

Systems Research Center

by

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## SYSTEMS RESEARCH CENTER

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## 1. The Research Theme and its Significance.

The University of Maryland and Harvard University are very pleased to have been selected for an Engineering Research Center award by the NSF. On the basis of this award a **Systems Research Center (SRC)** will be established at the College Park campus of the University of Maryland. The focal University of Maryland organizational unit participating in the activities of the SRC will be the College of Engineering. Broad participation from several departments is planned: Electrical Engineering, Chemical Engineering, Mechanical Engineering, Aerospace Engineering, within the College of Engineering, and Computer Science, Mathematics, Institute for Physical Science and Technology and the Center for Automation Research. The focal Harvard University organizational unit will be the Decision and Control program of the Division of Applied Sciences. In this brief paper I will summarize mainly the research theme and the educational and research programs of the Systems Research Center. In addition I will describe the planned industrial collaboration program, international program, information dissemination and other aspects of the center.

The research theme of the SRC is to **promote basic research in the implications and applications of the three technology drivers (VLSI, CAE, and AI) in the engineering design of high performance, complex automatic control and communication systems.** Recent advances in computer science (artificial intelligence, expert systems, symbolic computation), microelectronics (VLSI circuits development, availability of computer-aided design tools for special purpose designs) and computer aided engineering (enhanced interactive graphics, powerful work stations, distributed operating systems and data bases) have created a unique environment for innovative research and development in the discipline known as "*Systems Engineering*". For the purposes of the present paper by Systems Engineering we understand the discipline that combines automatic control systems, communication and signal processing systems with certain areas of computer engineering. The major research thrust of the discipline is the design and implementation of high performance electronic systems for automatic control and communication.

I shall now provide some motivation and historical perspective, that influenced our thinking and planning for the SRC. To begin with, let me first emphasize that recently the complexity of such systems has increased dramatically. This is manifested for example in the tighter engineering specifications, the need for adaptation, the requirements for multi-sensor integration, the need to account for contingencies (multiple modalities), totally digital implementations, the need for a mix of numerical and logical computations. Some of the challenging design problems that we plan to address in the SRC further illustrate this point:

Unfortunately, currently available theories and design methodologies for such problems are not in synchrony with the currently available or planned implementation media, be it special purpose chips or computers with specialized architectures and capabilities. To be more precise the available design theories and performance evaluation methods were developed for different, now often obsolete, implementation media such as analog circuits, sequential machines. Although for some problems, admittedly a small class, it is feasible to develop improved designs using the new hardware capabilities and existing theory, in the majority of problems there is a substantial lag between the available hardware potential and its realization in the systems being built. *That is precisely what the Systems Research Center is all about.*

Of course there are examples of successful *hardware solutions* to some of the design problems already mentioned. By this I mean the process whereby one adds hardware components or "boxes" in an *ad hoc* fashion, then tests each addition, and adds more components until a satisfactory system is built. I do not believe that a serious argument can be made to support this method as a superior method for exploiting the hardware potential available today. On the other hand substantial theoretical results and knowledge exists in automatic control and communication systems theories that have not been directly linked to hardware implementations. Actually the realization that a *a window of opportunity* exists, in that advances in CAE, VLSI, AI have made possible the design of "paper-algorithms" from powerful theories into real-time electronic "smart" boxes [1] was a major motivating force in planning for the SRC. A careful reexamination and development of new design theories that **incorporate component hardware advances and the related implementation constraints** is long overdue. We can no longer separate the design of a system from the implementation problem. This is a major thrust in the SRC program. The significance of the SRC program can be illustrated from yet another (financial) point of view. Huge investments have been made and will continue to be made for research and development in microelectronics and computer hardware. It is important and prudent to make a small investment (in comparison) for the **development of design methodologies and software tools that will be used to build systems with this hardware.** It is rather obvious that the sophistication and capabilities of the circuits and devices that we build will be limited by the power of the CAD tools that we use.

It is evident that the SRC theme encompasses two fundamental components of high-technology industries: *automation and communications*. It is important to emphasize that high-technology industries involved in automation and communications influence directly the competitiveness and performance of more traditional industries. Consider for example the influence that advances in automation may have on steel mill operation and automotive design and production. This consideration was an important factor in the development of our plans for the SRC.

