calls in a company.) After a software upgrade, there may be problems. The attendant function is very critical, because someone may call the president of the company, and the president of the company may call the president of the supplier, and there is an amplification effect in it that has nothing to do with the actual impact. It's just enhanced by the intervention of executives. Very quickly, we learned that this is a sacred part of the system. It's just good business.

Abramovici: In medical instrumentation that controls critical processes, there isn't only an economic cost.

Levendel: Yes? If a pacemaker costs $2,000, and another one costs $5,000, you will choose the cheapest one.

Motto: Medical applications have fixed standards. If a company makes a product that's inside these standards, it doesn't consider the fact that there can be a failure and someone



D&T:

"Could some kind of reuse of the offline test capabilities be used in the online VLSI test area?"

dying. There is market competition, so a company always tries to save as much money as possible. Sure, they have to keep inside the standards, but when they're just below the standard, it's fine.

D&T: Please explain further.

Motto: If I know that by spending much more I can improve reliability much more than what the standards require but I also know that I'm out of the market, I won't do it. From a moral point of view, I would like to invest a lot, and I wouldn't care about the standards. From an economical point of view, I care about the standards, and I care about the competition. If I decide to do something in these applications, I would probably have to give up the morality. I have to keep a balance.

Levendel: There is no other explanation. Look at the space problems with multiple modular redundancy, then look at telecom's 911 redundancy. We could produce 911 with many implementations—and many added costs. It would save more lives. Are the three astronauts going into space in a year worth more than three patients that need 911? We have many more patients that need 911, so why don't we add the same level of redundancy to 911 that we insist on in the space program? The reason are politics and cost. People don't want the mission to Mars to fail because they would get a lot of flak about it; it's not at all related to the loss of life.

Motto: As I said before, some technologies don't want a product to be used in medical applications when a human life is in danger, but that doesn't come from a moral motivation. People think of the clamor that may occur if something bad happens and the company made the product. I've spoken with people in many commercial firms, and nobody's taking care of the moral point of view. They care if the system is failing and their name is on the product; they care about bad publicity.

D&T: We've talked about various applications, and the needs of those applications, the competition, and the differences. Now, do you see today's online test solutions to be relevant and sufficient to tomorrow's needs? If we need to change them, what direction should we take?

Abraham: Today's technology provides a good foundation on the techniques that we need, and we have a good understanding of what kinds of tests as well as error checks we need. But as was mentioned earlier, the solutions do not move all the way up to the system level.

We also have a related problem. As the complexity grows along with Moore's law, there's a danger of design faults. Under certain conditions, we're going to get 100% failure. It's not the probability of a manufacturing defect happening in a chip, but a design fault causing all the chips to be faulty. Because of the hardware complexity, the software is matching complexity. Since it is cheaper to put more things in software, perhaps this community should start looking at those issues. Software degradation is one way of saying that the software defects that we cannot afford to correct at this time means we need to have tolerance mechanisms to deal with those defects and the data. There are very interesting research areas in balancing fault avoidance with fault detection and removal, and tolerance. Our community has a good opportunity to look at these areas.

Levendel: I want to second the last issue Jacob brought up. It is not really one that is developed in the hardware domain; it is fault avoidance. There is room not only for correction—which is mostly what is done in online testing—but also avoidance and containment. Containment is a little stronger than avoidance, while correction is the ultimate reactive mode. We have proactive models as opposed to reactive models.

Abramovici: One future trend is that advances in technology make online testing more of a requirement because of the new failure models. On the other hand, advances in some of the technology make the job of online testing easier. For example, programmable logic in general, and in particular, field-programmable gate arrays, is a technology that is expanding at a very high rate and becoming more and more popular for many applications. This technology has certain characteristics, such as regular structure and programmability of both logic and interconnect, that creates very important advantages for online testing. We have just embarked on such a project, and we see very good potential for exploiting programmable logic in achieving cost-effective online testing.

Nicolaidis: I am consciously restricting my remarks to online testable VLSI design that I am most familiar with, but this does not mean that I'm not considering the other domains.

As I have said, in a few years it will be mandatory to design online testable ICs. We will need low-cost solutions and design automation. We need to enrich existing solutions and discover new ones to cope with the low-cost constraint and implement them in CAD tools within a few years. If we want to take care of soft errors, we can use techniques such as self-checking design to perform concurrent error detection. After that, whenever we detect an error, we must perform error recovery to correct the result. However, if we want to resolve the problem at the chip level, we have to investigate how we will do it as well as the architectures we have to use.

D&T: Will this meet low-cost requirements?

