

# TC-CPS Newsletter

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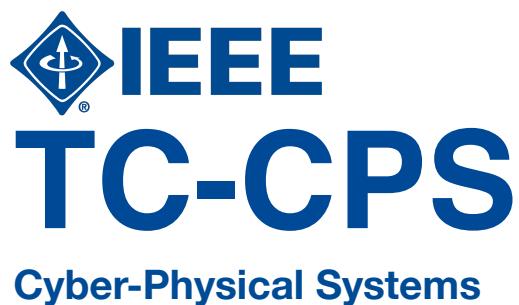
## Editorial

## Technical Articles

- Yanzhi Wang, Caiwen Ding: “*Luminescent Solar Concentrator-Based Reconfigurable Photovoltaic System for EV/HEV*”.
- Jingtong Hu: “*Accumulative Computing: Sensing With Unlimited Free Energy*”.
- Qi Zhu: “*Timing-Centric Software Synthesis for Cyber-Physical Systems*”.

## Summary of Activities

## Call for Contributions



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## Editorial

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Cyber-Physical Systems (CPS) are characterized by the strong interactions among cyber components and dynamic physical components. CPS system examples include automotive and transportation systems, smart home, building and community, smart battery and energy systems, surveillance systems, cyber-physical biochip, and wearable devices. Due to the deeply complex intertwining among different components, CPS designs pose fundamental challenges in multiple aspects such as performance, energy, security, reliability, fault tolerance and flexibility. Innovative design techniques, algorithms and tools addressing the unique CPS challenges, such as the fast increase of system scale and complexity, the close interactions with dynamic physical environment and human activities, the significant uncertainties in sensor readings, the employment of distributed architectural platforms, and the tight real-time constraints, are highly desirable.

The IEEE TC-CPS Newsletter, published twice a year, aims to report the recent advances on technologies, educations and opportunities and, consequently, grow the research and education activities in this area. This letter is affiliated with the Technical Committee on Cybernetics for Cyber Physical Systems under the IEEE Systems, Man, and Cybernetics Society. TC-CPS aims at promoting interdisciplinary research and education in the field of CPS.

This issue of the newsletter showcases the state-of-the-art developments covering several emerging areas: machine monitoring, automobile, social cloud, energy, etc. Professional articles are solicited from technical experts to provide an in-depth review of these areas. These articles can be found in the section of “Technical Articles”. In the section of “Technical Activities”, recent activities organized by the TC-CPS, including workshops, special issues, etc., are summarized. Finally, the Call for Contributions can be found at the end of this issue to solicit high-quality submissions.

I would like to express my great appreciation to all Associate Editors (Yier Jin, Rajiv Ranjan, Yiyu Shi, Bei Yu and Qi Zhu) for their dedicated effort and strong support in organizing this letter. I wish to thank all authors who have contributed their professional articles to this issue. Finally, please allow me to welcome all of you to the founding issue of the TC-CPS Newsletter. I hope that you will have an enjoyable moment when reading the letter!



Xin Li  
TC-CPS Editor  
Carnegie Mellon University

## Luminescent Solar Concentrator-Based Reconfigurable Photovoltaic System for EV/HEV

Yanzhi Wang, Caiwen Ding, Syracuse University

Photovoltaic (PV) cells provide us a clean and quiet form of electrical energy generation, and can be an ideal power source for EVs and HEVs. In general, the onboard PV system can provide up to 20%-30% of propelling power for a normal EV/HEV during cruising and city driving (which takes <10kW), and perhaps more importantly, it could charge the EV/HEV battery pack during parking time to reduce the recharging requirement and mitigate the power demand from the grid.

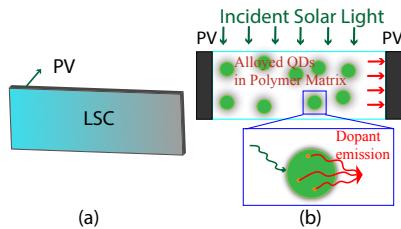


Figure 1: (a) Top view and (b) vertical cross section schematic of LSC-enhanced PV cell.

