The Systems Research Center:
Creating the Design Tools
For the Systems of Tomorrow

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INTRODUCTION

The Systems Research Center (SRC) at the University of Maryland and Harvard University is a new and unique forum of fundamental systems engineering research and education. Established by a National Science Foundation grant in 1985, SRC is developing innovative advances in design methods and software systems that address the basic productivity and competitive challenges facing American industry. At the same time, the Center is training a new generation of systems engineers in an environment that is designed to both expand intellectual frontiers and achieve important research objectives.

The impetus behind SRC's activities is a close and mutually supportive collaboration with industry and government. Its programs are designed with a twofold purpose: To make the best possible use of the expertise and interests of an interdisciplinary team of faculty members and available private and governmental research personnel and facilities, and to meet objectives consistent with the competitive needs of business and industry.

The Center's research theme is to promote basic study in the applications and implications of advanced computer technology--Very Large Scale Integration (VLSI), Computer-Aided Engineering (CAE) and Artificial Intelligence (AI)--in the engineering design of high performance, complex automatic control and communication systems. Its research activities are built around five inter-related focus areas: chemical process control, expert systems and parallel architectures, manufacturing systems, communications systems and signal processing, and intelligent servomechanisms.

Traditional industries as well as high tech industries depend on a critical way on automation and information processing systems. As the complexity and demand for these systems has increased dramatically in the past decade, it has become obvious that the modeling and design methodologies of the past are no longer adequate. More emphasis is needed on the modeling and empirical, experimental components of systems science and engineering. In addition, sophisticated system level design tools are necessary in order to integrate the sophisticated analytical and computational techniques of control and communication engineering with computer hardware and software advances. These system level design tools will increase the productivity and efficiency of engineers, and will facilitate teamwork. The Center's programs represent a premier example where advanced computer technology is used as an "amplifier" of human engineering skills and ingenuity.

Educationally, SRC's goals are to support and enhance educational programs and to serve as a source of new courses and material. In doing so, the Center is seeking to change the traditional focus of engineering education, placing a new emphasis on both education and training. In cooperation with Harvard University's Division of Applied Sciences, the Center's broad, interdisciplinary programs cut across the boundaries of a great many engineering and computer science disciplines, and are designed for interactive participation by America's foremost corporations. The ultimate goals are to gain new knowledge; to train the engineers who can apply it to a diverse set of complex, real-world problems; and to speed the transfer of research results into the industrial community.

To enhance the interaction between the academic, industrial and government research communities, an innovative and broad industrial collaboration program has been established. It includes joint research projects, industrial visitors to the University, faculty and student visitors to industry, joint use of laboratories, fellowship programs with industry, intensive short courses and workshops, colloquia, seminars, software library and a unique software research "club".

Let us first briefly recall the goals we set for SRC upon its creation:

- Provide "real" engineering tools for design. We wanted to increase the awareness of both faculty and students about the difficulties inherent in executing and validating a design.
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- Provide engineering with system level design tools to increase design productivity, quality and efficiency. These tools should include the heuristic/empirical component of the design process as well as the analytical/numerical sophistication of the new theories.

THE RESEARCH PROGRAM

As described in further detail in [1-3] the research program of the Systems Research Center has been arranged around five focus areas. During the first year serious efforts were undertaken in all areas to introduce computer-aided engineering, experimental and empirical design issues and to cross the traditional boundaries between the multitude of disciplines represented at SRC. In addition we put particular emphasis in the involvement of undergraduate students in design projects as early as possible in their careers. As emphasized elsewhere [1], in some sense, the subject of fundamental studies carried out at SRC is system science and engineering itself and not the particular application or manifestation in a narrow application area. This in itself justifies the emphasis we have placed on system level design tools for automation and information processing systems.

Our findings throughout the year not only reinforced some of our beliefs and expectations in the value of our approach to systems engineering, but reminded us with the discovery of some unsuspected connections between totally unrelated engineering problems. Several key ideas and concepts have already emerged: a pervasive utility of optimization based design in a great variety of engineering systems; the value of AI in the development of systems that can reason and aid in the design process; the superior efficiency and ability of symbolic algebra as an engineer's aid in complex calculations and modeling; the critical importance of representation and manipulation of engineering databases; the mandatory utilization of AI techniques to handle heuristics in the design process and to enhance and facilitate team work; the mandatory utilization of interactive graphics as the interface mechanism between the systems engineer and the computer; the critical importance of understanding VLSI systems, their architectures and limitations.

