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Cyber-Physical Systems Can Make Emergency Response Smart

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Abstract

A *Smart Emergency Response System (SERS)* prototype was built in the context of the *SmartAmerica Challenge 2013-2014*, a United States government initiative. SERS was created by a team of nine organizations led by MathWorks. SERS team member organizations include: BluHaptics, Massachusetts Institute of Technology, MathWorks, National Instruments, North Carolina State University, The Boeing Company, University of North Texas, University of Washington, and Worcester Polytechnic Institute. The project was featured at the White House in June 2014 and described by Todd Park (*U.S. Chief Technology Officer*) as an exemplary achievement. The SmartAmerica initiative challenged participants to build cyber-physical systems as a glimpse of the future to save lives, create jobs, foster businesses, and improve the economy. The SERS prototype primarily concentrated on saving lives.

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1. Context

The paradigms of cyber-physical systems (CPS) [1][2], industrial internet [3][4][5], Industry 4.0, and the notion of Internet of Things (IoT) [1][2] create an opportunity to look at hardware and software as modalities collaborating through the power of computation. This paper takes on this challenging vision and explores a concrete example applicable in emergency response. In particular, CPS and IoT advances are briefly discussed in this section. A prototypical CPS implementation in the form of a Smart Emergency Response System (SERS) [6][7][8] is

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introduced in the following two sections. First, the architecture of the system and the underlying software is discussed. Then, related work is described. A summary section completes the paper.

To set the context, a definition of CPS follows. CPS are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components [9]. The National Science Foundation (NSF) claims that advances in CPS will enable capability, adaptability, scalability, resiliency, safety, security, and usability that will far exceed the embedded systems of today [1][9]. The notion of CPS combined with IoT as a foundational underlying technology will transform the manner in which people make use of engineered cyber and physical systems.

CPS as a field of study is just beginning to receive traction and many challenges remain as discussed in related work [1][9][10]. The application of CPS as a means to attain the goals for smart emergency response is manifold and depends on the specific scenario type. On the one hand, the human-in-the-loop aspect must be considered when designing smart systems of tomorrow. Thus, any hardware equipment and human-machine interaction remains a challenge. On the other hand, environmental emergency occurs in various forms, as an earthquake, tornado, fire, hurricane, and so forth. Each of such scenarios requires a different type and scale of treatment.

The CPS paradigm offers an open design to embrace the scenarios under investigation as a coherent and consistent entirety. This CPS-based mindset forces a multidisciplinary collaboration and allows for dynamic changes in system configurations in real time. Therefore, CPS is frequently called a system of systems [9][10]. Architectures for open systems are still under development [9][10]. CPS must meet the demanding performance constraints of hard and soft real-time embedded operations of the collaborating software and hardware. These constraints become even more challenging when shared and when new functionality emerges while setting up new configurations. Hence, developing platform and communication technology stacks that are flexible and extendable becomes a necessity. These technology stacks should rigorously support continuous evolution to enable a broad range of features with safety-critical implications [8][11][12].

Challenges also remain in specific design methods for CPS. The business value of these design methods must still be evaluated and validated. The open nature of CPS implies that no one system integrator is responsible for the ultimate behavior of the system. This is a departure from standard design approaches where often a single original equipment manufacturer (OEM) assumes such responsibility (and liability). By collaborating in an open structure, the combined behavior of each of the constituent systems produces an emerging behavior that is not encoded *a priori* as a global system behavior [9][10]. As a result, CPS are almost always active and reconfigurable. Their robustness is a challenge to be addressed, in particular in light of necessary certification. Operating in an uncertain but manageable environment, the ability to remedy a failure mode as well as environmental disturbances and other side effects are only a subset of obstacles to be identified when designing a reliable and resilient CPS.

2. Introduction to the Smart Emergency Response

A *Smart Emergency Response System (SERS)* prototype was built in the context of the *SmartAmerica Challenge 2013-2014*, a United States government initiative [13]. SERS was created by a team of nine organizations led by MathWorks. The project was featured at the White House in June 2014 and described by Todd Park (*U.S. Chief Technology Officer*) as an exemplary achievement [14].