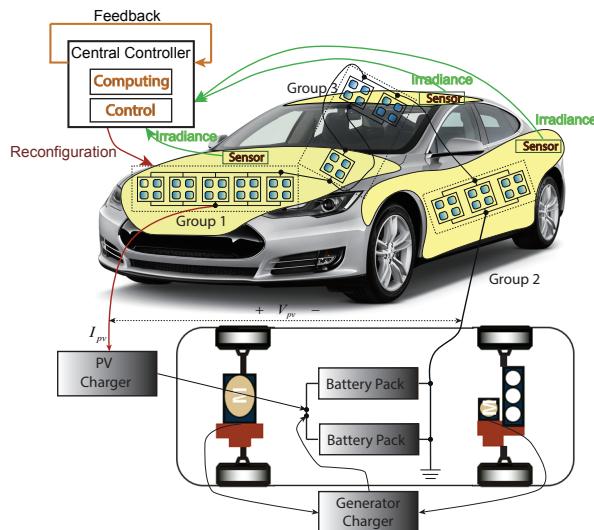


Figure 2: System diagram of an LSC-enhanced reconfigurable onboard PV system.

To increase PV power generation for EV/HEV, we should enlarge onboard PV cell modules by using all possible vehicle surface areas including the rooftop, hood, trunk, and door panels. These PV cell modules are connected to the EV/HEV battery pack through one power converter. This structure is called string charger architecture, and is a practical choice for onboard PV system accounting for cost considerations and high voltage of EV/HEV battery pack [1, 2].

However, onboard PV systems for EV/HEV exhibit certain limitations. Besides the relatively low energy conversion efficiency, common PV modules normally use flat-plate PV cells and may not fit the streamlined surface of trendy vehicles. PV cells (with typically a dark blue color) may not satisfy aesthetic standards of modern vehicles. Furthermore, the solar irradiance levels on different PV cells may be different from each other due to different solar incidence angles. For example, the solar irradiance level on the rooftop PV cells is higher compared with the door panel at noon due to smaller solar incidence angle. Under the non-uniform distribution of solar irradiance, it is difficult to make all PV cells operate at their maximum power points (MPPs) simultaneously [3], because the shaded PV cells will affect the operating point of lighted cells connected in series. This effect can lead to a dramatic output power degradation of PV system.

In order to address the limitation on appearance and compatibility with EV/HEV, we adopt semiconductor nano-materials-based *luminescent solar concentrator* (LSC)-enhanced PV cells for onboard PV systems. An LSC-enhanced PV cell (shown in Fig. 1) comprises an LSC polymer film [4] with vertically surrounding PV strips. The LSC polymer is magnetically doped by quantum dots (QDs), and can concentrate both direct sunlight and diffuse light onto attached PV strips to allow them to operate at higher efficiency. This new technology could mitigate the above limitations because (i) LSC-enhanced PV cells are flexible and can fit the surface streamlined designs of modern vehicles. (ii) LSC polymers are thin and transparent, and thus they do not affect aesthetic requirements of vehicle designs. (iii) LSC can potentially enhance the overall output power and reduce capital cost.

In order to address the problem induced by non-uniform solar irradiances, we have proposed a dynamic PV array reconfiguration technique which can extract the maximum output power of all PV cells simultaneously, thereby achieving a transformative improvement in the output power of onboard PV system. The reconfiguration mechanism exhibits polynomial-time complexity, and changes the internal connections of PV cells in the array without changing their physical locations. The reconfiguration mechanism should be triggered frequently to track the changes on solar irradiances during vehicle driving. The proposed LSC-based reconfigurable PV system for EV/HEV could simultaneously achieve high and reliable output power (2.5X enhancement compared with onboard PV system without reconfiguration), low capital cost and timing/energy overheads (less than 1% energy overhead), and full compatibility with EV/HEV.

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# Accumulative Computing: Sensing With Unlimited Free Energy

Jingtong Hu, Oklahoma State University

## 1 Introduction and Motivation

Sensors are an integral part of Cyber-Physical Systems (CPS). While battery and cable power are still the major energy source for many sensors, there is a class of devices in which it is challenging to employ battery or cable power since it is inconvenient, costly or even dangerous to replace or service them. Examples of such applications include implantable sensor, wearable health monitor, water pipeline or building HVAC status monitor, soil or water pollution monitor, etc. Energy harvesting techniques, which generate electric energy from their ambient environment using direct energy conversion techniques, are very attractive to these applications because they can eliminate the need for batteries or wires and enable long-term adoption of these systems.

Figure 3 shows the architecture for a typical energy harvesting based sensing system. Ambient energy such as light, kinetic, RF, thermal, or even biochemical energy, are harvested and stored in a small capacitor, which can be used to power the processor and peripheral devices with on-chip converters [6]. However, there is an intrinsic drawback with harvested energy sources. They are **intermittent**. Since almost all traditional computer systems are designed based on the assumption of a stable power supply, none of them can make significant progress under frequently interrupted power. In order to take advantage of unlimited free energy supply, a new computing paradigm which can make progress even under intermittent power is needed.

