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Transitioning Science to Practice

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Abstract

Many of the significant National Security challenges of our near future will require a new approach to collaborative problem solving across many specialized disciplines to address new and yet unforeseen challenges or opportunities. To effectively address these challenges, artificial intelligence (AI) technologies such as machine learning (ML), deep learning (DL), etc., are being developed. The development of AI/ML systems requires a shift in how research and development (R&D) is traditionally developed. New development processes need to support the understanding that research is iterative, technology insertion is incremental, and the final capability is evolutionary. In addition, AI/ML capabilities development requires a level of cross disciplinary research and involves some intersection - fusion - of technology and emergent scientific discovery. There needs to be a concerted effort for facilitated bridging of the respective research and development trajectories such that the corresponding advances may be applied in concert to achieve a desired outcome. This paper proposes a new systems engineering/research Vortical model concept as a more effective approach for R&D of complex AI/ML-enabled capabilities. The Vortical model extends the foundational and well characterized spiral systems engineering and development model to incorporate the agility and flexibility of agile systems engineering methods. Additionally, the Vortical model introduces an iterative framework through which emerging advances in research outcomes are effectively demonstrated and validated for integration, as new capabilities, at varying technology insertion points or windows of opportunity. Our goal is to encourage adoption of best practices that facilitate the transfer of knowledge from emerging research activities for more effective and more rapid adoption and integration into the IC's mission capabilities.

Introduction

Many of the significant National Security challenges of our near future will require a new approach to collaborative problem solving across many specialized disciplines whether the topic is a new intelligence algorithm, a new weapon system, or a focused response to a global threat such as weapons proliferation, climate change, drug trafficking, cyber security, or another yet unforeseen challenge or opportunity. For these or other unforeseen challenges the solution set will likely require a level of cross-disciplinary research involving the intersection- or fusion- of technology and emerging scientific discovery. This relationship between science and technology has been described by Michael Polanyi, Figure 1 Polanyi's Relationship Between Science and Technology. Polanyi postures that science informs the building of new technologies; as these technologies are implemented, they in turn open up new questions and challenges for scientific research [1].

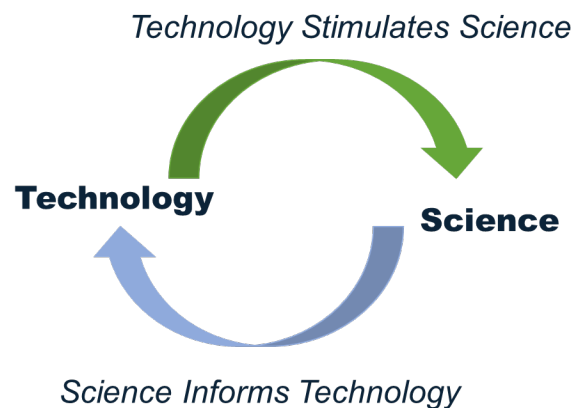


Figure 1 Polanyi's Relationship Between Science and Technology

This reciprocity between technology and science is particularly applicable for artificial intelligence (AI) and machine learning (ML)- enabled capabilities. By its nature AI/ML is emergent and exploratory; AI/ML enabled systems properties arise as a product not only of the individual components of the system, but also from the relationships and interactions of those relationships. This presents development challenges that require a combination of skilled engineering design in coordination with the advancement of scientific insight from research activities, enveloped within the context of a specialized domain.

Traditionally, realization of advances from data science research, as with other applications of emerging science, generally happens along one of two paths. The Research progression path, which is focused on enabling science and development execution, focused on engineering of a capability or system. Research progression involves a set of investigative activities, hypothesis-based, building on recent scientific discoveries or projected research outcomes, intended to mature conceptual applications into demonstrable, proof-of-principle results through deliberate experimentation. While research is, by definition, somewhat unpredictable, and speculative in nature and may often require new insights drawn from multiple scientific or technical disciplines to eventually realize the desired outcome, we

postulate that adherence to good scientific methodology, or research best practices, may improve the likelihood of a successful outcome.

Development execution, on the other hand, is much more process oriented and engineering driven. It includes a set of disciplined methodologies for translating the most promising and best performing research outcomes into repeatable and reliable applications over a somewhat more predictable timeframe through roughly projected human and technological resources. These pathways are depicted as parallel access in Figure 2, with the interdependent linkage between emergent scientific research and engineering development and integration, akin to Polanyi’s relationship between science and technology, provided through the transdisciplinary (more often cross-disciplinary) leadership framework introduced herein.

