Implications of Intelligent, Integrated Microsystems for Product Design and Development

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Abstract

Intelligent, integrated microsystems combine some or all of the functions of sensing, processing information, actuation, and communication within a single integrated package, and preferably upon a single silicon chip. As the elements of these highly integrated solutions interact strongly with each other, the microsystem can be neither designed nor fabricated piecemeal, in contrast to the more familiar assembled products. Driven by technological imperatives, microsystems will best be developed by multi-disciplinary teams, most likely within flatter, less hierarchical organizations. Standardization of design and process tools around a single, dominant technology will expedite economically viable operation under a common production infrastructure.

The production base for intelligent, integrated microsystems has elements in common with the mathematical theory of chaos. Similar to chaos theory, the development of microsystems technology will be strongly dependent on, and optimized to, the initial product requirements that will drive standardization – thereby further rewarding early entrants to integrated microsystem technology.

I. Introduction.

Intelligent, integrated micro-systems combine some or all of the functions of sensing, processing information, actuation, and communication within a single integrated package, perhaps even within a single silicon chip. Such advances promise the ultimate customization of future products optimized (cost, performance, reliability) for the intended application. However, should single-chip micro-systems become a reality, they will radically transform the engineering environment for product development and the manufacturing infrastructure.

Intelligent, integrated micro-systems are enabled by the increasing power and sophistication of modern semiconductor processing capabilities. Over 30 years ago Nathanson, Newell, Wickstrom, and Davis [1] demonstrated a surface micromachined device, a Resonant Gate Transistor which consisted of a transistor with a free-standing metal cantilever beam as the transistor gate. However, the power of such integration was not appreciated until Howe and Muller [2] provided the first description of polycrystalline silicon (polysilicon) surface micromachining. As described by J. J. Sniegowski [3], the needs of the Department of Energy's defense mission motivated Sandia National Laboratories to overcoming the numerous technical difficulties in developing a viable approach to fab-ricating sensors and actuators in silicon and integrating those elements with on-chip electronic circuits. These highly integrated solutions impose constraints

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on staff and structure not encountered by organizations that deliver products assembled from discrete components.

Presently, even complex compact systems such as hand-held computers and cellular telephones are assembled from standard components with minimal customization. Individual functions are designed and optimized within standard interface architectures from discrete components. The standardized components are obtained from any of a number of potential providers, the choice of which makes minimal impact on the final product. For purposes of this discussion, we will refer to such products as “assembled” products – in contrast to integrated microsystems that are manufactured all at once.

We wish to emphasize that although intelligent, integrated microsystem technology is presently in its infancy, certain trends are beginning to emerge. In this article, we extrapolate from in-house experience in design and production of these integrated electronic solutions toward a future industry optimized around integrated products.

II. Developing Assembled Products

Using the simplest possible analogy, we envision the development of technological products as the process of invention, reduction to practice, and then production for sales [4]. At the turn of the 20^{th} century, research and development laboratories began to formalize the process of invention and reduction to practice for application to mainstream markets, leading to the familiar concept of research to development to application, or the R to D to A process (Fig. 1). As products increase in complexity, concurrent cycles of research to development to

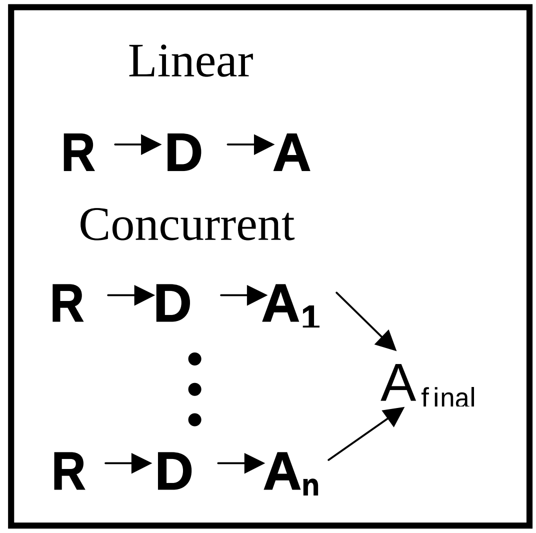

Figure 1. Under concurrent engineering, the linear research (R) to Development (D) to Application (A) process becomes a parallel stream of R to D to A processes for each component (A_1 through A_n) that are assembled into the final product A_{final}.

application are required to develop the constituent elements that comprise the final product. This process is illustrated schematically in Fig. 1. This model explicitly assumes that the constituent elements do not interact strongly within the ultimate product A_{final}, so that each constituent element A_i can be developed and optimized independently.