In order to make progress, we have to **accumulate** the computing across intermittent power cycles. The key idea is to save the processor's volatile registers to a non-volatile memory (NVM) when there is a power failure and restore the processor state when the power comes back on. There have been several works to achieve this with either software assisted approach [1, 2, 5] or hardware approach [4]. While existing research shows exciting advancement, there are still challenges that need to be answered to make self-powered accumulative computing a mature platform.

- First, while most existing works are successful in achieving the continuous computing functionality, few of them considered optimizing the checkpointing efficiency. On one hand, the energy harvested in such systems is usually limited. On the other hand, not only registers need to be checkpointed, but on-chip and off-chip memories also need to be checkpointed if they are volatile. Therefore, fast and efficient checkpointing is needed for the whole volatile memory hierarchy to ensure successful checkpointing. Meanwhile, more energy can be used for system forward progress.
- Second, while the computing status can be saved, I/O interfaces associated with peripheral sensors and communication devices are hard to checkpoint due to their time-sensitivity and atomicity. In many cases, interrupted operations need to be restarted from the beginning, which will severely affect the forward progress. Meanwhile, checkpointing for processor and I/O operations in interrupt service routines (ISRs) has to be handled properly to ensure correct execution.
- Third, when multiple tasks are running concurrently in the system, the OS scheduler and task management will also affect the forward progress upon power failure.
- Additionally, our study [7] showed that without considering the volatility across the memory hierarchy, data inconsistency might happen and lead to fatal errors.

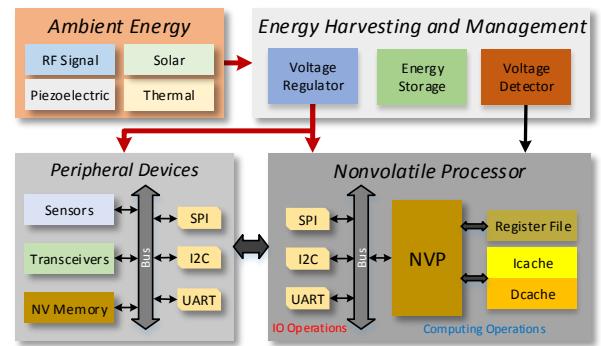


Figure 3: Energy Harvesting System

## 2 Checkpoint Efficiency Optimization

Several works have been done to optimize the checkpoint efficiency. First, we have developed a stack trimming technique to minimize stack data that need to be checkpointed [3]. The idea is to reduce the stack size via address space sharing. Within a program, each function instance is associated with a *frame* (also called *active record*) to store the context information for this function. Local data, including local variables and compilation temporary variables, are stored in this frame. A conventional stack based allocator works as follows: a specific memory address is assigned to the *main* function's frame. When a function is called, the callee function's frame is allocated on top of the caller function's frame. When a function returns, the callee function's frame is deallocated from the top of caller function's frame. Traditionally, the stack space is separately allocated for the caller and callee functions, which is conservative and results in a large stack size.

```

1 struct T
2 {
3 int i;
4 int j;
5 char arr[10];
6 };

7 int cpyT( T *t1, *t2 )
8 {
9 int a;
10 int b;
11 modify(&a);
12 t1.i = t2.i + a;
13 modify(&b);
14 t1.j = t2.j + b;
15 strcpy(t1.arr, t2.arr);
16 return 0;
17 }
```

Figure 4: An example program

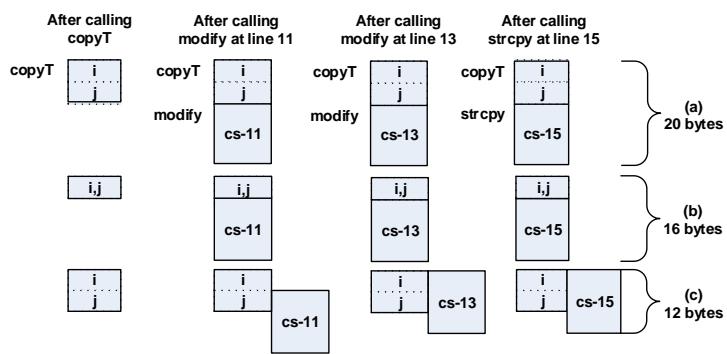


Figure 5: Comparison of stack size under different stack allocation schemes. Assume that the frame size of *copyT*, *modify* and *strcpy* is 8, 4 and 12 bytes, respectively.