Nicolaidis: Unfortunately, self-checking design will not meet either low-cost requirements or the high soft-error detection capabilities for all circuit cases. We need a wide range of solutions so we can select the most appropriate one for each circuit case. Fault avoidance or time redundancy techniques are possible alternatives. For instance, if we have to take care of memories, we can solve the problem of big memories using error correction. But what do we do about smaller memories when the error-correcting code is very expensive? Perturbation-hardened techniques are more appropriate in this case and for distributed storage cells (register latches). In addition, as we go into deeper submicron levels, devices begin to have probabilistic behavior, and the error rates increase significantly. Self-checking design is not appropriate in this situation, because its error detection capabilities are not scalable, while the other techniques are.

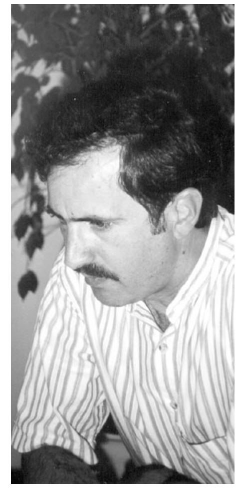
D&T: Could some kind of reuse of the offline test capabilities be used in the online VLSI test area?

Abraham: Theoretically, it is possible to leverage. Unfortunately, the two disciplines are so diverse that manufacturing tests have developed with the assumption that there is a tester that has some amount of intelligence to be able to do the testing. We can't do that online.

D&T: How about a self-test?

Abraham: Self-tests, functional kinds of tests that people want to apply for detecting nontarget defects, may be applicable in the online domain.

Nicolaidis:
"… even if we test the circuit and have circuits that don't have structural or parametric faults, we will still have erroneous behavior in the field due to soft errors."



D&T: Some participants have commented on how research should be done. Does anyone else care to add to this?

Abraham: The research community has two charters. One is to look ahead and try to solve problems before they become real problems. The second is to try to ensure that the solutions are scalable and are applicable to real designs. Moore's law says that things are going to double every 18 months. We see many techniques that require certain analysis, say, of the complete state space of the design, to find a solution. Those techniques don't scale when you double the amount of hardware. Researchers should work closely with industry to be sure that their solutions are relevant.

Levendel: The areas of avoidance and containment are more concerned with effects than with causes, whereas the current discipline of online testing is more concerned with causes. This is interesting because of its trade-off in terms of the real-time requirements. At a separate level, we are interested in causes, and because of the real-time requirement we want to do it very effectively. When we elevate the testing, we are more concerned with effects at the large application level and our reaction time doesn't have to be as fast if we rely on avoidance and containment.

We have a wide-open area for the reusability of all that's associated with online testing at the system level, and the reason is very simple. Recovery software makes up 60% of the total volume of software. This results in an increased software complexity because of this combination. In fact, the reason for the complexity is that the two are very tightly integrated. We can find online testing software at every line of the code, potentially.

A very important breakthrough will be to have reusable constructs that the application designer or the system integrator would not necessarily have to actually program; it could be done automatically. When we assemble the operations software, we would automatically tag in these reusable constructs. Basically, the key element of the solution is to create a hardware analogy in software. The assembly becomes possible if we have strict definition of the boundaries from the testability viewpoint. It's just the beginning; there is more work to be done in this area.

Nicolaidis: It will be interesting to hear more about this part of the work because it is very important.

Motto: Are silicon vendors working on VLSI online testing for the future libraries of deep-submicron technologies?

Nicolaidis: Some vendors are. I just gave an invited talk on it at a big IC vendor, and I am also working on a project with some European companies. However, many companies are starting to be interested in it. We had a panel session at ITC on the domain of very deep submicron concerning soft errors. My discussions with people from Intel, ST Microelectronics, and others indicate that they worry about these problems.

D&T: Let's go back for a moment to the problem of combining VLSI-level offline test and VLSI online testing.

Nicolaidis: First of all, testing is very important for reliability and will be increasingly important in the future because of the newer problems and the more complex defect behavior in the very deep submicron processes. However, even if we test the circuit and have circuits that don't have structural or parametric faults, we will still have erroneous behavior in the field due to soft errors. It is not only a problem of testing after manufacture. The question is how we can use manufacturing and test to solve the problem. We need to monitor the circuit continuously in the field. Eventually, we can try to merge online test solutions with BIST, but this will not work in all cases. Concurrent checking techniques have not required test pattern generators for BIST, but they can replace the signature analyzers. Built-in current sensors can also be used for manufacturing and online testing, but other manufacturing testing and online testing approaches are hard to merge.

D&T: Thank you all for helping us understand this field better. I'm sure online testing will continue to be part of our lives for quite some time.

Participants

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