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**A Framework for Cybernetic Modeling and Analysis of
Naval System of Systems**

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A Framework for Cybernetic Modeling and Analysis of Naval System of Systems

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Abstract

Modern naval warfare requires more than individual platform superiority; it demands systemic agility and disciplined Systems of Systems (SoS) engineering to deliver decisive capability. As combat operations rely on interconnected platforms, the challenge is not just inserting new technology, but preserving mission coherence, operational relevance, and architectural adaptability in a changing environment.

Emerging technologies must be integrated in ways that maintain constituent-system autonomy while strengthening overall mission effectiveness. The architecture must also remain modifiable so it can evolve with threats without disrupting operations.

This paper presents a cybernetic, systems-theory-based framework for SoS engineering and technology insertion tailored to naval missions. Technology insertion is reframed as a closed-loop learning process using behavior models, executable mission threads, and predictive performance models to establish and monitor a system of systems homeostat based on fleet feedback and continuous modeling across a system and mission-focused hierarchy. This framework incorporates aspects of Agency theory that treats the framework as a living system that can sense, learn, and evolve in order to help the Navy accelerate innovation while preserving systemic coherence, enabling fleet architectures and acquisition cycles to remain mission-viable amid rapid technological change and emerging threats.

Introduction

This paper introduces a cybernetic and systems-theory based framework for system of systems engineering and analysis to provide technology insertion recommendations aligned to the operational tempo and the increasing complexity of naval missions. This concept makes use of a novel theoretical framework for recursion in complex system governance referred to as the Recursive Metasystem Governance Framework (RMGF; Goddin, 2026). While the RMGF is a general cybernetic governance framework, it is specifically employed for adaptive mission dominance using a naval system of systems. This framework represents a third-order cybernetic system for the governance of complex systems of systems that is grounded in systems theory, cybernetics, recursion, holonic principles, agency theory, and metacybernetics. This paper begins with a background of foundational concepts and a brief description of the RMGF. It then describes the application of the framework for the modeling and analysis of naval systems of systems for adaptive mission dominance.

Background

The RMGF, which represents the intersection of six primary theoretical disciplines—systems theory, cybernetics, recursion, holonic principles, agency theory, and metacybernetics—is a theoretical framework for recursion in complex system governance. Each



of these disciplines are briefly described below specifically as they contribute to this modeling and analysis framework.

Systems Theory

Ludwig von Bertalanffy first introduced the idea of a “general systems theory” in 1937 during his research in biology (von Bertalanffy, 1969). Von Bertalanffy (1969, p. 91) describes general systems theory as “trying to derive from a general definition of “system” as a complex of interacting components, concepts characteristic of organized wholes such as interaction, sum, mechanization, centralization, competition, finality, etc., and to apply them to concrete phenomena”. Von Bertalanffy’s research came during a time when “system” emerged as a key concept in scientific research, with the tendency moving toward the study of systems and their characteristics as an entity instead of the studying the individual parts (von Bertalanffy, 1969). Ackoff (1971, p. 1) refers to this as the systems approach, which focuses on total-system performance because “some properties of systems can only be treated adequately from a holistic point of view,” and that these properties are based on the relationships between the parts. While the systems approach has played an increasingly critical role in science, there is still no unified set of concepts that define a general systems-theory across disciplines (Ackoff, 1971; von Bertalanffy, 1969).

Adams et al. (2014, p. 113) built upon these and other previous works to improve the depth of understanding for systems theory and concepts by defining foundational propositions and axioms for systems theory, stating that “although there is not a generally accepted canon of general theory that applies to systems, we believe that there are a number of individual systems propositions that are relevant to a common practical perspective for systems theory.” Their work evaluated 42 specific fields of science, identifying 30 accepted systems propositions and concepts within each (Adams et al., 2014). Yolles (1999, p. 45) describes propositions as “a language [defining a truth system] that enables a set of explicit statements . . . to be made about the beliefs and other attributes that enable everything that must be expressed to be expressed in a self-consistent way.” Keating and Katina (2019, p. 11) apply these propositions to system operation, stating that “all systems are subject to the propositions (laws, principles, and concepts) of systems” and “violations of systems propositions in design, execution, or development of a system are ‘pathologies’ and carry consequences.” Adams et al. (2014) go on to state that the relationship between theory and its propositions is not direct, instead the level of axioms is introduced to form a relationship between theory, propositions, axioms, and real systems—the relationships between these areas is as follows. Any real system is represented by its propositions and is explained by theory. Theory is defined by axioms, which are supported by propositions (Adams et al., 2014). Seven such axioms were identified—Centrality, Contextual, Goal, Operational, Viability, Design, and Information. These axioms, which were inductively developed, defined as “presumed true by systems theory, from which all other propositions can be induced, and together are called ‘theorems of the system or theory’” (Adams et al., 2014, p. 119).