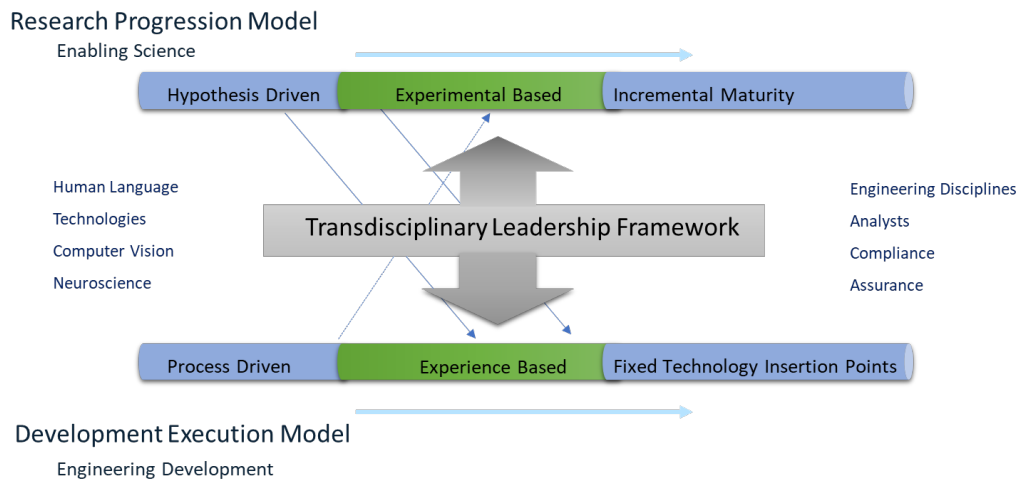


Figure 2, Research Enabled Development Model

A key constraint to note here is that the Development Execution pathway can only accept new research outcomes at certain windows of opportunity, or technology insertion points, within the development lifecycle. This constraint thus requires close coordination and regular communication between the research and development project teams such that both teams are aware of timing for upcoming insertion points and are equally prepared to support the transition of new enabling technologies into the development process when ready. In addition, AI/ML innovation cannot be done solely along one axis or, in some cases, multiple parallel research axes. There needs to be a concerted effort for facilitating bridging of the respective research and development trajectories such that the corresponding advances may be applied in concert to achieve a desired outcome. In addition, effective AI/ML capabilities are context driven and the science/technology relationship needs to be fortified for a successful transition and ultimate adoption of the technology to occur. This characteristic requires a strategic transdisciplinary approach to development. Transdisciplinarity is a strategy for bridging insights from multiple discrete disciplines in an attempt to create a holistic view with the goal of creating new conceptual, theoretical, methodological, and translational innovations that integrate and move beyond each respective discipline [2, 3, 4]. Rather than simply having multiple disciplines represented or working on the same project team, the transdisciplinary framework described herein attempts to foster a deeper level of collaboration and insight. The AI/ML ecosystem forces transdisciplinarity because of its emergent behavior as it often contains one or more trajectories that evolve, integrate, and co-adapt to

each other to evolve as the problem itself changes and the system and its environment co-adapt to each other [2, 3, 4]. While transdisciplinary collaboration, when properly orchestrated, can yield outcomes with far greater efficiency than the sum of independent efforts, effective transdisciplinarity does not come easily or naturally.

This paper proposes a new Systems Engineering/Research vortical model concept as a more effective approach for R&D of complex AI/ML-enabled capabilities. The vortical model has a conceptual process template for hybrid R&D programs, expands on the spiral nature of underlying systems engineering practices. The model, which applies systems engineering practices in concert with a set of research best practices to incorporate a degree of systems engineering perspective and rigor, is intended to support and enhance transdisciplinarity. The goal of transdisciplinarity is that researchers from various disciplines, cultures, and experiences, contemplate problems from a perspective beyond personal experience; using new insights gained from imagining the problem through a transdisciplinary lens to consider aspects of the problem from the perspective of their corresponding peers and not just from their own point of view.

Several key aspects of this approach are currently being applied to ML based computer vision research to improve optical character recognition capabilities. The work involves a cross disciplinary team of mathematics researchers, software engineers, analysts, and systems architects. We will use their work as a case study to illustrate how using this model accelerates the path toward successfully transitioning research results to operational practices.

Challenges with systems engineering practices in research

Formal methods have long been utilized in engineering projects to ensure the suitability of the resulting product or system for its intended purpose. Systems engineering provides the necessary methods and tools to effectively manage relationships, interdependencies, and interactions across all system components. By incorporating systems engineering rigor, risks can be reduced, uncertainty can be controlled, and the transition from research to operations can be facilitated. While systems engineering is commonly applied in development activities to enhance the design and development process, it is often overlooked in the realm of research, as it is perceived to limit exploration and creativity. However, to accelerate innovation, it is essential to harmonize research and development processes, enabling the smooth transition of new technologies into operational use. This requires improved communication and coordination between those involved in emerging research outcomes and those responsible for resource planning and prioritization for enterprise system integration.