The system provides the survivors and emergency personnel with information to locate and assist each other during a disaster. SERS allows users to submit help requests to a MATLAB [15] based mission center connecting first responders, apps, search-and-rescue dogs, a 6' tall humanoid, a teleoperated robot arm, autonomous aircraft (both fixed wing and quadrotors), and ground vehicles. The command and control mission center generates an action plan for the overall mission that optimizes the available resources to serve every incoming request in minimum time (see Fig. 1, left). A WiFi network is created on the fly by autonomous rotorcraft (drones) equipped with antennas. In addition, the autonomous rotorcraft, fixed-wing aircraft, and ground vehicles are simulated in real time with Simulink [15] and visualized in a 3D environment (e.g., Google Earth [16]) (see Fig. 1, right).

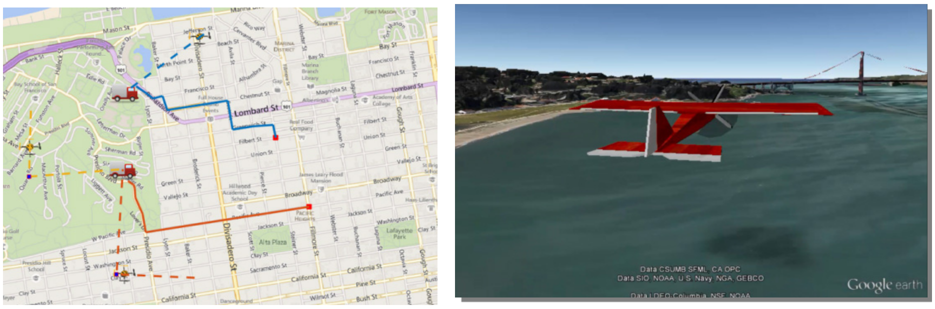

Fig. 1 Illustrative presentation of (a) the optimization process on a geographic map (left) and (b) the mission simulation (right).†

3. Architecture of the Smart Emergency Response System

The components of the SERS architecture are presented in Fig. 2. The mission command and control center in the middle of the figure is the computational 'brain' of the system. Every time a help request from the Android-based smartphone application [17][18] comes in, a fleet of robots, dogs, and autonomous vehicles are sent to the field to serve the need.

The fleet consists of the following hardware elements (illustrated on the left-hand side of Fig. 2):

- WiFi drones equipped with antennas to set up a WiFi network [19][20].
- Biobots (i.e., dogs equipped with sensors such as cameras or gas detectors) to sense and monitor the situation [21].
- A teleoperated mobile robotic arm with haptic feedback to perform difficult field activities, such as gas leak removal [22][23].
- An ATLAS humanoid to perform operations that involve heavy lifting and to reach areas too dangerous for a human [24].
- A fleet of unmanned aerial vehicles (UAVs) consisting of rotorcraft and fixed-wing aircraft as well as ground vehicles, all of which are also simulated and shown in a virtual 3D environment [6][25][26].

In addition, SERS consists of the human-machine interfaces depicted on the right-hand side of Fig. 2:

- A Simulink to Google Earth interface for visualization of the simulated field operations.
- A component for analysis of the video stream provided by cameras placed on the autonomous quadrotors (e.g., AR.Drone [27]) to perform real-time face detection and recognition of survivors.
- Wearable electronics for observing and manipulating certain elements of SERS.

The necessary communication infrastructure is provided by an opportunistic network based on an app [17] that relays messages between mobile devices, as well as an ad hoc WiFi network set up by autonomous rotorcraft equipped with directional antennas to increase reach.

The communication between the components is realized using User Datagram Protocol (UDP), Transmission Control Protocol (TCP), and serial connections, depending on the integrated component. The complexity of the system integration is embraced by the software logic that is implemented in MATLAB. The simulation of the dynamic systems (e.g., fixed wing aircraft) included in SERS is implemented in Simulink and related products.

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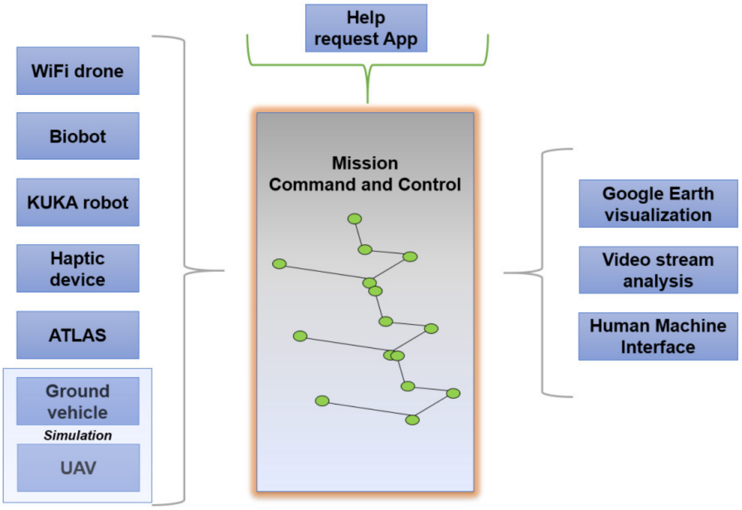

Fig. 2 Illustrative presentation of (a) the optimization process on a geographic map (left) and (b) the mission simulation (right)..