These propositions and axioms become the foundation for the study of systems (especially complex systems), or using the words from Katina (2015, p. 153), “systems theory includes laws (e.g., law of requisite variety), principles (e.g., principle of basins of stability) and theorems (e.g., recursive system theorem) that might be used to understand complex systems.” The laws, principles, theorems, propositions, and axioms that are foundational to systems theory point to a different level of thinking that is “based in understanding systems behavior, function, and performance of all [natural or manmade] systems . . . not being explained from traditional reductionist thinking” (Keating & Katina, 2019, p. 3).



Cybernetics

Ashby (1956, p. 1) states that “cybernetics was defined by [Norbert] Wiener as “the science of control and communication . . . as the art of steermanship,” and that the themes of cybernetics are coordination, regulation, and control. Bertalanffy (1969, p. 21) similarly defines cybernetics as “a theory of control systems based on communication between system and environment and within the system, and control of the system’s functions in regard to the environment”. Ashby (1956, p. 1) goes on to state that “the truths of cybernetics are not conditional on their being derived from some other branch of science,” and “what cybernetics offers is the framework on which all individual machines may be ordered, related, and understood.” Beer (1995, p. 17) found that there are “fundamental principles of control that apply to all large systems” that have been found after 25 years of research, and that these principles apply to living biological systems, electronic (automated) systems, and in social and economic systems (Beer, 1995; Espejo & Reyes, 2011; Sisti, 2017).

The concept of variety and the law of requisite variety is a foundational concept in cybernetics as evidenced by the three cybernetic laws described in Sisti (2022)—Self-Organizing System Law, Feedback Law, and Law of Requisite Variety. The self-organizing law states that “complex systems organize themselves; the characteristic structural and behavior patterns in a complex system are primarily a result of the interaction among the system parts” (Sisti, 2022, p. 120). The feedback law states “the output of a complex system is dominated by the feedback and, within limits, the input is irrelevant” (Sisti, 2022, p. 120). In cybernetics, the number of distinguishable elements is referred to as variety (Ashby, 1956; Beer, 1995). Beer (1984, p. 10) put it another way, stating that “a precise measure of systemic complexity had been proposed as variety, meaning the number of distinguishable elements in a system, or by extension the number of distinguishable system states.” The law of requisite variety states that “only variety can destroy variety,” and that “control can be obtained only if the variety of the controller is at least as great as the variety of the situation being controlled”(Ashby, 1956, pp. 206, 207; Beer, 1995, p. 41). In tying the law of requisite variety to the viable system model, Beer (1984, p. 12) states that “what was perhaps novel, for the record, was the recognition that in the VSM. homeostats requisite variety applies in three distinct ways: to the blocks of variety homeostatically related, to the channels carrying information between them, and to transducers relaying information across boundaries.”

Other key aspects of cybernetics are the interrelated areas of communications, control, and learning. Whitney et al. (2015, p. 26) states as part of the Centrality Axiom that “the communication of information ‘drives’ the system and that causes interactions among systems.” Rios (2025, p. 4) frames cybernetic communication as the “organization’s nervous system [that] provides the essential element (information) that allows all functions to perform their tasks.” The communication architecture also serves as a mechanism to “bind each recursive layer to the overall agent organization and effect information transfer between layers (Laws et al., 2001, p. 11). The cybernetic control function relies on feedback of system operations through these communication channels, with feedback “mediating between system goals and system operations at every level of recursion” (Whitney et al., 2015, p. 29).

