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The Hybrid Computer: A Paradigm Shift

❶ What is the problem and why is it hard?
Many challenging STEM problems require solving a large number of simultaneous differential equations. Some require years of computer time to simulate seconds of real-time.

❷ How is it done today, and what are the limits of current practice?
Digital computers approximate continuous dynamical systems with discrete switching circuits, each of which must switch repeatedly for each step through time. The supercomputers needed to do this on a large scale are very expensive and consume a lot of power.

❸ What's new in your approach, and why do you think it will be successful? What gives evidence that it will work?
Our solution, a hybrid computer, requires no such approximation. Instead it creates a simulacrum of the system directly in an analog circuit controlled by a digital counterpart, which requires much less switching. Thus a hybrid computer combines the best of both analog and digital computers without the drawbacks of either.
Simulations and PCBs (Printed Circuit Boards) prototypes have demonstrated these mixed-signal circuits.

❹ Who cares? If you're successful, what difference will it make?
The archetypes are people and organizations that require extremely fast computations to solve STEM problems at a fraction of supercomputers' cost and power consumption. If successful, we will have supercomputer performance on a desktop size and have created a new computer paradigm.

❺ What are the risks and the payoffs?
The risk is that the technology is not as fast and accurate as expected because of fabrication methods. The benefit is 1,000 times current supercomputer speeds at a fraction of their cost. The result is a computer that could solve problems at speeds between supercomputers and quantum computers.

❻ How much will it cost? How long will it take?
We anticipate in the long run, the project will cost about $10M and it will take close to 6 years. The initial development may cost $5M and it will take about to 4 years. In order to validate a discrete components solution will require $1M and 18 months.

❼ What are the midterm and final "exams" to check for success?
For the validation: prove speed acceleration and accuracy results. For the initial development: compare IC performance with validation results. For the long run, apply tool to complex problems in representative application areas.

SUMMARY

Solving differential equations is critical to Science, Technology, Engineering, & Mathematics (STEM) areas. Current digital computers, compute only with integers (a FPs are integer approximation of real numbers). Digital computers require small time-steps to simulate complex nonlinear-hard dynamic problems, requiring days or weeks to simulate seconds of physical reality, making the simulation too slow for practical applications. Researchers at The University of Texas at Austin have developed technologies named **H_XC**, that combines analog and digital computers that overcome the most difficult drawbacks of each technology. The result is a computer that could solve problems at speeds between supercomputers and quantum computers.

After WWII, the US developed both *analog* and *digital* computers. Using analog integrators (op-amps with feedback capacitors), the analog computer programmer wired circuits that had dynamic behavior identical ("analog") to the system they wanted to simulate; They excited these circuits with external sources or initial conditions, and observed & recorded voltages that represented physical quantities of the original (physical) equations. Analog computers solved at speeds never approached by their digital counterparts at the time of their introduction. However, by 1980, they were abandoned due to problems like saturation and nonlinearities while at the same time, digital computers steadily increased in speed and reducing power consumption, making them ubiquitous in scientific computation.

Researchers at The University of Texas at Austin have developed[1] a mixed-signal solution that combines both analog and digital computers, taking the best of each and complimenting the weaknesses of the other. The result is capable of solving nonlinear-hard dynamic problems in practical time. Our **HxC** (*Hybrid eXtreme Computer*) includes *mixed-signal integrators* with time-continuous integration, simultaneous digitization of the integral without data sampling, and no drift or saturation; a mixed-signal **Taylor series circuit** to approximate any arbitrary function; calculations with **real numbers** via **mixed-signal floating point** representation with mantissa register, exponent register, and a continuous "*analog bit*" (fraction of the LSB – least-significant bit); and **eXtreme Devices** technologies that are resilient and self-calibrate to compensate for manufacturing errors and varying operating conditions. All circuits are *Field-Programmable* (FP) and ARE NOT sampled-data systems. Simulations and PCBs (Printed Circuit Boards) prototypes have demonstrated these mixed-signal circuits.

Presently, we are in the process of building our second generation of discrete-components PCBs where we can realize a fully-connected 6th-order system. The new boards use fully-differentiable operational amplifiers for more accurate integration and less noise. We have filed a application patent of the H_XC to chaotic hybrid encryption. We also have preliminary designs for circuits and system-level integration into various levels of computers. We seek to finalize the construction and testing of the PCB demonstration; do detailed designs; fabricate IC prototypes in CMOS, and test them. The plan is a multi-year project with deliverables of ICs with increasing level of complexity (size of ODEs that can be solved). Our first systems would operate as a (hybrid) co-processor in a PC host.

[1] Patents `# US 0117083`: Apparatus for solving differential equations, `# US 7454450`: Mixed-signal system for performing Taylor series function approximation, and `# US 7796075`: Method and apparatus for internally calibrating mixed-signal devices.

We anticipate developing computational systems capable of solving large sets of differential equations *faster* and *cheaper* than current systems. We have targeted as our first (validation) problem to attack, chaotic encryption. It is a simple (dynamically speaking) problem, but very important for our National Security. We envision immediate dual-use applications for signal processing, controllers, scientific computing such as weather simulation & molecular dynamics protein unfolding, Virtual Reality, animation, War games, missile targeting, non-linear stochastic filtering, system diagnostics and prognosis, and Cybersecurity. The road map of the products to target these areas follows the number of integrators in the IC and/or number of ICs on a board. Specific applications systems can be developed for specific customer needs.