The SERS software is divided into six logical components as shown in Fig. 3.[‡] In particular, it consists of components such as simulation and visualization, user interface, optimization of the resources, hardware integration, requests, and helpers. The SERS software is built based on an object-oriented approach [28]. That is, each logical component is represented by one of a number of classes and their methods.

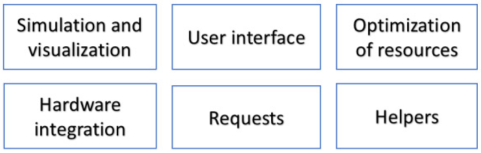

Fig. 3 SERS software architecture.

The SERS concept illustrates how to arrange for an effective and structured disaster response. The CPS paradigm unlocks the potential for collaboration of hardware and software systems. A seamless interoperability between hardware and software components is enabled with Model-Based Design [11] that is typically advocated for embedded systems development and evidences a high return of investment [29]. Also, the rapid prototyping of components is supported by real-time simulation technology across wireless network technology [30]. Most importantly, an open design makes the accessibility, processing of data, and computation meaningful for the rescue operations directly in the field, which holds the promise of a game-changing technology in emergency response.

4. Related Work

This section presents research related to smart emergency response and illustrates the opportunities and obstacles to achieve the advances described thus far. Specific to unmanned autonomous vehicles (UAV), a recently launched humanitarian UAV network bridges humanitarian and UAV communities internationally [31]. The objectives of this

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[‡] A prototypical implementation of SERS is available on GitHub: *https://github.com/justynazander/SmartEmergencyResponse/ [41]*.

community include providing coordination support, facilitating information sharing, enabling safe UAV operations, and establishing clear standards for humanitarian use [31].

Technical solutions for fighting wildfires exist. Such wildfires occur each year and destroy thousands of acres in a few hours, to a large extent because the wind can push the fire in unexpected directions. The WIFIRE project [32] at the University of California San Diego capitalizes on information from weather sensors and satellite images to predict where wildfires are moving, all in real time. The images and data create a network of real-time wildfire information that then unlocks the potential to forecast where the fire will move while it is burning. However, projects such as WIFIRE are not yet scaled up in terms of deployment.

More field application progress has been achieved in the use of social media for situational awareness during emergencies. Success in the field is illustrated by extensive studies in other work [33][34][35]. Community participation in common goal-driven initiatives as such has been researched as well. For example, in other work [34] evidence is provided that collective intelligence outpaces the intelligence of an individual contributor.

In this spirit, bringing simulation to the masses constitutes a tremendous opportunity to keep the society—and not only first responders—informed about operations in the field. Further, using simulation as a mass-scale information provider opens up the area of actionable intelligence as discussed in previous work [36][37]. That is, following the knowledge that can be retrieved from the computational space, the doers and makers may be given the tools to act and improve field operations whenever such an improvement is required and desired. Capitalizing on the existing and broadly-used platforms such as Google Earth allows for a high-level understanding of the realistic scenarios as illustrated in previous work [6][8]. Communication between the stakeholders becomes more efficient.

Currently, much attention in robotics is directed toward humanoids. These are being developed by multiple organizations, for example, Honda [38] and extended through the DARPA Robotics Challenge [39]. Beyond robotics, Model-Based Design enables researchers to also make tremendous progress in engineering systems such as communication devices, cars, and airplanes. Such research relies on executable modeling and numerical computation for creating behavioral predictions in a virtual world of simulations. These activities ultimately allow for the auto-generation of millions of lines of code out of models and the ability to deploy this code on a physical machine. For example, the Chevrolet Volt was created with such methods in only 29 months [40] in full compliance with legislation, whereas a typical manual process would have taken approximately 5 years.