It is impossible in the limited space and time available to describe the multitude of exciting projects currently undertaken by SRC faculty and students. Instead I will present an overview of the research programs and I will highlight a few significant projects to illustrate the nature of our work and our findings. The selection of the projects discussed in some detail, reflects, to a certain degree, my finite memory and capacity to represent the details of many excellent projects underway, but also reflects my perception of projects where intellectual integration across disciplines has occurred at the greatest degree.

First the focus areas and the thrusts within each area are:

1. Intelligent servomechanisms. Major thrusts are the design of robust control systems with many sensors and many feedback loops and in particular advanced robotic manipulators and flight control systems for advanced aircraft and spacecraft.

2. Chemical process systems. Major thrusts are modeling and control of industrial processes and integration of reliability and safety in the computer aided design process.

3. Manufacturing systems. Major thrusts are the integration of CAD with MRP, scheduling and resource allocation problems in flexible manufacturing systems and applications of AI in manufacturing.

4. Communication and signal processing systems. Major thrusts are the modeling, design and control of computer and communication networks, image processing and speech processing and recognition.

5. Expert systems and parallel architectures. Major thrusts are VLSI systems design and architectures for control and communication systems, expert systems for control and signal processing, reliability integration in computer aided design.
vides the direct interface with the user, the (often symbolic) problem description and modeling. The multiprocessor "number cruncher" provides the necessary computing power for almost real time execution. Finally the graphical output engine provides real time graphics for simulation, testing, validation and feedback to the designer.

We have also emphasized the integration of symbolic and numerical computation. We are convinced that symbolic languages such as LISP, PHOLOG, MACSYMA offer a superior medium for design, conceptualization and implementation. They are also superior for modeling engineering systems and the advantage offered by these languages is further enhanced by universal communication tools between engineers and scientists from diverse disciplines and backgrounds.

We have introduced and implemented sophisticated simulation tools. These include analytical software and hardware tools. For example we plan to use critical sampling theory for fast Monte Carlo simulation. We will also make use of the computational networks and manufacturing systems. The mathematics justify techniques, which reduce simulation times by several orders of magnitude, are quite sophisticated. We also plan to use LISP based, and object oriented programming for high level simulation of chemical plants, flexible manufacturing systems and communication networks. All labs will be linked to real data and a design automation tool (provisioned by Professor P. S. Krishnaprasad and T. I. Ada) to plan to rely heavily on AI and expert systems to handle the "routine" and heuristic part of the design automation, and on graphics for the machine interface. Examples of the environment are being created which will be given in the description of selected research projects below.

In the area of intelligent servomechanisms we have the following projects: Infaration control and multiinput multioutput systems (with applications to flight control) (Profs. Abd., Krishnaprasad and Tats). Complex analytical methods for design of controllers and signal processing (Profs. Berstein and Baran). End-to-end machine (Profs. Brockett, Maragos and Wohl), nonlinear control and robotic manipulators (Profs. Krishnaprasad, Berstein, Tats and Abad), optimization-based CAD (Profs. Theodorou and Levine).

I would like to provide some details about the project on nonlinear control and robotic manipulators under the direction of Prof. Krishnaprasad. Research in this project ranges from specialized hardware and construction to very sophisticated theories of nonlinear dynamics of multi-body systems. Progress has been achieved in several directions. Professor Krishnaprasad in collaboration with the mechanical engineering faculty at UC Berkeley and a team at Caltech (led by Professor E. Zernicke of Ford University) worked out the Hamiltonian structure of systems of rigid bodies with flexible attachments that obeys finite strain elastic models and are geometrically exact. These results should have significant impact on the control theory of multibody spacecraft and in the modeling of control of robotic manipulators. They have also been able to establish the Poisson structures underlying a wide variety of problems in interconnected rigid body systems and use those in obtaining stability criteria for interesting equilibria. Certain examples have been simulated and displayed graphically on our IWS workstation to reveal for the first time the useful topological structures of the phase portraits. Results of this approach should prove useful in the study of control problems for actuated spacecraft and robotic manipulators operating on space platforms (e.g. the Space Station "Zephyr").

