5.3 Computational Technologies

Despite the potential for many beneficial improvements, current software development practices are relatively stable and effective, at least for conventionally building singular products. In contrast, advances in computational technology continue that enable more advanced software capabilities. These advances have foreseeable implications on both development practices and the capabilities that resulting products can support.

Specialized Processors

Advances in computational capabilities are often first realized as complex software built to operate on existing general-purpose computational devices. As these advances become better understood, refined, and standardized, specialized hardware devices (digital and analog) are built that improve the efficiency of those capabilities for use by software. Such purpose-built hardware devices may then be converted into specialized computational elements, for subsequent integration back into general-purpose computing hardware.

The effect of this progression on software development practices is to accommodate:

- Software services that exist to encapsulate specialized hardware capabilities (physical or emulated) for simplified access
- Virtualized hardware having enhanced capabilities either through deviceembedded software or in encapsulating software
- Software-first development, emulating hardware behavior, to allow a product to be targeted to operate on a platform of varying computational devices
- Collaborative hardware-software design ("codesign") to expose tradeoffs

Product capabilities that may be augmented through the use of specialized hardware devices include:

• Signal processing (detecting, processing (e.g., analog-to-digital and digital-toanalog conversion), and emitting electromagnetic signals)

- Sensory processing (i.e., sensing, transforming (e.g., smoothing), and producing physical phenomena within an environment, e.g., visual, auditory, tactile)
- Media processing (i.e., audio/video encode/decode/transcode/compression)
- Optimization of time-sensitive functionality (e.g., motion tracking, identity, security processing, image processing, remote sensing, speech/language translation)
- Parallel processing of mathematical operations to synchronously transform a homogeneous data set (e.g., process graphical content for visual display; processing of highly parallel operations for data mining/analysis)
- Neural network processing (i.e., parallel processing of AI logic for data analysis and machine learning (e.g., for pattern-based categorization and transformation of text/image/visual or sound/speech data))

Distributed Computing

Distributed computing is the ability to effect behavior over time and space, augmented by access via a shared distributed physical platform. This capability has several elements:

- Physically distributed processing (computation, communications, data storage)
- Mobility (devices, vehicles, drones)
- Software augmentation of hardware behavior
- Autonomy (robots/nanobots, spacecraft)

This requires acceptably overcoming challenges in terms of stable connectivity, time synchronization, transmission delays/latency (sometimes over galactic distances), and coordinated fault tolerance, handling of failures, and managing self-repair.

Distributed computing may be realized in several specialized or extended forms, including remote and virtualized computing, spatial computing, and cyber-physical computing..

Remote and Virtualized Computing

{high-performance/parallel computing (local multi-core/multi-processor node controls network process; complex predictive models/simulations (mega-data process analysis: weather, ocean dynamics)} {smart grids, autonomous vehicles, healthcare systems, and industrial automation}

{build assuming virtualized computational resources disregarding location while accounting for latency; build to defer selection of most appropriate resources}

{augmented/virtual reality in context of product verification}

Spatial Computing

Spatial computing is a framework for a combined representation of physical and virtualized content, supporting an augmented view of an ecosystem of interest. This defines a hybrid environment having both physical and virtualized elements in which a product can operate (e.g., for product evaluation or user training).

S. Greenwold, Spatial Computing (graduate thesis), Massachusetts Institute of Technology, Cambridge, MA, June 2003. < https://acg.media.mit.edu/people/simong/thesis/ SpatialComputing.pdf >

Spatial Computing | Wikipedia < https://en.wikipedia.org/wiki/Spatial_computing >

Cyber-Physical Computing

Cyber-physical computing is the software-coordinated management of autonomously operating physical devices as nodes of an integrated system operating within a containing ecosystem. The motivation for this conception is the unified monitoring and control of ecosystem behavior by means of ecosystem-embedded devices to achieve visibility into and control of ecosystem behavior. This results in the connected operation of these devices for the coordinated collection and sharing of ecosystem data among ecosystem entities and initiation of device actions toward meeting the system's purpose.

Cyber-physical computing is enabled by size and cost advances in sensor-effector technology, integrated to operate using distributed and remote computing capabilities. This enables distributed monitoring, data collection, and control of actions within a

containing ecosystem. Autonomously operating devices may be replicated to be dispersed and embedded in natural or artificial elements of the environment.

Cyber Physical Systems | NIST <https://www.nist.gov/itl/ssd/cyber-physical-systems>

Cyber-Physical System | Wikipedia < https://en.wikipedia.org/wiki/Cyber-physical_system> Introduction to Cyber-Physical System | GeeksforGeeks < https://www.geeksforgeeks.org/ introduction-to-cyber-physical-system>

R.Rajkumar et al, "Cyber-Physical Systems: The Next Computing Revolution", Design Automation Conference 2010, Anaheim, California, USA. < https://dl.acm.org/doi/ 10.1145/1837274.1837461>

Manufacturing Technology

Manufacturing technology includes an industrial process and enabling machinery for manipulating and transforming materials to fabricate physical machinery, devices, or structures, and the computational capabilities for sensor-based monitoring, analysis, and control of the manufacturing process and machinery. A manufacturing process may support mass customization of realized products to provide products tailored to specialized needs (e.g., based on the concept of a product family)

software-first system design and hardware-software codesign

supply chain process

hardware fabrication and assembly based on specification-defined models and behavioral emulations

additive (3-D printing) and robotics-integrated manufacturing techniques (for devices and structures)

Quantum Computing

The emerging science and technology of quantum computing is likely leading to the ability to solve problems that are infeasible or inefficient to solve conventionally (e.g., related to encryption, machine learning, simulation of complex systems, or analyses of alternatives). As quantum computing capabilities are developed, questions are being

considered concerning how best to develop software that defines computational behavior using this technology.

It may be feasible to apply existing forms of software specification to be expressed and translated into a form that defines the expected behavior of a quantum computing engine. Alternatively, new forms of expression may be conceived for specifying quantum processing capabilities. The ideal initially, from a software engineering perspective, would be to have an expressive form for software behavior that can be targeted to either digital or quantum processing technology, depending on accessibility to that technology and feasibility for solving a given problem, with the type of hardware to be employed being decided, and changed, as circumstances warrant.

In software development practice medium-term, quantum computing is likely to be realized by means of a suitable aggregation or interconnection of conventional and specialized processors having particular capabilities that are needed but infeasible or inefficient with only conventional computing. During early product development, it may be feasible to approximate (e.g., simulate) quantum computations on conventional processors for purposes of verifying non-quantum aspects of product behavior.

Biologic Computing

Organic (chemical and biologic) and other physical (analog) mechanisms can be viewed as performing a computational process. As with quantum computing, practical biologic computing would most likely take the form of a specialized computing engine for solving problems that are not well suited to conventional digital or analog computing capabilities.

Viewing genomics from a computational perspective, DNA is the encoding of genetic instructions that determine the capabilities and potential behavior of an organic system. DNA can in principle be expressed or modified so as to define a system having prescribed biologic capabilities. Experimentally, particular realizations of DNA have been achieved for performing massively parallel computations or mass data storage. Although the ability to implement DNA-based computation raises unresolved ethical

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questions and potential risks, its similarities to other forms of computation is of at least theoretic interest.

https://en.wikipedia.org/wiki/Biological_computing https://en.wikipedia.org/wiki/DNA_computing https://en.wikipedia.org/wiki/Genomics https://en.wikipedia.org/wiki/Real_computation https://en.wikipedia.org/wiki/Analog_computer https://en.wikipedia.org/wiki/Computer#Digital_computers