5. Summary

The Smart Emergency Response System (SERS) concept illustrates how to arrange for an efficient and trackable disaster response. The Cyber-Physical Systems (CPS) paradigm unlocks the potential for hardware and software systems as collaborating across modalities. Integrated interoperability between hardware and software components at various levels of abstraction is enabled with Model-Based Design. Also, the rapid prototyping of components and integration into the system under design is supported by real-time simulation technology across wireless network technology. Most importantly, a design on an open and trusted platform makes the accessibility, processing of data, and computation meaningful for rescue operations directly in the field, which holds the promise of technology forces dramatically changing the equation in emergency response efforts.

While the technology advances, business models for humanitarian actions are still under development and not quite clear yet. The incentives to empower the execution of a smart emergency roadmap come from the technical areas. They have the potential to disrupt the current solutions if we take on the challenge.

References

[1] *Strategic Vision and Business Drivers for 21st Century Cyber-Physical Systems,* Report from the Executive Roundtable on Cyber-Physical Systems, January 2013.

[2] *Ensuring American Leadership in Advanced Manufacturing*, PCAST report, June 2011, http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

[3] Peter C. Evans and Marco Annunziata, *Industrial Internet: Pushing the Boundaries of Minds and Machines,* November 2012.

[4] *Winning the Future with Science and Technology for 21st Century Smart Systems*, NITRD white paper, March 2011.

[5] *Designing a Digital Future*: Federally Funded Research and Development in Networking and Information Technology, PCAST report, December 2010.

[6] Pieter J. Mosterman, David Escobar Sanabria, Enes Bilgin, Kun Zhang, Justyna Zander, A Heterogeneous Fleet of Vehicles for Automated Humanitarian Missions, *Computing in Science and Engineering*, vol. 16, no. 3, pp. 90-95, May-June, 2014.

[7] Justyna Zander, Pieter J. Mosterman, Smart Emergency Response System, Global City Teams Challenge, kick-off event, September 29-30, 2014, NIST, Washington, DC.

[8] Pieter Mosterman, David Escobar Sanabria, Enes Bilgin, Kun Zhang, Justyna Zander, Automating Humanitarian Missions with a Heterogeneous Fleet of Vehicles, *IFAC Annual Reviews in Control*, vol. 38, issue 2, 2014.

[9] The NITRD CPS Senior Steering Group's 2014, *CPS Vision Statement 2014,* https://www.nitrd.gov/nitrdgroups/images/6/6a/Cyber_Physical_Systems_%28CPS%29_Vision_Statement.pdf.

[10] *Strategic Opportunities for 21st Century Cyber-Physical Systems*, Foundations for Innovation in Cyber-Physical Systems workshop, Chicago, IL, March 13-14, 2012.

[11] Bernhard Schätz, *Model-Based Development of Software Systems: From Models to Tools*, Habilitation Thesis, Technische Universität München, 2009.

[12] Justyna Zander and Pieter J. Mosterman, Computation for Humanity—Information Technology to Advance Society, ISBN-10:1439883270, *CRC Press/Taylor & Francis*, Oct. 2013.

[13] SmartAmerica Challenge of the White House 2013-2014, http://smartamerica.org/.

[14] Rebecca Carroll, Nextgov online, *How Robots and Dogs May One Day Work Together to Save Your Life*, June 11, 2014, http://www.nextgov.com/emerging-tech/2014/06/how-robots-and-dogs-may-one-day-work-together-save-your-life/86305/.

[15] MathWorks® (2014a), MATLAB®, *Using MATLAB*®, Simulink®, *Using Simulink*®, *MATLAB and Simulink Product Families*, Natick, MA, March 2014.

[16] Google Earth™, https://www.google.com/earth/.

[17] ShAir, a Platform for Mobile Content Sharing, Yosuke Bando, Daniel Dubois, Konosuke Watanabe, and V. Michael Bove, Jr., MIT Media Lab, http://shair.media.mit.edu/, http://shair.media.mit.edu/tmp/shair_emergency_app.apk.

[18] Daniel J. Dubois and Yosuke Bando and Konosuke Watanabe and Henry Holtzman, ShAir: An Extensible Platform for Wireless Resource Sharing on Mobile Devices, *In The 9th Joint Meeting of the European Software Engineering Conference and the ACM SIGSOFT Symposium on the Foundations of Software Engineering* (ESEC/FSE 2013), 687—690, 2013.

[19] Y. Wan, K. Namduri, Y. Zhou, and S. Fu, A Smooth Turn Mobility Model for Airborne Networks, *IEEE Transactions on Vehicular Technology*, vol. 62, issue 6, September 2013.