Currently, there is a lack of documented processes or models outlining the structure of research and discovery advancement. Moreover, there is no "silver bullet" that guarantees successful innovation and effective technology transition into operations. Existing literature acknowledges the challenges associated with technology transitions [5, 6, 7]. Ellwood et al. note that the complexity of the process, along with competing stakeholder goals and multiple potential pathways, makes technology transitions difficult to achieve. Managing uncertainties, risks, and the diverse needs of each stakeholder along these pathways is crucial. Contrary to the notion of linear progression, technology development is an iterative, parallel, and integrative process involving various stakeholders. Successful technology transition proposals emerge from purposeful integration of stakeholders' needs, risks, and values. In the work by Lefebvre et al. (2022), they emphasize the importance of trust, effective communication, and information flows as contributing factors to successful technology transitions [8].

Exploring agile systems engineering for research

Research is a cyclical and iterative. It starts with a vision, an hypothesis, or an understanding; but as work progresses and is evaluated, research often transforms and can diverge from its initial intent. Agile systems engineering, based on iterative and incremental development - where solutions evolve through collaboration between self-organizing, crossed functional teams - can be a good fit for this environment. The agile systems engineering methods can provide an appropriate balance between the discipline needed to achieve results while maintaining flexibility for research exploration and agility to accelerate innovation. The process also promotes a more collaborative environment, provides an opportunity for rapid feedback, and more readily allows adjustments to the research direction if needed at earlier stages.

However, while research is an interactive process that focuses on one specific capability, each of these capabilities are refined, matured, and then integrated (through development) into a larger complex workflow/system. In these systems it is very important to pay particular attention to the larger broader system/workflow that the capability will be a part of, to ensure that full system intricacies and interactions, and unexpected emergent consequences of AI/ML output are considered [10]. To effectively provide for bridging and interlacing R&D from a holistic system perspective, the systems engineering model must allow for evolutionary/emergent dynamics and distributed collaborative design, while also maintaining the broader system view [11].

Introducing the vortical development model concept

The development execution model depicted in Figure 2, is traditionally modeled as a cyclical process of piecewise linear activities that can be represented as the spiral process depicted in Figure 3.

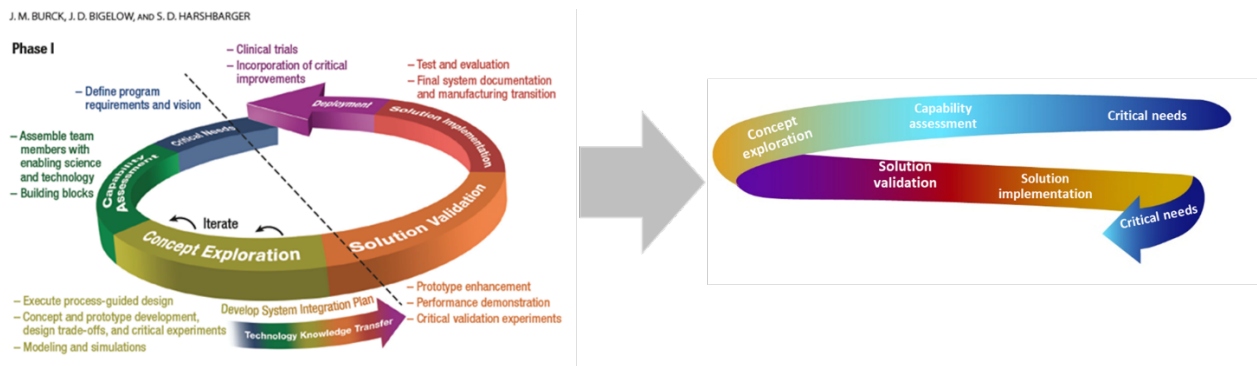


Figure 3 Spiral Development Model Uncoiled

This spiral development process has been successfully applied to address changes in user needs, obsolescence, or significant improvements in technology over the span of a products (or system's) lifecycle [9].

However, the development of AI/ML systems requires a shift in how research and development (R&D) is traditionally pursued, and new development processes need to support the understanding that research is iterative, technology insertion is incremental, and the final capability is evolutionary. To

address the unique challenges in developing AI/ML enabled systems, and to facilitate R&D progress, the concept of a vortical systems development model is introduced. The vortical model extends the foundational and well-characterized spiral systems engineering and development model, Figure 3, to incorporate the agility and flexibility of agile systems engineering methods. Additionally, the vortical model introduces an iterative framework through which emerging advances in research outcomes are effectively demonstrated and validated for integration as new capabilities at the next technology insertion point or window of opportunity. This iterative process of accelerating, evaluating, and preparing emerging research outcomes for potential incorporation into the development cycle adds a third, vortical, dimension of increasing maturity to the traditional spiral development approach.