Cybernetic control relies on effective control loops of communication to maintain system viability (Keating & Katina, 2019). Metasystemic control operates as a higher-order regulator modeling, monitoring, and guiding subordinate systems through recursive feedback loops (Axelsson, 2025; Keating & Katina, 2019; Rios, 2025; Yolles, 2021). The metasytem hierarchy from metacybernetics means that multiple levels of feedback loops are continuously operating, attempting to maintain homeostasis by detecting deviations, comparing performance against goals or reference norms, and adjusting operations through corrective or amplifying feedback (Axelsson, 2025; Jenkinson et al., 2025; Yolles, 1999). These loops maintain homeostasis by



detecting deviations, comparing performance against goals or reference norms, and adjusting operations through corrective or amplifying feedback (Axelsson, 2025; Jenkinson et al., 2025; Yolles, 1999).

Cognitive learning is critical to maintaining system viability, particularly within second-order cybernetic frameworks (Yolles & Fink, 2015). Two forms of learning are described in the literature—single-loop learning and double-loop learning (Argyris & Schön, 1997; Hammond, 2013; Mohaghegh et al., 2009; Yolles & Fink, 2015). Single-loop learning, associated with surface knowledge, adjusts routines and behaviors based on feedback to maintain operational effectiveness (Hammond, 2013; Yolles, 1999; Yolles & Fink, 2015). Double-loop learning, associated with deep knowledge, incorporates ethical, normative, and relational considerations, and aligns with the principles of the “learning organization” (Hammond, 2013; Yolles, 1999; Yolles & Fink, 2015).

Beer (1979, p. 24) applied these cybernetic principles to organizations as he created the viable system model, for which he refers to cybernetics as “a collection of principles that systems cannot violate if they are to maintain their identity.” He coins the term “management cybernetics” to refer to the “science of effective organization” pertaining to the “Viable System” (Beer, 1979, p. 24). The management cybernetic concepts play a critical role in research on recursion. The VSM is itself a recursive model (Beer, 1979, 1984, 1995). Further, Beer (1984, p. 10) states that “the management of any viable system poses the problem of managing complexity itself, since it is complexity (however generated) that threatens the system’s regulators.” Beer (1979) defines three different ways of describing a system relative to its viability in terms of Actuality, Capability, and Potentiality. Actuality refers to what the system is actually doing now—its realized performance in current conditions with present constraints. Capability is what the system would be able to achieve under its current design and existing constraints if it is functioning like it should. Potentiality is what the system could be made to do through adaptation, learning, or investment.

Holon

The concepts of holons and holarchies provide a foundational framework for understanding complex, multi-level, and self-organizing systems. A holon is defined as an entity that functions simultaneously as a whole in itself and as a part of a larger system, possessing emergent properties at its own level while interacting dynamically with both subordinate and superordinate holons (Koestler, 1970; Mella, 2009). This dual nature allows holons to retain individual identity and operational autonomy while contributing to the coherence and function of the larger system (Mella, 2009). By transcending the traditional dichotomy of atomism versus holism, holons serve as a conceptual bridge that emphasizes relational, hierarchical, and recursive organization rather than isolated components or undifferentiated wholes (Koestler, 1970; Mella, 2009).

Holarchies—also referred to as system hierarchies—are structured arrangements of holons organized through nested, recursive, and vertically integrated relationships (Yolles, 1999). Each holon encompasses subordinate holons while simultaneously functioning as a component of a superordinate holon, forming a stratified hierarchy with base holons at lower levels and final holons at the apex (Mella, 2009). Koestler’s formulation of holarchy emphasizes inclusion rather than mere interconnection, highlighting how systems are composed of embedded units rather than loosely linked parts (Koestler, 1970; Mella, 2009). Holarchies may be constructed bottom-up through the composition of base holons or top-down through the decomposition of a primal holon, with their depth determined by the number of observable hierarchical levels (Mella, 2009).



Feedback mechanisms are central to holonic organization, enabling regulation, self-organization, and adaptive learning across hierarchical levels (Mella, 2009). Feedback loops allow holons to improve performance incrementally without altering the fundamental patterns of underlying skills or processes, while supporting both operational coordination and cognitive adaptation (Koestler, 1970; Mella, 2009). Knowledge within holarchies can be understood as recursively nested across deep domains—such as cognition, worldview, and metasystemic understanding—and surface domains, including behavior and structure (Mella, 2009). This recursive nesting gives rise to metaholarchies, in which knowledge and decision-making are hierarchically organized, with each level corresponding to distinct forms of intelligence and governance (Herrera et al., 2011; Yolles, 1999). Through learning and adaptation, holarchies evolve toward greater efficiency, allowing advantageous changes to propagate while constraining maladaptive variations (Mella, 2009).