At the next level of complexity, sustaining an enterprise requires feedback from the marketplace into research and development of improved products. Feedback from the marketplace must be handled appropriately by the corporation (as described by Christensen [5]) and must be weighed differently for sustaining vs. disruptive technologies. Feedback from the marketplace and the need for continuous improvement thus converts the linear R to D to A cycle into a closed loop (Fig. 2).

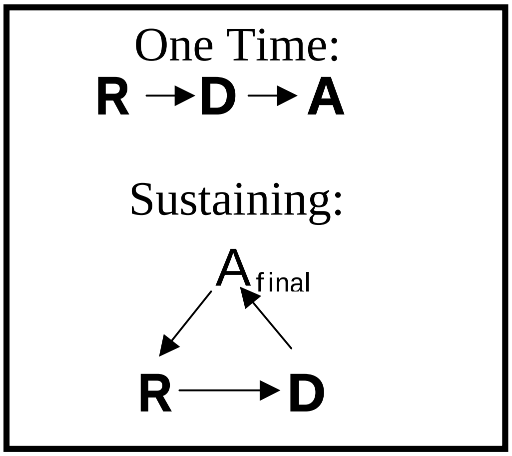

Figure 2. Schematic illustration of how market feedback converts the linear R to D to A process into a closed loop for continuous improvement of the final product $A_{final.}$ Such feedback is essential to creating a sustainable organization.

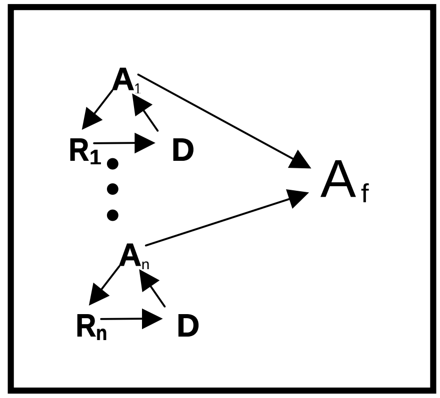

Figure 3. Schematic illustration of how the R to D to A process for an assembled final product draws upon decoupled R to D to A loops for each constituent components.

Because the constituent components of assembled products can be manufactured separately, their interactions within the final product serve to constrain design (specification of the constituent components) rather than manufacturing methodologies. Furthermore, the production infrastructure for each of the constituent components is decoupled from that of the others – as are the research and development activities specific to each constituent component. This decoupled R to D to A stream is illustrated in Fig. 3.

III. Developing Simultaneously Manufactured Products

In contrast to the development of products that can be assembled from discrete components, the ultimate microsystem will be fabricated within a single package and ideally even simultaneously upon a single silicon chip. These intelligent, integrated microsystems will provide electronic solutions for specific problems by combining some or all of the individual functions of sensing, processing information, acting, and communicating. However, on-chip interactions between the constituent elements of the integrated microsystem will require advance coordination not only of design but also of manufacturing to optimize the final product.

In this new methodology, on-chip interactions will drive product development away from discrete steps of design, component specification, component procurement, assembly, and qualification. Instead, these integrated solutions will require unprecedented levels of concurrent design, specification, and manufacturing.

Unless the design infrastructure can become sufficiently robust to buffer the systems designer from the details of on-chip interactions, these single-chip systems will demand greater coordination among technical specialists in functional design and manufacturing, as well as ultimate product testing and qualification. All potential interferences must be resolved to prevent schedule delays and expensive redesign before the product goes forward into production.

IV. Implications for Organizations and Investments

The development of single-chip solutions will produce major disruptions in traditional engineering organizations.

At the level of the individual staff member, simultaneously manufactured products will require the development of broader, overlapping competencies among the members of the design team. While each team member must be proficient within a technical specialty, all must share the responsibility for integrating their expertise into the final product. Thus, each team member must also serve as part system integrator for the team to realize the intended product. All must possess (at the minimum) a common vocabulary and a shared insight into each other's technical disciplines so that each can communicate and coordinate the demands of their expertise in trade-offs with those of the other team members to optimize the final product.

Technical imperatives will also drive team dynamics and structure. As any interference between components or functions could prevent the final product from achieving the desired functionality, there is no a-priori hierarchy in status or responsibility. Such teams will be better matched to less compartmentalized, less hierarchical organizations.

However, it is at the level of the self-sustaining corporation that the technological imperatives of intelligent, integrated microsystems will require the greatest accommodations.