We have demonstrated and documented an agile research methodology intended to provide improved focus on research activities and awareness of progress in advance of upcoming technology insertion windows, with the additional goal of more quickly validating or rejecting emerging research outcomes for increasing the velocity of transitions from research to development. As a particular research project matures, the component of underlying research risk are gradually retired and any required training and evaluation datasets are curated and iteratively expanded, policy and resource constraints are inevitably addressed, and validation, performance characterizations become more efficient. Accordingly, the tightening of corresponding spirals representing research progression activities, or maturity, along the third dimension, informs a new graphical visualization model that evolves the morphing of traditional spiral development into the vortical research and development model shown in Figure 4.

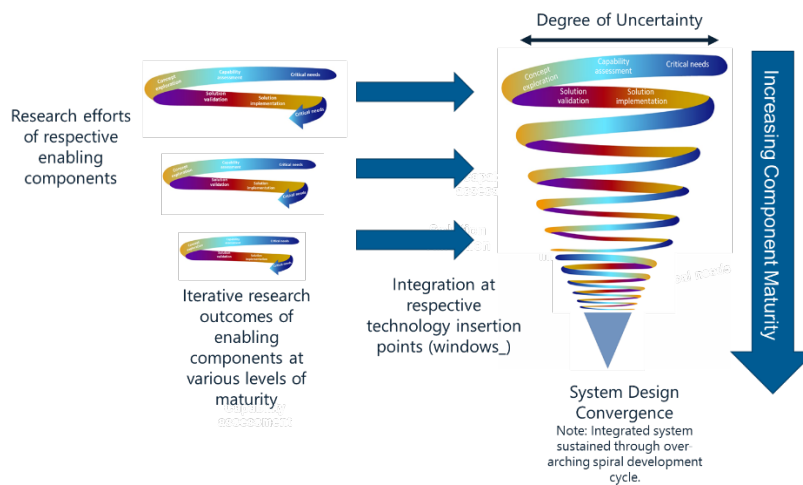


Figure 4 Vortical Development Model Concept

The model also provides a mechanism for facilitation of transdisciplinary research progression. The model is based on the premise that an AI/ML-enabled system is usually a large effort comprised of several components or discrete building blocks, each with its own unique and concise research questions or more manageable design tasks. While each of these components are viewed as independent, they are related to each other through the contextual framework and management structure of the larger system, or what is termed a system-of-systems. System-of-systems engineering principles delineate the need to understand and optimize subsystems, then optimize subsystem-to-subsystem to system interactions [11]. The same system-of-systems optimization approach, with

incremental integration, must be followed to fully realize the potential of AI systems, hence the feedback path indicated in Figure 2. As a complex project is distilled into concise research questions or more manageable design tasks, these components begin to look more like independent projects - related to each other only through the contextual framework and management structure of the larger system. Figure 5 illustrates this framework.