The Systems Research Center aims at the establishment of a strong advanced research and educational program in the above areas. Given the broad knowledge and intellectual basis required by the SRC research theme we have assembled a interdisciplinary team of scientists and engineers from the two major Universities involved. They include electrical, mechanical, and chemical engineers as well as mathematicians, numerical analysts, computer scientists, microelectronics and artificial intelligence experts. At its projected full operational level the SRC research programs will involve some 40 faculty, 120 graduate students and at least 120 undergraduate students. A larger number of students will be influenced by its educational programs. We strongly believe that there is a real need, quite critical for the nation,

to educate and train engineering students in the mix of disciplines and knowledge represented in the SRC programs. A similar critical need exists for retraining practicing engineers, and this will be incorporated in our plans.

## 2. The Research Program

In this section we provide a brief summary of the current research program for the SRC. The research program is an expansion and natural extension of research work already underway by members of our interdisciplinary team. The research activities listed below served as the inspiration and provided much of the motivation for the planning and implementation of the ambitious research goals of the center. They are in some sense the *seeds* for interaction and further development of the key ideas behind the conception of the SRC. The SRC will provide the fertilized ground for the development of the major thrusts emanating from these early works. They are:

- (a) Optimization-based design in chemical process control.
- (b) Perturbation analysis and AI modeling in manufacturing systems.
- (c) Symbolic computation and VLSI architectures for the design of real-time non-Gaussian detectors.
- (d) Design of a VLSI DFT processor.
- (e) Vision sensors and feedback in robotic manipulators.

The research program implementation that we selected for the SRC was influenced by three factors. First, the areas of strength for the participating faculty. Second, the expected impact of SRC research. Third, the strong commitment to a problem driven interdisciplinary program. We have as a result selected five **focus application areas**, to help us measure the success of the basic research program and to help motivate it by applying the design tools to a diverse set of complex real world problems. These areas are described below together with the currently planned thrusts in each.

- (1) **"Intelligent" CAD of stochastic systems.** We shall combine CAE and AI methods for the design of advanced nonlinear signal processors capable of real-time operation. One thrust is in the development of expert systems that can "reason" mathematically and can understand a variety of signal and system models. The other two thrusts address questions of distributed computations in stochastic systems and implementation by "optimal" VLSI architectures. In particular silicon compilation and special high level signal manipulation languages will be studied.
- (2) **"Chemical Process Control".** Here we shall investigate how CAE, AI and Optimization can be applied to the design and control of chemical plants. Modeling and simulation questions will be analyzed and built in the CAD process. In addition we shall attempt to integrate reliability and safety considerations in the design software and workstations.

- (3) **"Telecommunications"**. There are two major thrusts. The first centers around the development of powerful simulation and CAD systems for computer/communication networks (LANs, flow control, reconfigurable networks). This will involve interactive graphics, expert systems and high level command languages. The second involves image and speech processing problems and their hardware implementation. Numerical and hardware complexity will be studied as well as fast digital implementations.
- (4) **Advanced Automation and Information Processing in Manufacturing Systems**. We shall investigate applications of CAE, AI and optimization. In particular an integrated program will be pursued that addresses scheduling problems, adaptive resource allocation, AI systems in manufacturing, data base integration, flexible manufacturing cell, CAD integration in Manufacturing Resource Planning (MRP), Optimization based design and advanced interactive simulation.
- (5) **CAD of Intelligent Servomechanisms**. Two major thrusts. Theory and design of an advanced prototype hand-eye machine, and the design of flight controllers for high-performance aircraft. Both involve the integration of many "smart" sensor data and the control of systems with very complicated dynamics, often requiring the use of symbolic algebra for their derivation. Implementations by special purpose VLSI processors will be examined. In the area of robotics the program will address primarily feedback control of a mechanical hand with many degrees of freedom based on integration of data from several sensors. In the design of flight controllers we will focus on optimization based design for unstable aircraft.