INTELLECTUAL MERIT

Our innovative mixed-signal computation circuits overcome problems of both digital and analog computing, is fast, stable, field-programmable, and performs computations with real numbers. Differential equations –ubiquitous in science, engineering, technology, commerce and other areas– could be solved in real-time or faster: what now takes hours in supercomputers could take seconds in our system. The mixed-signal integrator performs time-continuous integrations, maintains a real number representation, digitizes results with a natural threshold, avoids amplifier saturation and drift, and outputs at those times when the result is exactly a floating point integer. Computations will be unconditionally stable, and without truncation and rounding errors. Signal processing could be done without data converters, generally the weakest link to signal throughput. The mixed-signal Taylor series circuitry can approximate any arbitrary piecewise continuous function in analog. Together, the integrator and approximator can permit ultra-fast solution of strongly nonlinear systems. The mixed-signal floating point extends computations to real numbers. Embedded firmware allows the circuit to self-calibrate. The operating software API makes the processor transparent.

BROADER IMPACTS

The proposed research could lead to a computational revolution. These innovative circuits and architectures could render programmable, mixed-signal, computational circuits to revolutionize a segment of the computer industry; and spawn new computer and signal processing & control industries. Recent calls for white papers from DARPA, the White House, and many other federal agencies, stressed industry need to develop exactly these types of circuits, components, systems, and calibration methods described. Important problems (e.g., climate modeling and simulation, nuclear and astrophysics, etc.) could be solved at near real-time speeds. New paradigms may develop, given the existence of such processors. Since these circuits will employ CMOS, this could create new opportunities for the semiconductor industry. There are many applications in support of Homeland Security, medicine, and manufacturing. We will teach these new techniques in graduate and undergraduate courses in mechanical, electrical, and computer engineering, including new courses. We will disseminate this material through conferences, workshops, and journals. Our prototype chips will be tested in academia and industry with student involvement. Our industry partners will support and advise our research; the interactions will also benefit our students. The PIs will submit an REU proposal to involve undergraduates in an exciting new field.

CURRENT STATUS AND ROADMAP

CHECK Chaotic Hybrid Encryption Communication Kit

The last decades, information has emerged as the most important asset to protect for corporations and persons. We often see in the news that cyber-attacks no longer exclusively target the military or enterprise. The world is more virtual, and thus more *exposed*. Everyone – from world governments to business to private citizens – demands secure communications. There are several patented methods of encryption available in the market today, most of which rely on digital schemes to encrypt and decrypt messages. Methods of attack and defense in cyberspace require constant change, similar to biological arms races between, for instance disease and immunity. This project proposes a novel method and apparatus that can combine analog computing, digital computing and chaos in order to generate potentially infinite keys for encryption and decryption. UT researchers have successfully developed intellectual property and a *software-only proof-of-concept* of this technology. The long term vision of the invention includes building a hardware encryption device to secure peer-to-peer communication. Since the solution will ultimately be implemented in hardware, it will execute faster than current techniques of similar complexity, while reducing or eliminating overhead, and allowing one time pad encryption. In summary, this invention is a novel way to perform encryption that has tremendous potential to protect both critical national infrastructure and individual privacy using an infinite key that provides more secure encryption while reducing encryption overhead.

Technology Road Map	Archetype Applications	Revenue Stream
Intellectual Property	Encryption	IP Licensing
Board 0: Discrete components	Encryption	Manuf., DS, OEM
IC I (small < 8 `HxI` cells) Box I: IC I Board	 Encryption, Filter, Control	IP, OEM OEM, SI, VAR
IC II (medium < 64 `HxI` cells) Box II: IC II Board	Simulation, Optimization, Diagnostics, Prognosis, Prediction	IP, OEM OEM, SI, VAR
IC III (large < 1024 `HxI` cells) Box III: IC III Board	Healthcare, Video/War games, Power plants, Power grid, Transportation	IP, OEM OEM, SI, VAR
IC IV (very large > 1024 `HxI` cells) Box IV: IC IV Board	Research: molecular dynamics, physics, Weather, Astrophysics, Military	IP, OEM OEM, SI, VAR

Table 1: Archetype Applications based on complexity (number of `HxI` cells needed). Notation: IP-Intellectual Property;

Item	IAP	HXC
Speed: actual time in which real event occurs compared to computer time needed to simulate	Would solve 6 times slower than time of real event	Would solve 1,000 times faster than time of real event
Precision limited by	Truncation rounding errors	Noise 0.1% Rs & Cs
Numbers for computations	Set of integers	Set of real numbers
Cost (1 unit)	$10,000,000 to $20,000,000	$1,000 to $10,000
Size of machine	197 tons	PC insert
Power requirements	4.7 MW	100 to 500 W
Time to develop next generation machine	Several years	1≈2 years

Table 2: Comparison IBM ASCI Purple (IAP) with Hybrid eXtreme Computer (HXC)

Application	Description
Forecasts	Weather, ocean activity, hurricanes, earthquakes, space phenomena
Reality Simulators	Flight & tank simulators, war & video games
Diagnostics	Predict failure and condition of critical equipment
Design	Simulate performance of designs of machinery
Medical	Imaging & simulations of effects of treatment on patient
Controllers	Missile guidance, aircraft, targeting
Research & Development	Simulated surgery, effects of pacemakers, effects of implants on patients
Communication	RF & UHF spectral optimization, telephone & network connections
Signals	Signal processing, nonlinear sonar & radar interpretation, applications, encryption, nonlinear filters
Assess physics of threats	Security, terrorism, counter measures

Table 3: Sample applications areas comparing current solution with $\mathsf{H}_{\mathsf{X}}\mathsf{C}$.