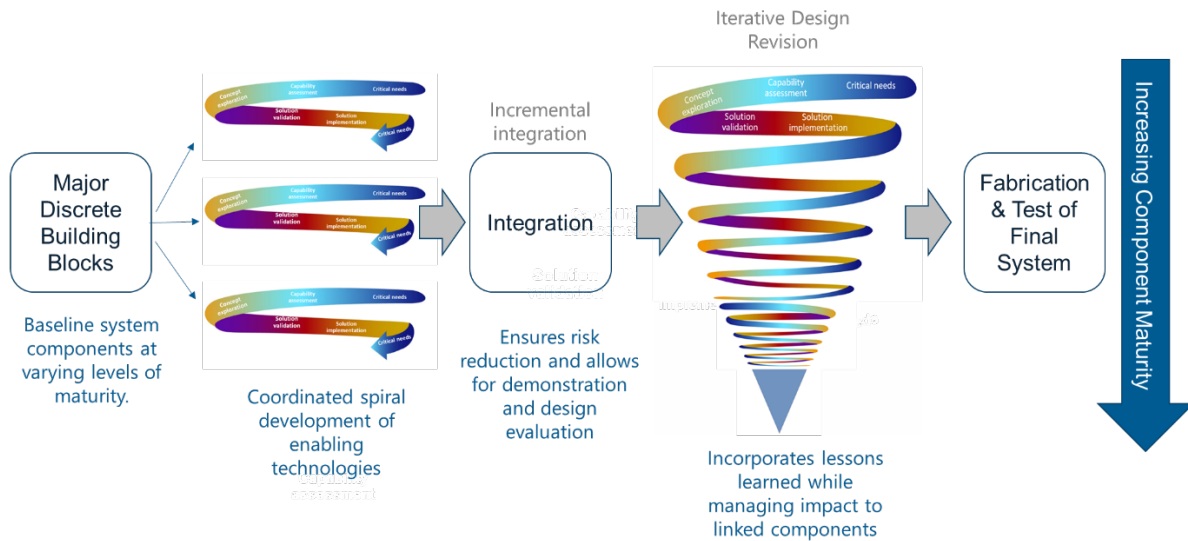


Figure 5 , Adapted from A Conceptual Process Template for Hybrid R&D Programs [14]

Unfolding Figure 5, the R&D baseline begins with various system components that can be viewed as discrete building blocks. Distillation of the system components into smaller pieces allows parallel research tracks or development efforts, for higher risk subsystems/technologies. This enables the option to prioritize critical items that may pose development risks for schedule or performance objectives. It also breaks the overall system into smaller projects; and on this smaller scale, we can more readily explore new research management models to facilitate and potentially accelerate research progress [14, 15, 16]. Because these baseline components are often at various levels of maturity, the vortical model uses several synchronous agile development sprints that allow for a coordinated spiral development of these enabling components/building blocks. These components are then incrementally introduced into the workflow. Incremental integration of each building block/slash enabling technology helps to reduce risk and allow an evaluation of the system design as each component is integrated. This also allows the emergent behaviors of the integrated capabilities to be evaluated before continuing. Allowing for redesign and rethinking to occur at an earlier point in the total system design process reduces risks and allows for redirection sooner rather than later in the development timeline if needed. In addition, these iterative designs allow the team to incorporate lessons learned while managing impact to linked components.

Case Study

As an example, we provide a case study where the Vortical Model concept was applied to machine learning based computer vision research to improve Optical Character Recognition (OCR) capabilities. We will use this work to illustrate how the model is used.

Background – Developing OCR Capabilities.

A group of human language technology (HLT) research teams and a team of computer vision (CV) researchers began to look into building a new, and improving existing, capabilities that would allow them to generate information from document images over diverse languages and scripts (writing systems), and over widely-varying layout complexity. This led to creation of a system workflow that would allow them to accomplish the required fusion of HLT with CV technologies under the direction of specialists in the various languages and application domains. While at a high level it seems that there are only three areas of convergence, OCR, machine translation, and entity extraction; the fact is the complexity of the problem required the exploration of several new capabilities. For example, document images can have varied amounts of page layouts; 3- columns, 2-columns, or 1-column layouts, with images interspersed throughout the page. Computer vision capabilities were needed to identify the page layout, extract the actual text from the image, and then group the text accordingly for the machine translation capabilities to then translate the extracted text. Ground truth or labeled data needed to be generated, which was a project onto itself, as there were no tools that were effective in developing the ground truth, and sufficient data to use for training was not readily available. In addition, machine translation and entity extraction technologies needed to be modified for the various language scripts.

Team Structure

To bridge the respective scientific challenges with the domain understanding and technologies necessary that would lead to a fully integrated and demonstrable system required a transdisciplinary team of mathematics researchers, software engineers, analysts, and system architects. The goal was to have a development process that would lead to a fully integrated and demonstrable end-to-end system and facilitate research progression while initiating development/engineering design for data preparation and end-to-end system workflow. The research teams collaborated to identify what the technology high-level workflow should look like at completion, and then the system was broken down into manageable research or development pieces. The details of each workflow before convergence was left to the research leads. Distillation of the system components into smaller pieces allowed the research leaders to insert diverse teams within the innovation process.

Figure 6 illustrates a team structure where research principal investigators work in conjunction with designated subsystem development team leads to ensure research outcomes converged at design decision points. This structure is facilitated by other team engagement strategies and visioned to bridge the respective scientific research and development domains, and to create a transdisciplinary effort to bridge insights from across the various disciplines.