On the software side, DYNAMAN has been further developed to include symbolic Jacobiian calculations. DYNAMAN is a symbolic algebraic system, developed at SRC and written in MACSYMA, which automatically generates the dynamical equations of multi-body systems in symbolic form. Further refinements will be incorporated and tested using the SRC Lisp Machines.

On the experimental side, Mr. Hoven Frank, an M.S. student, has been actively involved in a project to implement a controller for a single flexible arm. The arm was built at the Westinghouse model shop to our specifications. Preliminary controller designs using DELIGHT/Marylin are being translated for implementation and testing on an IBM PC/AT with an onboard data acquisition and control system. In this experiment we are learning how to use accelerometers on real time closed loop control with minimal overshoot of the link tip based on the rate and sampling. We are in the process of developing new experiments on the use of piezoelectric materials for sensing and actuation. These investigations will expand towards the study of accelerometer arrays and the development of several novel data processing and control.

DELIGHT/Marylin is an interactive system for optimization-based design of linear control systems. It was developed (and is still under further development) at the University of Maryland, College Park under the direction of Prof. Tats. It is an offshoot of the DELIGHT general purpose interactive system, originally developed at the University of California, Berkeley. It makes extensive use of DELIGHT's optimization facilities, developed jointly at Berkeley and College Park. It also makes use of linear systems analysis routines developed by various groups.

With the DELIGHT/Marylin tool, a control system designer can take advantage of recent powerful optimization algorithms from the DELIGHT algorithmic library to automatically adjust design parameters of the control system being designed. One of the most striking features of DELIGHT/Marylin is its extreme flexibility. Using a recently proposed (by Tats and Nye) applications-oriented design methodology, the designer may optimize arbitrary performance criteria as well as interactively explore the tradeoffs between multiple competing objectives, while simultaneously keeping several constraint specifications met. Success has been achieved on design problems pertaining to various application areas, including the design of a flight controller for high performance aircraft (in a joint project between SRC faculty; Levine and Tats and Grumman aerospace engineers) and the design of an airborne optical-electric system.

A group of ten students was involved in a design project under the sponsorship of NASA headquarters, NASA Goddard Space Flight Center and the Systems Research Center. The project is under the supervision of Professor P. S. Krishnaprasad and is one of eighteen projects under way in universities across the nation in this advanced pilot program in advanced space systems design. A primary goal of this NASA program is to encourage and support graduate students in space-related programs in University curricula at the undergraduate and graduate levels. The goal of the project at the University of Maryland is to design a Mobile Manipulator System (MIRMS) for the Space Station. Students participating in this project (under the direction of Professor P. S. Krishnaprasad and T. I. Ada) have been especially active.

Based on guidelines obtained from the Space Station Reference Configuration and other material published on operational requirements, the Maryland team is developing the design for the MIRMS. The proposed MIRMS is planned to have a reach of approximately 22 meters and is intended to perform a variety of tasks ranging from assembly of the Space Station itself to transferring payloads from the Space Shuttle to the Space Station. The preliminary design of the system has been completed. A scheme of enclosing certain degrees of freedom to reduce the complexity, kinematic constraints for obstacle avoidance are being written and debugged. The control laws for the joint servos are designed from simulation. A comprehensive simulation environment is being developed. The simulation environment is being developed. The simulation environment is being developed. The simulation environment is being developed. The simulation environment is being developed.
Planning (MHP II) is suggested to host Computer Aided Design (CAD) as a first step towards integration. MHP II is by definition addressing all facets of industrial business, from marketing planning through engineering to manufacturing. Productive CAD systems provide the front end of the product-life cycle and to focus on engineering, design and drafting-related activities.

The integration will be founded on a data base level. Sample features of the proposed integration include:

- Automatic part master record generation and single level product structures on completion of a new CAD drawing
- Engineering Change Control via checks performed at inventory and order levels and through status messages transmitted to MHP II and CAD screens
- Ability to retrieve and emplace upon pictorial and textual information on parts and assemblies at every level of the organization.

The basic problem in homogeneous database integration is the required initial design of the global schema which is the union without redundancy and internal conflicts - of the schemas of the databases to be integrated. We propose the interoperability approach to database integration based on the philosophy that conflicts and redundancy must be accepted, but controlled. We define the global schema as the concatenation of the existing schemas and we add a set of updated dependencies to control the redundancy and conflicts between them. Update dependencies monitor operations changing a database and propagate the changes to other databases by remote operation calls.