A simple motivation example is presented to illustrate how stack allocation schemes affect the stack size. The example code is shown in Figure 4. Note that each call site (cs) is also viewed as a local object, and its size is equal to the callee function's frame size. Figure 5 illustrates the stack size under different schemes. Figure 5(a) shows that the conventional allocation scheme, without any overlay in stack, holds the largest stack size of 20 bytes. Since *i* and *j* have disjoint live ranges, they can be coalesced. The result is shown in Figure 5(b). Here, the frame size of *copyT* is reduced by 4 bytes, and the maximum stack size is reduced to 16 bytes. In order to further reduce stack size, we aggressively overlay call sites with disjoint live ranges [3]. Figure 5(c) shows the result, in which the maximum stack size can be reduced to 12 bytes. From this example, we can see that objects with disjoint live ranges can share the same address without violating the data integrity and thus reduce the stack size. The experimental results show that the proposed technique can reduce the stack size by 28.6% on average for a wide range of benchmarks.

In addition to the stack trimming, there are also optimization opportunities in the temporal domain. Figure 6(a) shows an example code, where the *main* function invokes function *g*; *g* invokes *h*; and *h* invokes *i*. The stack usage is shown in Fig. 6(b). From the figure, we can see that the stack size fluctuates as the functions are invoked and return. Assume that the system detects power failure at time *t*<sub>1</sub>. The conventional backup strategy is *instant backup*, where all the processor states are backed up immediately at *t*<sub>1</sub>. In this case, this system needs to checkpoint four stack frames. However, instead of consuming a large portion of remaining energy to checkpoint, we can spend some energy to continue the program execution until *t*<sub>2</sub>. At *t*<sub>2</sub>, there is only one stack frame to checkpoint since all the callees already returned. Based on this observation, we developed a three-step approach [8], in which the best backup positions are derived in polynomial time. The evaluation results show considerable checkpoint content

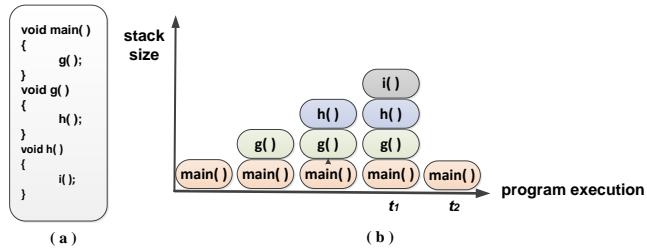


Figure 6: Stack Fluctuation.

reduction compared with instant checkpoint.

### 3 Conclusion

Realizing accumulative computing on unstable harvested energy will enable a new class of self-powered sensing/monitoring systems that can last for years and require the least maintenance effort in various non-timing critical applications. It will simplify system installation and maintenance in many areas such as health care, building monitoring and maintenance, traffic, agriculture and environment monitoring, and even crisis management. Meanwhile, it will help bridge the gap between ever-increasing electronic power needs and battery scalability and have the potential to provide a large infrastructure for opportunistic computing with great social impact. However, there are still several challenges to be answered to achieve the goal. This article presents two checkpoint efficiency optimization techniques which aim to overcome these challenges.

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## Timing-Centric Software Synthesis for Cyber-Physical Systems

Qi Zhu, University of California, Riverside

Software design and implementation have become increasingly challenging for cyber-physical systems, with growing software complexity in terms of both scale and features as well as adoption of more distributed and networked hardware platforms. As an example, in automotive domain, embedded software increased from 2% to 13% of a vehicle’s total value from year 2000 to 2010, and the number of lines of code increased from 1 million to more than 10 million [15, 1]. On the hardware side, the number of ECUs (electronic control units) in a standard car has gone from 20 to over 50 in the past decade [1]. The traditional federated architecture, where each function is deployed to one ECU and provided as a black-box by Tier-1 supplier, is shifting to the integrated architecture, in which one function can be distributed over multiple ECUs and multiple functions can be supported by one ECU [6]. This leads to significantly more sharing and contention among software functions over multicore and distributed platforms.

At the core of CPS software challenges is *timing*, which has critical impacts on both functional correctness and various design metrics such as control performance, fault tolerance and security [8, 16, 14]. In particular, the synthesis of CPS software remains hindered by timing-related issues: 1) *diversity of timing requirements* from different design metrics, some with conflicting constraints; 2) *complexity of timing analysis* under complex scale, hierarchy and concurrency of computation and communication; and 3) *uncertainty of timing behavior* resulting from dynamic environment, data input and platform conditions.