[20] Y. Gu, M. Zhou, S. Fu, and Y. Wan, Airborne WiFi Networks through Directional Antennae: An Experimental Study, in *Proceedings of 2015 IEEE Wireless Communications and Networking Conference*, New Orleans, LA, March 2015.

[21] Tam Harbert, *On the Internet of Things, Nobody Knows You're a Dog*, June 2014, http://spectrum.ieee.org/computing/embedded-systems/on-the-internet-of-things-nobody-knows-youre-a-dog.

[22] Aaron Dubrow, Telerobotics puts robot power at your fingertips, July 23, 2014, http://phys.org/news/2014-07-telerobotics-robot-power-fingertips.html.

[23] F. Ryden, A. Stewart, H. J. Chizeck, M. Lunde. Haptic Navigation for Subsea Manipulation. Underwater Intervention. New Orleans, Feb. 2014.

[24] Worcester Polytechnic Institute Robotics Engineering C Squad (WRECS), http://archive.darpa.mil/roboticschallengetrialsarchive/node/63/index.html, 2013.

[25] Justyna Zander and Pieter J. Mosterman, From Internet of Things through Computation of Things to a Prediction Engine–SmartAmerica Challenge 2013 Workshop at White House, Washington DC, Dec. 2013 (with Peter Norvig).

[26] Pieter J. Mosterman, Enes Bilgin, David Escobar Sanabria, Kun Zhang, Justyna Zander, Autonomous Vehicles on a Humanitarian Mission - SmartAmerica Challenge 2013 Workshop at White House, Washington DC, Dec. 2013.

[27] User guide *AR.Drone* – Parrot, http://ardrone2.parrot.com/media/uploads/support_ardrone_1/ar.drone_user-guide_uk.pdf.

[28] Object-oriented programming with MATLAB®, Documentation, Release 2014a, Natick, MA, March 2014, http://www.mathworks.com/help/matlab/object-oriented-programming.html.

[29] Joy Lin, *Measuring return on investment of model-based design*, EE Times blog, May 2011.

[30] Katalin Popovici and Pieter J. Mosterman, *Real-Time Simulation Technologies: Principles, Methodologies, and Applications*, CRC Press, Boca Raton, FL, 2012

[31] Patrick Meier, Humanitarian UAV Network (2014). http://http://uaviators.org/.

[32] Miles O'Brien, Ann Kellan, *WIFIRE helps firefighters get a jump on wildfires*, http://www.nsf.gov/news/special_reports/science_nation/wifire.jsp, July 28, 2014.

[33] J. Yin et al., "Using Social Media to Enhance Emergency Situation Awareness," *IEEE Intelligent Systems*, vol. 27, no. 6, pp. 52–59, 2012.

[34] Anita Williams Woolley, Christopher F. Chabris, Alex Pentland, Nada Hashmi, Thomas W. Malone, Evidence for a collective intelligence factor in the performance of human groups, *Science* **330** (6004) 686-688, 2010.

[35] D. Lazer, *et al.*, Computational Social Science, *Science* **323**, 721-723, 2009.

[36] Justyna Zander, Pieter J. Mosterman, *What-If Search Engine*, Global City Teams Challenge, kick-off event, September 29-30, 2014, NIST, Washington, DC.

[37] Simon J E Taylor, Azam Khan, Katherine L. Morse, Andreas Tolk, Levent Yilmaz, Justyna Zander, Pieter J. Mosterman, Grand Challenges for Modeling and Simulation: Simulation Everywhere – From Cyberinfrastructure to Clouds to Citizens, *SIMULATION: Transactions of The Society for Modeling and Simulation International*, accepted to be published in 2015.

[38] Jason Falconer, "Honda Developing Disaster Response Robot Based on ASIMO," *IEEE Spectrum*, 2013; http://spectrum.ieee.org/automaton/robotics/humanoids/honda-new-disaster-humanoid-robot.
[39] DARPA Robotics Challenge 2013-2015, http://www.theroboticschallenge.org/.
[40] GM Standardizes on Model-Based Design for Hybrid Powertrain Development, MathWorks User Story, Apr. 2011, http://www.mathworks.com/tagteam/67422_91714v01_GMHybrid_UserStory_final.pdf.
[41] The Smart Emergency Response System software implementation in MATLAB® and Simulink®, https://github.com/justynazander/SmartEmergencyResponse, doi: 10.5281/zenodo.13449, August 2014.