It is estimated that a large number of companies already using or planning to use MHP II and CAD will benefit substantially from such an integrated set which ensures a smooth and effective flow of information. Future plans include the establishment of more links between MHP II and Computer Aided Manufacture (CAM), Computer Aided Testing (CAT) and others, all of them aiming at building ultimately one single Computer Integrated Production (CIP) system.

As an extension of this project, and in recognition of the critical significance of engineering databases in engineering design we have initiated a new major project on engineering information systems, under the direction of Professor Hauskelloffs. In response to NRC projects the database group of the Computer Science Department was increased by two new faculty members. All computer aided design engineering activities will be supported by Engineering Information Systems which are based on these techniques and include Conceptual, AI and distributed processing systems. The environment of an EIS is naturally distributed. Therefore, the concurrency and consistency of the databases is present. Furthermore, an EIS has additional distribution requirements that are distributed by the presence of tools interacting with it. The basic research undertaken here is for the development of an Object Oriented Database Management System to support EIS. More specifically (a) An Object Oriented Data Model is being developed for defining engineering objects, (b) the database protocols needed for concurrent access and update of multiple version objects, and (c) access methods and update protocols of distributed EIS architectures will be developed.

A well integrated, interdepartmental effort is being undertaken under the direction of Prof. Pecht for the development of a Reliability and Maintainability Computer Aided Design (RAMCAD) workation. Litton Amecom industries will be an integral part of the project with funding pending from the AF. The construction of the workstation will be performed by Litton. This research effort aims at the integration of reliability and maintainability of electronic circuits in the computer aided design process.

This project involves the development of a second level electronic packaging design process consisting of tools and procedures with reliability design capabilities. The goal of this effort is to make R&D an integral, real-time, fully automated design process directly linked to the design process. For example, reliability analysis is generally conducted late in the design process, often when it is too late to make significant (or the most appropriate) design changes. The goal of this effort is to make R&D an integral, real-time, fully automated design process directly linked to the design process.

The advent of computers in almost every manufacturing corporation, together with the plethora of relevant software packages aiming at increased efficiency and profitability have produced an uncontrollable situation. Attainable benefits evaporate due to the unprecedented multiplication of input/output and internal output. The amount of money and manpower expended to implement and keep all these systems under some sort of coordination.

In recognition of this problem we have started an integration project headed by Professors Harahalkis and Mark, which will eventually lead to optimization of data transfer and of the burden to run such a variety of "data-vehicles" and data processors. A core system, Manufacturing Resources
required for parameter selection and prediction, tradeoffs.

In the area of communication and signal processing systems, we have the projects: performance evaluation and design of networking protocols (Profs. Makowski, Baras, Ephremides and Tripodis), multi-user interference (Profs. Geraniotis, Ephremides and Narayanan), link performance in the presence of eavesdropping (Profs. Geraniotis, Ephremides and Narayanan), multi-antenna systems (Prof. Nowatzki), and the function of these systems in wireless sensor networks and sensor network analysis (Prof. Nowatzki).

In the area of expert systems and parallel processing, we have the projects: integrated CAD (Prof. Baras), expert system for stochastic nonlinear control and filtering (Prof. Blankenship), VLSI systems (Profs. Jalali and Nakajima).

Professor Blankenship in collaboration with J.P. Quadrat at INRIA has been developing an expert system based on symbolic manipulation programs for the analysis of stochastic control and nonlinear filtering problems. The software system brings to the practicing engineer, in a single, usable form, such sophisticated techniques as Belman’s dynamic programming. Professor Nakajima has been investigating several problems in VLSI layout and silicon compilation. The ultimate goal is to develop a hierarchical layout design system for VLSI circuits. Recently the development of efficient algorithms for the topological aspect of the layout problem has been initiated. In particular, we have developed an efficient channel routing algorithm for three layers. Experimental results show that this algorithm produces, in most cases, a channel routing pattern which requires a smaller number of horizontal tracks than previous algorithms.

In the area of via minimization, a polynomial time algorithm has been developed for testing whether all nets of two or three terminals can be connected without using any via. Additional work is focusing on the development of a silicon compiler.