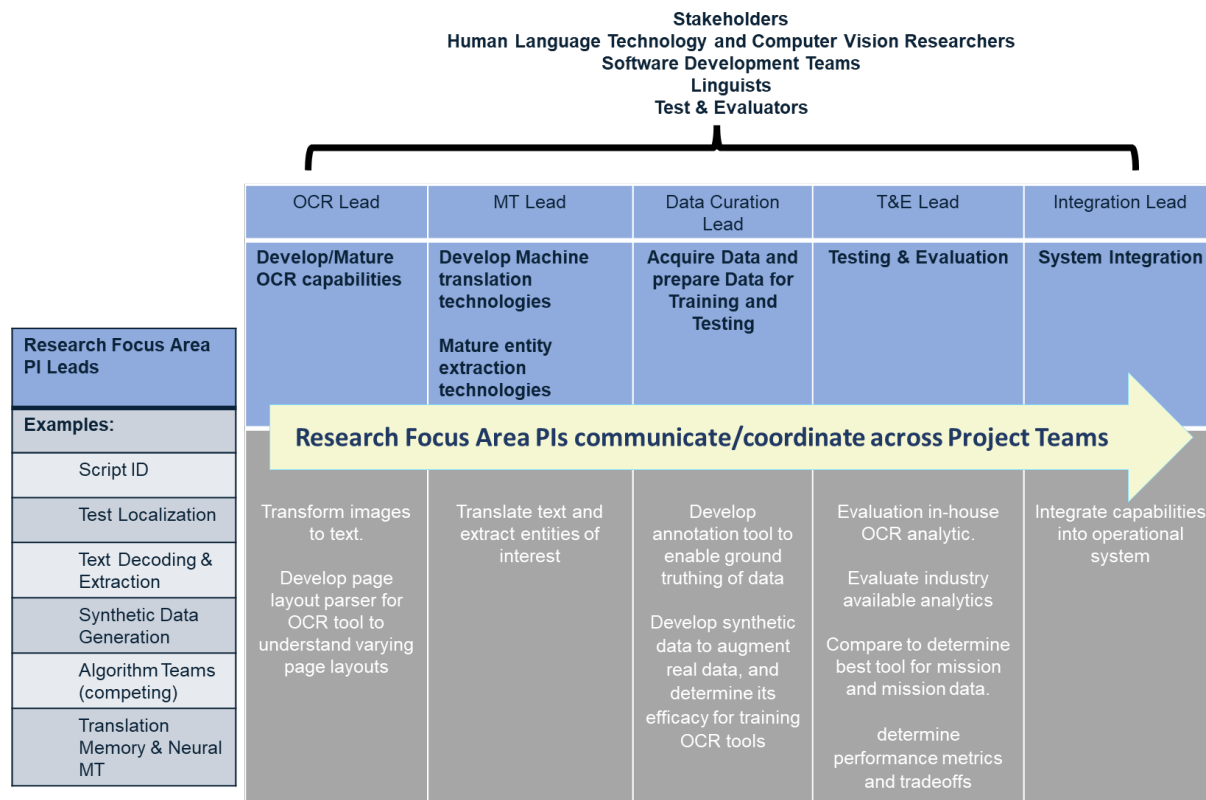


Figure 6, Collaborative Team Structure

As Figure 6 depicts, the CV team worked on developing algorithms/capabilities to parse image documents and extract text from the images. This work depended heavily on annotated data of image documents: to enable that portion of the work, a specific annotation tool was developed and adopted. The Testing & Evaluation team worked on evaluating industry and academically available tools, as well as developing a baseline on which to measure. The linguists were used to do language translation, and domain experts worked with the human language technology teams to provide domain knowledge needed for developing effective translations and to identify entities of interests.

The key here is that each component leader understood their respective functional role, corresponding system requirements, and interfaces with their subsystem and within the context of the entire system so that the components could easily interoperate. They set specific goals for their team, as well as prescribed the system inputs, outputs, and what evaluation metrics must be met. Additionally, they had to work in concert with the corresponding PIs to enable scientific research to ensure a clear understanding of the state of emerging science for incorporation of best available results. Similarly, each PI shares the responsibility for thinking beyond their research focus area to consider aspects of how their research outcomes would be incorporated together with other supporting technologies and ultimately integrated into the resulting system.

Using the Proposed Vortical Development Model

Bridging the respective scientific challenges required a process that would develop a fully integrated and demonstrable system. The full system development process needed to be iterative, as information gleaned from one step was incorporated into the next. Distillation of the system components into

smaller pieces allowed for parallel development for higher-risk subsystems/technologies and enabled the option to complete critical items that may pose development risks for schedule or performance objectives. It also delineated the overall program into smaller projects that more closely approximate the size and scope for self-contained explorations or tasks that may be assigned to a smaller research team, intern, student project, time-bound event, or leveraging an industry available technology. On this smaller scale, we could readily explore new research management models to facilitate and potentially accelerate research progress. Figure 7 illustrates the iterative, incremental, and evolutionary process for the OCR project.