The common thread in all areas described is the emphasis on *the development of advanced CAD tools that combine the specific theory and practice of systems engineering with the three technology drivers: CAE, VLSI and AI*. These advanced design methods provide the intellectual bond in this diversified program. The program cuts across the boundaries of many disciplines including: chemical process modeling, polymers, bioreactors, chemical reactors, aerodynamics, flight controllers, robotic manipulators, vision, sensor design, signal processing, communication networks, information theory, coding, optimization, control systems design, stochastic control, detection and estimation, algorithmic complexity, algorithm architecture, VLSI array design, optimization-based CAD, numerical linear algebra, numerical mathematics, rule-based expert systems, knowledge-based expert systems, computer algebra, stochastic processes, queueing systems, manufacturing, mechanical machining.

The program is interdisciplinary, problem driven and *technique specific*. We believe that the fundamental tools and methodologies for their design, that will be developed as a result of the SRC research program, will have a much broader applicability. Furthermore, it is expected that these generic CAD tools will evolve out of strong interaction between the research performed in the five focus areas. Each area includes systems of high complexity and design problems that cannot be attacked by conventional methods. As research progresses in each area we expect to see a cross fertilization to take place in the effort for the development of CAD tools. At the University of Maryland we have already witnessed this phenomenon in design projects on chemical process control and advanced aircraft.

More significant for the SRC's mission is the interaction between the three technology drivers (CAD, VLSI and AI) with the disciplines of control and communication systems as represented in the five focus applications areas. It is anticipated that the broadly interdisciplinary program will cause fundamental reexaminations of control and communication systems theory and methodology. Furthermore, it is expected that this latter interaction will foster a secondary level of interaction among the focus areas as hardware implementations for different applications will be analyzed and compared.

The research program of the SRC will have two major components:

- (1) In depth investigation of the impact of VLSI, CAE, AI.
- (2) Basic research in modeling, mathematical analysis, optimization, computational and numerical methods, control systems techniques, communication system techniques, computer engineering techniques.

The first component shall address the following: Regarding VLSI (the implementation medium) we shall investigate algorithmic and architectural aspects of VLSI; signal processing chips; control chips. The design methodologies to be developed must account for VLSI implementation constraints. Regarding CAE (the implementation environment) we shall investigate the effects of interactive graphics, interfaces etc. in the design of sophisticated CAD systems. For example in developments related to the DELIGHT.Marylin system ( a powerful optimization-based design system we use at Maryland), the fact that advanced graphics were to provide the output, enabled the numerical analyst to develop an interactive procedure that could handle multiobjective optimization. In addition this environment permits the engineer to study a design problem in his own language, without being overburdened with complicated computer procedures. Regarding AI, we shall investigate the effects of symbolic computation and knowledge based systems.

The second component is needed because sophisticated new theories and methodologies are required in order to extract the maximum benefit possible from the advances in microelectronics, CAE, AI. As Roland Schmitt [2] describes the situation very eloquently,

In the technology of controls, for example, fundamental theoretical advances are needed to catch up with the speed and power of microelectronics.

I would like to offer some additional remarks regarding the technology drivers. The impact of VLSI technology on signal processing and automatic control systems, is emerging as very influential. However, for success in this direction very advanced CAD tools must be developed and popularized. The rapid developments in VLSI chip design and production, were made possible by the development and rapid dissemination of precisely such advanced CAD tools. *The SRC program aims at producing similar sophisticated CAD tools in the general area of control and communications systems engineering design.*

An important factor in future systems engineering theories and design techniques will be the development of *expert systems* for CAD [3]. In applying expert systems to design tasks, the idea is to pit knowledge against complexity, using expert knowledge to whittle complexity down to a manageable scale. It is anticipated that expert systems will eventually be applied in many design areas, but an important example is their use in digital system design, particularly in computer-aided design (CAD). The planned SRC program will develop a broad research activity in this area. *AI and symbolic computation promise to revolutionize design.* There are very