Professor Jalali’s research problems related to the complexity, architecture, design and fabrication of VLSI circuit systems. Many applications to signal processing problems in digital signal processing systems. The automated generation of optimized circuit layouts from a high level description is currently considered as the most challenging problems in VLSI research. The ultimate goal is to relieve the user from all low level details and to allow him to design in a very high level language. The resulting layouts should be optimized for the target architecture on a few less ambitious general methods such as gate arrays, standard cells, full custom. While these methods have been used successfully in the past few years, they all suffer from the fact that intermediate manual intervention is required in different phases of the design process and that they will generate highly nonoptimizing layouts for simple and natural tasks. We have developed several layout problems that have to be resolved before such optimized tools exist. These problems include mapping logical functions into optimal layouts, placement and routing for special-structured environments and mapping structures represented by graphs into optimized layouts. Significant progress has been made in all these areas.

A new system software called SYMBL (SYSTeMerie Boolean Layout) has been written to implement our approach. SYMBL is based on a strategy that first partitions the set of input variables into equivalence classes such that the given functions are symmetric with respect to each equivalence class. It turns out that this step can be implemented quite efficiently. The second main step is to determine a near-optimal “cover”, i.e., a set of appropriate multifunctions whose logical sum produces the function. We use a decomposition tree whose leaves are symmetric functions of the partitioned variables and the partitions are combined as we go up the tree. Finally, the last phase consists of placement and routing routines that optimize the layout structure. The user can introduce his design in a high level language which is then converted into a truth table. The truth table is handled by SYMBL which produces the final layout without any intervention from the user.

We are also exploring the possibility of mapping functions into a general array type called Weinberger arrays. There are two basic problems that have to be tackled in this approach. The first consists of manipulating the given functions into an optimized form. The second has to place and route the Weinberger cells corresponding to the logical form obtained. This second problem can be formulated as a purely graph theoretic problem in which combinatorial tools can be used. We have developed a set of good heuristic algorithms that work well for almost all cases. Our next step will be to implement these algorithms and try them on real world cases.

Several architectures have been proposed in the literature for handling basic signal processing computations. These architectures are highly regular and allow a good degree of concurrency. However, most of the implementations have considered the standard algorithms and mapped them into these architectures. We have introduced fully pipelined structures that are based on a novel strategy consisting of decomposing a computation into a set of subcomputations that can be executed in parallel. A problem of size \( n \) will be roughly decomposed into \( \sqrt{n} \) subproblems each of size roughly \( \sqrt{n} \). Such that all these subproblems can be solved in parallel on a fully pipelined bit-serial systolic architecture.

For the class of problems for which such decompositions exist include filtering, convolution and computing the Discrete Fourier Transform. We have shown that these problems can be efficiently implemented using very fast parallel computers. As a matter of fact, we have designed a 25-64 chip for computing the 256-point DFT that can handle up to 50,000 such computations per second. We now give a brief overview of the architecture.

The structure has two major components, one for computing the 15-point DFT and the second for the 64-point DFT. Each of these components consists of three subcomponents: the summation, the transposition, and the transpose. The summation subcomponent consists of an array of bit serial adders, subtractors, and delay elements. The input is processed in a fully pipelined bit-skewed fashion. The scaling subcomponent consists of an array of bit serial multipliers (25-64 chip) to perform the required multiplications. The input/output requirements are identical to the summation subcomponent. Finally, the transpose subcomponent consists of an array of shift registers that execute a pipelined transposition operation satisfying the same I/O requirements as the previous subcomponents. The clock period that can be used for reliable operation is 10ns at a clock frequency of 25 MHz. At this frequency with our fully pipelined approach, we can compute 3000 DFTs per second with 16 bits of input/output precision.