Current synthesis solutions and practices do not adequately address these timing challenges. Timing constraints are often set in an ad-hoc fashion without quantitative analysis of their impacts on multiple related metrics, and software synthesis is often conducted without continuous and holistic consideration of timing. In the widely-adopted model-based design paradigm, system functionality is first captured in a functional model for early simulation and validation, and then commonly synthesized to software task implementations on hardware platforms. While timing is usually considered during the mapping of software tasks onto hardware platforms, it is *rarely addressed during the generation of software tasks from initial functional models*, and thereby leaving a significant gap in the synthesis process. As we have observed from our prior work [18, 3, 5, 19, 7, 4], such issues during software synthesis often lead to infeasible solutions, long design cycles, and ultimately inferior and error-prone CPS software implementations.

**Our Software Synthesis Work:** In past, we have worked on task mapping problems for distributed embedded systems and cyber-physical systems, including task allocation and scheduling for schedulability, latency, memory usages, and extensibility [21, 20, 22, 17], exploring task activation periods for schedulability [2], and task mapping with security considerations [9, 10, 11]. As traditional mapping problems, these approaches only focus on the mapping stage.

Recently, we started investigating timing-driven task generation, and have proposed algorithms for multi-task generation of finite state machines (FSMs) for timing robustness [19] and multi-task generation of dataflows with respect to schedulability, reusability and modularity [5, 3]. These works only address non-hierarchical functional models with single model of computation, however, the results have demonstrated *significant improvements from considering timing during task generation of functional models*. For instance, in [5], a 20%-40% reduction in latency is achieved by addressing timing during multi-task generation of dataflows. In [3], timing schedulability is addressed together with modularity (defined as the number of generated runnable functions [12, 13]) and reusability during synthesis of dataflows. It demonstrates that for a fuel injection system example, only considering modularity and

reusability during synthesis (with algorithms from literature [12, 13]) results in infeasible solutions. While using our approach that considers timing during dataflow synthesis, a trade-off of modularity for schedulability results in multiple task generation solutions that can be feasibly allocated and scheduled onto the hardware platform.

Software synthesis for cyber-physical systems is a critical and challenging area. The works above have only addressed the tip of the iceberg. There is an urgent need to have more design automation methods and tools to tackle the challenges in CPS software design, implementation and validation.

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## **Summary of Activities (2016.01 – 2016.07)**

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### **1 Workshops**

- [DAC-2016 Workshop on Design Automation for Cyber-Physical Systems \(CPSDA-2016\)](#)
- [INFOCOM-2016 Workshop on Cross-Layer Cyber-Physical Systems \(CPSS-2016\)](#)

### **2 Special Issues in Academic Journals**

- [IEEE Transactions on Sustainable Computing \(TSUSC\) Special Issue on Sustainable Cyber-Physical Systems](#)
- [IEEE Transactions on Big Data Special Issue on Big Data for Cyber-Physical Systems](#)
- [ACM Transactions on Cyber-Physical Systems \(TCPS\) Special Issue on Smart Homes, Buildings, and Infrastructure](#)
- [Integration, The VLSI Journal Special Session on Hardware Assisted Techniques for IoT and Big Data Applications](#)
- [IEEE Transactions on CAD Special Issue on CAD for Cyber-Physical System](#)
- [IEEE Transactions on Computers Special Issue on Smart City Computing](#)
- [IEEE Transactions on Multi-Scale Computing Systems Special Issue on Hardware Software Crosslayer Technologies for Trustworthy and Secure Computing](#)

### **3 Special Sessions in Academic Conferences**

- [ISVLSI-2016 Special Session on Cyber-Physical Systems: Architecture and Security in Smart Buildings and Autonomous Driving](#)
- [ISVLSI-2016 Special Session on Emerging Devices for Hardware Security: Fiction or Future](#)

### **4 Book Publications**

- Springer Book “[Leveraging Big Data Techniques for Cyber-Physical Systems](#)”

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## Call for Contributions

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### Newsletter of Technical Committee on Cyber-Physical Systems (IEEE SMC Society)

The newsletter of Technical Committee on Cyber-Physical Systems (TC-CPS) aims to provide timely updates on technologies, educations and opportunities in the field of cyber-physical systems (CPS). The letter will be published twice a year: one issue in February and the other issue in October. We are soliciting contributions to the newsletter. Topics of interest include (but are not limited to):

- Embedded system design for CPS
- Real-time system design and scheduling for CPS
- Distributed computing and control for CPS
- Resilient and robust system design for CPS
- Security issues for CPS
- Formal methods for modeling and verification of CPS
- Emerging applications such as automotive system, smart energy system, internet of things, biomedical device, etc.

Please directly contact the editors and/or associate editors by email to submit your contributions.

#### **Submission Deadline:**

All contributions must be submitted by **Jan. 1st, 2017** in order to be included in the February issue of the newsletter.

#### **Editors:**

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