sound reasons for this prediction : first, the cost of generating special-purpose Fortran-based "codes" is fast getting out of hand. Massive investments in design tools can become either a brake on innovative designs or an argument against further development. AI and symbolic computation transfer the mathematical models of the physics of the system being designed from the "code" side ("applications code") to the data side of the system, where they can be used, manipulated, shared, modified, and even created by the system as easily as numerical data elements. This transfer is essential for the attainment of cheap, easily reconfigurable design tools. Second, AI and symbolic computation prevent the designer's entrainment in specific design procedures and processes provided by custom-coded Fortran programs, and allow for a very flexible approach to the design. Symbolic manipulation has immediate and powerful applications in CAD. For example, the amount of "nuisance programming" required to develop and maintain large design packages is reduced to a practically negligible part of the overall code. Furthermore, increasing the level of abstraction at which data and code are specified reduces significantly the complexity of code transportability. Finally, it allows treating entire mathematical models — logic as well as its numerical parameters — as data capable of being manipulated, examined, and modified, as well as being executed like a Fortran subroutine. Further advantages offered by AI include natural language processing, automatic deduction, cognitive models, learning and inference. An excellent example for an application of AI and symbolic computation in aerospace design is given in [4].

Systems engineers today are called upon to solve complex control and communication design problems, for systems often described by huge simulation models. The traditional approach has been to reduce the complexity to a small number of mathematical equations and eventually apply rather simple elements of available theories. Clearly, we can do much better than that, if we utilize the full power of techniques from CAD and AI. Furthermore, the speed provided by VLSI arrays promises to support the often real-time processing need of advanced control and communication systems. For systems of today's complexity it is often difficult to write and manipulate the governing equations correctly. Think for example of the task facing a chemical engineer who is trying to describe a complex industrial chemical process, starting from simple, elemental chemical reaction equations. His final goal is to design a process controller. Or consider the aerospace engineer who is developing a mathematical model for a complex, multi-body, flexible, large space structure. Again his final goal is to design a controller. Both have to manipulate a large number of equations (often more than one hundred) of different types (algebraic, differential, partial differential, Boolean). Symbolic manipulation and rather elementary AI techniques (such as search heuristics, sup-inf decision procedures etc) can readily reduce these tasks to routine and permit the engineer to concentrate on the design issues. More generally, there is clearly an *established need* in utilizing *AI methodologies* in *CAD*. In the design of flexible manufacturing systems, for example, one encounters coordination problems that can benefit enormously by the use of *automated reasoning programs*. The latter can supervise the lower level numerical CAD programs. To ask a systems engineer to solve the complex design problems of today without such a combined arsenal of tools, is similar to asking a VLSI chip designer, to design the chip without the expert CAD tools available today. The foregoing discussion then provides an account of the basic ideas behind the research program of the SRC.



### 3. The Educational Plan.

Here we provide a brief summary of the Educational programs of the SRC. The theme of these educational programs is that **the SRC supports and enhances educational programs and is a source of new courses and material.** Furthermore the SRC and the two Universities involved are committed to the principles of *lifelong education* [5].

The SRC will establish within the first two years a modern environment for rapid information dissemination via a local computer/communication network, appropriately connected to the University-wide network and other industrial and government networks. Adequate work stations and advanced terminals will be provided in order to support sophisticated computer assisted instruction tools. Software libraries, case studies, design examples will be maintained and updated. It is planned to utilize, in a timely manner, powerful educational tools such as video-discs, videotapes, personal computers and work stations. The recently initiated University (of Maryland)-wide drive for such an environment will accelerate and support this effort. Similar efforts are under way at Harvard University and the electronic linkage of these two educational networks will establish a superb educational environment.

The Harvard University faculty group will participate in the development of course material. We plan to maintain these materials in computer files (in a troff standard format) and to exchange them together with other course materials developed at Maryland through computer mail. This will permit rapid revision and reproduction of lecture notes and other materials.

Each research project at the SRC, will generate a research seminar on related background and research topics. The seminars will be flexible and will attempt to produce lecture notes on the research performed. Successful projects and seminars will then endeavor to produce polished versions of these lecture notes for publication and wide distribution.

Seminars will involve graduate as well as undergraduate students. In fact, it is planned to utilize the software systems developed by the proposed SRC as educational tools for students. This will serve two important purposes:

- (a) timely codification of new knowledge and research results, and
- (b) continuity in training and education for the students participating in the center.

In the current planning, all courses affiliated with the center will be initially of the seminar or independent study type, and closely linked to ongoing research projects. Undergraduate students will participate in every research project.