Professor Baras and Jalali, in a joint project with engineers from Sperry, are studying VLSI architectures for linear and nonlinear signal processing. Professor Baras has been developing the DEPHEL expert system for integrated design of VLSI chips for nonlinear real time signal processing. This software system has several modules signal model development and validation, computation of sufficient statistics, architecture selection and chip design. It will be “intelligent” enough, when fully developed, to perform all of the steps involved in the design of signal processing systems. It brings to the practicing engineer a sophisticated array of techniques and methodologies from stochastic signal processing, applied mathematics, VLSI complexity and architectures, in a directly usable form. Several open problems in real time sequential estimation and detection are being resolved by an innovative combination of sophisticated numerical techniques and VLSI architectures. Two other Baras students LaVigna and Simmons are currently completing the design of a special purpose VLSI chip, which provides a real time solution to the celebrated nonlinear filtering problem. A printed circuit board prototype will be finished soon, and then the fabrication of the large (about 140,000 transistors) 22 MIP chip will be undertaken. After that, these two problems have revealed a need for a new generation of currently used signal models for communication and control: they are not properly structured for real-time computing. Planned research includes the investigation of massively parallel architectures (like connection machines), networked art type architectures, and applications in adaptive array processing and speech processing for reduced bit-rate communication.

I would like to close this section with a few remarks regarding the interaction and integration of the problems and disciplines represented at the SRC. Our research has revealed that systems science and engineering is a powerful unifying, interdisciplinary approach to engineering design problems. Our focus on automatic control and communication systems amplifies this point further. We found that chemical plants and printed circuit boards cannot be handled by the single design approach. Design with scalable design aids for scheduling, planning, operations and even design. Large flexible space structures and highly advanced robotic arms and hands used the same laboratory design environment, and can benefit from sophisticated theories and software systems analyzing multi-body dynamics and distributed sensor fusion. Computer and communication networks and flexible manufacturing factories can benefit from the system level design tools for modeling, simulation, and performance evaluation that we are developing. Polymerization reactor control and sequential target discrimination rely heavily on our ability to design digital, real-time estimation systems. Design of very large VLSI chips and the integration of CAD with CAM need the object-oriented data-base management and control schemes that we are developing. As we continue our efforts at the SRC we expect this vast cross-fertilization to guide us in the creation of the design tools for tomorrow’s systems.

**THE EDUCATIONAL PROGRAM**

The educational program of the SRC is aimed at developing undergraduate and graduate curricula with emphasis on the five four-technical areas of the center. This program complements the research activities of the Center and reflects our commitment to developing an extensive and continuing exchange of educational information with other universities and research institutions, private industry and government R&D laboratories.
Of particular concern in the development of the educational programs of the SRC is the planning and timing of specific courses targeted at bringing the advancements in AI, VLSI and CAE to many undergraduate and graduate students. This is critical in order to create the necessary "technologically literate" student core for the SRC programs. Special-purpose courses on artificial intelligence will be offered in the Fall semester of 1986, in four separate sections (in the electrical, mechanical, chemical engineering and computer sciences departments) at the sophomore and junior levels. In addition, a graduate course/seminar on AI tools will be given from the currently under development Applied AI Laboratory.

The SRC is rapidly developing plans for a specialized program of short courses which will bring state-of-the-art research results to industrial research scientists. This program will be an SRC-wide extension of the very successful short course on chemical process control offered by the Chemical Engineering Department. These courses will be sponsored by SRC and will bring as speakers, authorities on various subjects of interest to SRC, both from faculty affiliated with SRC and elsewhere.

In addition, we have initiated the sponsoring or cosponsoring of colloquia, workshops, satellite video-conferences and symposia, in order to facilitate the educational function of the center.

In what follows, I would like to briefly describe the highlights of what has been achieved to date. Further details can be found in [2-3].

- We initiated a shift to AI language programming from FORTRAN. As explained earlier we believe that AI languages offer many advantages for the description and resolution of engineering design problems.
- We introduced or modified some twenty engineering courses with particular emphasis on VLSI, AI and CAE technologies.
- We sponsored a variety of interdisciplinary systems colloquia, including weekly ones for SRC students.
- We emphasized undergraduate research projects and facilitated the necessary "matching" between faculty and students. Students were strongly encouraged to build real systems.
- We established procedures for co-advise and joint teaching, breaking several cross-departmental boundaries.
- We established an advanced design laboratory for college-wide classroom use. Optimization based design and other advanced software tools will be introduced to students.
- By insisting that the students actually go through the design process we have increased student awareness on implementation and design issues.
- We created a distinguished graduate and undergraduate SRC fellowship program, with explicit industrial connections. We try to provide the student with an industrial "mentor" in addition to his academic advisor.
- We facilitated student visits and residencies at industrial sites. Seven graduate and four undergraduate SRC students will be spending part of this summer on internships with industrial or government R&D labs.

REFERENCES