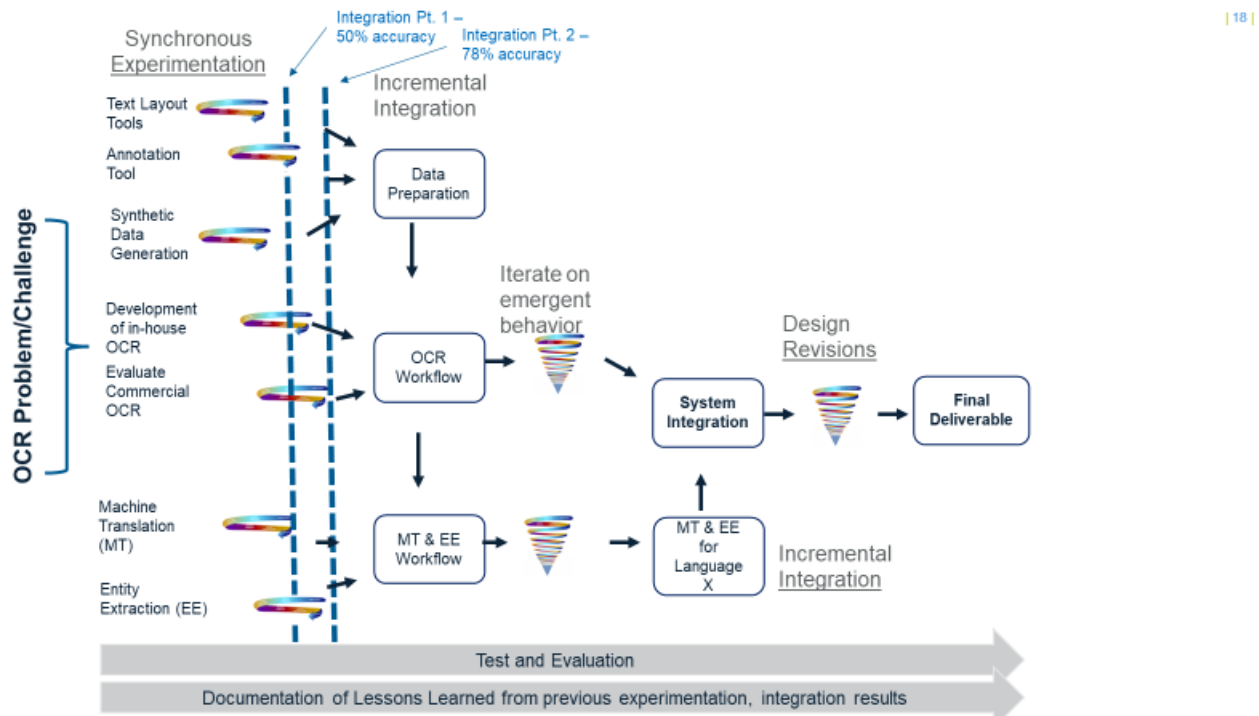


Figure 7, Example of Iterative, Incremental, and Evolutionary Development for OCT

The project was broken down in small base components: text layout tools, annotation tools, evaluation of commercial OCR tools, entity extraction tools, etc. While the HLT teams, working hand in hand with domain experts and linguists, focused on improving their machine translation for several languages and their entity extraction analytics, the CV team focused on exploring methods and available industry/academic analytics to improve their baseline OCR capabilities. In addition, several spinoff experiments were conducted to develop and prepare ground truth data. This included the exploration of the efficacy of synthetic data generation. These teams worked within a modified agile development process using pseudo sprint cycles of approximately 3-weeks induration. This modified agile approach incorporated lessons from the individual execution models and allowed AI/ML properties to emerge through the incremental integration into the overall system workflow. While research is clearly not software development, we adopted these agile (sprint-like) cycles to encourage best practices that promise to positively affect research progression.

While research maintained their cadence of new exploration, the T&E team maintained their own cadence in evaluating commercially and academically available tools. The cyclical process generated

valuable lessons learned from the engineering development processes, and research experimentation results achieved during one stage were captured and incorporated into the subsequent phase efforts. Establishing an agile cadence allowed the team to synchronize communication and perceptions as it provided checks and balances from various perspectives. Issues were regularly discussed, tips and lessons learned readily shared, and solutions to problems were creatively solved collaboratively. For example, a synthetic data generation system was developed to see if the OCR engine could benefit from additional training. The two teams worked together to develop training data in a specific language and further train the OCR engine. The resulting model was then evaluated where it was found that the additional training not only improved error rates in the target language but in other languages as well. These findings led the team to generate and train the OCR on an expanded language set of synthetic data that eventually led to the universal language OCR engine.