The SRC will maintain strong and active visiting programs for scientists from both academic and industrial as well as governmental research laboratories. The SRC will also utilize extensively outside scientists as instructors.

The center will organize an advanced level retraining program for practicing engineers from industry, government, and other institutions. The center will establish also cooperative programs with industrial affiliates that will provide summer employment to students at governmental or industrial research laboratories.

Dissemination of research results from the SRC will be implemented via: technical research reports, a quarterly technical magazine, software systems, and lecture

undertaken in a critical high-technology area by the three most concerned communities: University, Industrial R&D and Government R&D.

Industry will be appropriately represented in the administrative, management and research structure of the SRC. Thus there will be industry representatives in the Administrative and Research Councils of the SRC, professional resident Fellows from the sustaining affiliates, and visiting scientists from industry.

I close with a brief mention of the increased need for university-industry collaboration in the areas of the SRC. First, we believe that a key to innovation is a close coupling between the researchers and developers of a technology and its users. This coupling must be in place during the entire innovation process. Second, certain of the technology drivers of the SRC, as VLSI and AI, have been vigorously pursued by industrial research labs, due to their enormous potential commercial value. Third, lack of skilled manpower is particularly acute in the mix of disciplines underlying the SRC. **Strong industrial research participation in the proposed SRC will enhance considerably the probability of success of its mission.**

## 5. Epilogue.

The Systems Research Center links two major Universities with broad intellectual, engineering and scientific basis. It also links two major and complementary high-tech centers. Two exceptionally strong and complementary groups of systems scientists and engineers will collaborate in an ambitious program that is expected to interact and impact all other Engineering Research Centers established to date. In addition to the announced \$16M NSF support for the first 5 years, the SRC has strong commitments from both Universities and the state of Maryland. Thus the University of Maryland has committed \$1M for administrative personnel support for the first five years, 10,000 sq.ft of high quality contiguous space within two years, 12 new half-time faculty appointments, \$1M dedicated equipment and \$1.6M shared equipment. While Harvard University has committed two new faculty positions, 1500 sq.ft. of new space and computer networking. The Maryland Department of Economic and Community Development will help and support the establishment of the SRC and in particular its industrial collaboration plan. The SRC will collaborate on research, education and industrial programs with the University of Maryland ERC (Engineering extension service, equipment grants, incubator facility), with the University of Maryland Institute for Advanced Computer Studies and with the NSA Supercomputing Research Center at the Maryland Science and Technology Park.

Let me finish with a brief recapitulation of our goals. The future design of electronic control and communication systems must be performed via sophisticated computer-aided methods all the way: *from problem definition to blueprint specifications for the electronic circuit or the software implementing the design.* This "vertical integration" should be accomplished in the next decade and is indeed the driving goal in the research program of the SRC. By utilizing expert systems and CAD tools across different application areas substantial cross fertilization occurs as the "experience" and "expertise" passes from area to area in an unending loop; each time improving the power and efficiency of the design methodology. This type of interaction is not possible without the utilization of these two technology drivers in particular. We believe that the interdisciplinary program of the SRC will cause fundamental reexamination of control and communication systems design. We want to

develop the design tools for the electronic "smart" boxes of the future. I want to emphasize again that the proposed research program includes a substantial component of basic fundamental research in mathematical modeling, analytical studies in optimization and dynamics, sophisticated methods from statistics and probability and advanced computational methods and numerical algorithms. This is essential if we are going to demand that the produced designs offer *substantial* performance improvement over conventional ones. Indeed, we are proposing to develop CAD tools that would be able to produce special purpose software and hardware implementations utilizing very advanced albeit expensive technology. Without sophisticated analytical/computational foundation the advisability of such designs is questionable. Put it simply, we are going to need very advanced analytical/computational tools in order to "squeeze" out of the final implementation (be it hardware or software) every possible performance improvement. CAD is clearly the economical way to go; the alternative being a sequence of untested trial and error experimental designs. It basically affords extensive testing and evaluation at a low cost.

The harmonious marriage of powerful analytical/computational methodologies with the three technology drivers, as described in the SRC research program is bound to produce what we would like to call *the ultimate systems engineering technology*. Finally the SRC is dedicated to the education and training of a new generation of control and communication systems design engineers.

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