To varying levels of emphasis, sustainable product-generating organizations must address business operational issues, manage fixed costs, and optimize products for the market-place. Enduring corporations must migrate their production infrastructures as technologies advance. Similar to the R to D to A process for products assembled from discrete components, feedback from the marketplace drives each of these R to D to A processes into closed loops, as was illustrated in Fig. 2. A fundamental organizational difference arises with integrated microsystems because (unlike assembled products) the integrated microsystem requires simultaneous manufacturing of multiple functions (any subset of sensing, information processing, actuation, and communication). Thus (Fig. 4), the R to D to A chain for any specific function (e.g., sensing) must be developed in anticipation of and must be made compatible with the requirements to

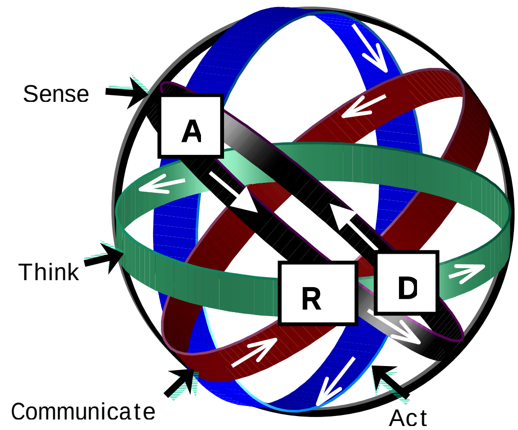

Fig. 4. The on-chip interactions in integrated microsystems require that the R to D to A process for each function (illustrated for the sensing elements) of an integrated microsystems must be coordinated with, anticipate the needs of, and must be traded against those of the other functions of the integrated microsystem to optimize the final product. Thus the need to resolve interactions within the chip results in a need to integrated the entire enterprise.

achieve of the other functions integrated on the same chip (e.g., information processing). Thus, the technological imperative of resolving strong on-chip interactions imply that development and continuous improvement of integrated solutions within a corporation must be made within an integrated team. While not the point of the present paper, it is essential to realize that the R to D to A stream for each system function must also include cross-disciplinary teams that encompass experts in design, manufacturing, and product assurance. Of course, the enterprise still must align products to the market place and migrate the entire production base as technology evolves – all while performing the remaining essential business functions.

V. Implications for Infrastructure

Limited experience with the development of integrated technologies at Sandia suggest that not every application of interest will require the same set of functions (sensing, information processing, actuation, and communication) as any other potential application. This observation leads us to predict a dynamic tension within the technology base.

Initially, there will be a natural tendency for the technology base supporting various embodiments of integrated microsystems to diverge as different vendors attempt to optimize their internal infrastructures toward their target markets. However, the expense associated with developing a completely custom infrastructure will lead to a counter-trend, namely toward standardization of design and process tools around a single, dominant technology. Such standardization will be essential to enable economically viable operation of a microsystems industry under a common production infrastructure.

Thus, we predict a spectrum of factories will produce different single-chip solutions. Some factories will produce high volumes of low-cost, standardized solutions, most likely for such mass markets as information display and communication. Other factories will likely support a family of mutually compatible, high-value products rather than the single "killer application" that would profitably occupy an entire facility. Such customization will open manufacturing to small-lot fabrication of low-volume components to supplement more standard products. This could lead to greater prototyping of innovative, speculative products or alternatively to production of relatively low-volume custom components, e.g., for defense.

The production base for intelligent, integrated microsystems thus has elements in common with the mathematical theory of chaos. Similar to chaos theory, the output of these versatile factories will be strongly dependent on, and optimized to, the initial product requirements, whether for a single product or a versatile product mix. We suspect human inertia will strongly favor product evolution around established competencies and capabilities, thus increasing sensitivity of the overall system to initial conditions – in essence creating a "strong attractor" from economic and product perspectives. Technologies, such as silicon surface micromachining, that can exploit existing production technologies common to semiconductor processing thus will encounter reduced barriers to investment compared to technologies that diverge from mainstream microelectronics fabrication. Thus economics and inertia will motivate a standardized infrastructure.

Finally, the above observations provide unambiguous indications of just how disruptive will be the technology for intelligent, intelligent microsystems. As described by Smith and Walsh [6], integrated microsystem technology is still in its infancy. It suffers from a lack of an installed manufacturing base and a dominant manufacturing technique. Similar to Smith and Walsh, we believe that development of a standard technology will reduce the barriers to investment toward establishing a production infrastructure. As of this writing, demand for silicon integrated circuits is nearing its all-time high. This demand will temporarily delay corporations from suffering the revenue discontinuities of converting production from familiar integrated circuits toward integrated microsystems. However, the drive to establish early standards and capture emerging markets will reward early entrants to this new technology.

VI. Summary

The technological imperatives inherent in single-chip intelligent, integrated microsystems will shape the resulting production industry. These technology-driven organizational imperatives will impact the working engineer, the structure of the teams in which the engineers perform their work, and structure of the corporation and the industry that produces such integrated electronic solutions.

VII. Acknowledgements

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