As depicted in figure 7, the research teams worked alongside the production designers to ensure the effective transfer of knowledge into an operational capability; Using incremental integration practices, continually incorporating mature capabilities up to the last insertion point opportunity, and then optimizing as an integrated whole until the next insertion point.

Conclusion

The challenge remains to accelerate the implementation and adoption of AI/ML capabilities for mission because research and development is associated with high risks, great uncertainty, and unpredictability. As scientists explore the “known unknowns”, as well as the “unknown unknowns”, introducing some needed system engineering discipline- while maintaining agility- is key in accelerating the operationalization of new capabilities; yet very difficult.

In addition, AI/ML environments are emergent systems, requiring a transdisciplinary approach for effective adoption, and traditional systems development methodologies do not fully support the needs of this environment. We proposed a new Vortical Development Model concept that balances flexibility for research discovery, introduction of engineering rigor for easier transition to operations, as well as support for incremental and optimization requirements to address systems-of-systems complexity.

The model begins by using the systems engineering foundational practices that provide a degree of engineering rigor and incorporates agile systems engineering methods to support and accelerate transitions. The model also supports transdisciplinarity in the hope that researchers from various disciplines, cultures, and experience may begin to contemplate problems from a perspective beyond personal experience, using new insights gained from imagining the problem through a transdisciplinary lens.

As this process is further developed the goal will be to incorporate additional aspects of the Vortical Development Model, and to potentially encompass a full set of emerging best practices for effective facilitation of transdisciplinary research progression for artificial intelligence systems.

REFERENCES

- [1] Polanyi, Michael, and Personal Knowledge. "Towards a post-critical philosophy." *NY: Harper Torchbooks* (1958): 266-67.
- [2] Colwell, Rita, and Robert Eisenstein. "From microscope to kaleidoscope: merging fields of vision." *Transdisciplinarity: Joint Problem Solving among Science, Technology, and Society*. Birkhäuser, Basel, 2001. 59-66.
- [3] Committee on Facilitating Interdisciplinary Research, National Academy of Sciences, National Academy of Engineering, Institute of Medicine. *Facilitating interdisciplinary research*. The National Academies Press; Washington DC: 2005
- [4] Madni, Azad M. *Transdisciplinary systems engineering: exploiting convergence in a hyper-connected world*. Springer, 2017.
- [5] Ellwood, Paul, Ceri Williams, and John Egan. "Crossing the valley of death: Five underlying innovation processes." *Technovation* 109 (2022): 102162.
- [6] Dean, Tereza, Haisu Zhang, and Yazhen Xiao. "The role of complexity in the Valley of Death and radical innovation performance." *Technovation* 109 (2022): 102160.
- [7] Stefan, Ioana. "Does Open Innovation Enable or Hinder Crossing the Valley of Death?." ISPIIM Summer Conference, 4-8 June 2022, Copenhagen. 2022.
- [8] Lefebvre, Vincent, Gilles Certhoux, and Miruna Radu-Lefebvre. "Sustaining trust to cross the Valley of Death: A retrospective study of business angels' investment and reinvestment decisions." *Technovation* 109 (2022): 102159.
- [9] Bhuvaneswari, T., and S. Prabakaran. "A survey on software development life cycle models." *International Journal of Computer Science and Mobile Computing* 2.5 (2013): 262-267.
- [10] Krishnan, M. Soumya. "Software development risk aspects and success frequency on spiral and agile model." *International Journal of Innovative Research in Computer and Communication Engineering (An ISO 3297: 2007 Certified Organization)* 3.1 (2015): 301-310.
- [11] Dahmann, Judith S., and Kristen J. Baldwin. "Understanding the current state of US defense systems of systems and the implications for systems engineering." *2008 2nd Annual IEEE Systems Conference*. IEEE, 2008.
- [12] Sillitto, Hillary, et al. "Defining "system": A comprehensive approach." *INCOSE International Symposium*. Vol. 27. No. 1. 2017.
- [13] Dingsøy, Torgeir, Tore Dybå, and Nils Brede Moe, eds. "Agile software development: current research and future directions." (2010).
- [14] S. Harshbarger, "Systems Integration for Grand Challenge Problems", Merging and Managing Scientific Discovery with Engineering Process, Johns Hopkins University "Hopkins Heart Symposium", February 8, 2014.
- [15] S. Harshbarger, "A Systems Approach to Transdisciplinary Thinking", Workshop on Collaborative Research, McGill University, Montreal, Quebec, May 19, 2014.

[16] Burck, James M., John D. Bigelow, and Stuart D. Harshbarger. "Revolutionizing prosthetics: Systems engineering challenges and opportunities." *Johns Hopkins APL Technical Digest* 30.3 (2011): 186-197.