Central to holonic theory is the Janus effect, which characterizes holons as dual-aspect entities that simultaneously assert autonomy and submit to higher-level integration (Koestler, 1970; Laws et al., 2001). This intrinsic duality governs how holons balance self-regulation and individuality with systemic responsibility and coordination. Through this mechanism, holonic systems achieve resilience, coherence, and adaptability by allowing each unit to operate autonomously while participating in larger-scale integrative and feedback-driven processes (Laws et al., 2001; Mella, 2009). As a result, holarchies provide a robust explanatory model for complex adaptive systems, emphasizing the interplay of autonomy, dependence, hierarchy, and multi-level feedback as foundational mechanisms of systemic stability and evolution.

Agency Theory

Agency theory explores viable autonomous living systems and their capacity to behave and change (Yolles, 2021). Higher levels of agency consciousness can be generated through processes of internalization, assimilation, and accommodation (Yolles, 2021). Agency is a population of adaptive operative agents that create effects through their superstructure and substructure, governed by a common metasystem that internalizes its environment (Axelsson, 2025; Yolles, 1999, 2021; Yolles & Frieden, 2021). Agencies and agents “are taken to be autonomous entities that interact with each other in a given domain” (Yolles, 2021, p. 7). Substructure relates to a system operating with its metasystem, which aligns with the VSM and with what Yolles (2021) refers to as the “system-metasystem couple” and superstructure relates to a higher-level. Superstructure exists over and above the substructure to “maintain and shape it through conceptual and relational functionality” (Yolles, 2021, p. 6).

A key feature of agency is that it is capable of internalizing aspects of its external environment (Yolles, 2021). This internalization “occurs through the dual processes of assimilation and accommodation” (Yolles, 2021, p. 7). Assimilation occurs “when an observed effect is brought into an agency as information through some inherent process of categorization and encoding” (Yolles, 2021, p. 7). Assimilation enables the integration of these observed effects into a virtual ideate (internal model), and learning is possible only when assimilation is active (Yolles, 2021). Accommodation occurs “when said information becomes incorporated into an agency as an ideate, thereby modifying agency as part of an adaptive process” (Yolles, 2021, p. 7). Accommodation creates an “anticipative structure as a precondition for adaptation” (Yolles, 2021, p. 7). These processes underpin anticipatory capacity, enabling systems to maintain identity, process information, and respond proactively to environmental changes (Yolles, 2021). Feedback loops inform both operational and structural adjustments, linking cognitive and behavioral change (Yolles, 1999). Higher-order internalization allows the system to co-evolve with its environment, enhancing resilience and innovative capacity (Yolles, 1999, 2021). Cognitive learning, internalization, and anticipatory processes form the core mechanisms through which complex systems achieve viability, adaptability, and resilience (Yolles, 2021).



Internalization is seen as a substructural agency feature that “enables it to adapt, and which is facilitated through autopoiesis” (Yolles, 2021, p. 7). Yolles (2021, p. 7) expresses this in terms of necessary and sufficient conditions: “accommodation is a necessary condition for adaptation since without it requisite variety is not possible, while assimilation is a sufficient condition that enables accommodation.” Finally, agency theory includes the concept of internalization through assimilation and accommodation via an ideate (Yolles, 2021). This concept of agency sensing, learning, and adapting is closely related to the System 4 and the 3-4-5 homeostat from the VSM and the Metasystem 4 in the CSG metasystem.

Metacybernetics

Metacybernetics “is a general theory of higher-order cybernetics that involves intelligent complex agencies, these being dynamic systems with various self-properties that enable them to adapt to changing contextual conditions” (Yolles & Frieden, 2021, pp. 22, 23). Metacybernetics builds upon agency theory to define cybernetic orders to “understand, describe, and model complex systems” (Hadorn et al., 2015, p. 2). These cybernetic orders frame complex system governance as a nested hierarchy of recursive, reflexive, and anticipatory regulatory orders, where stability, adaptability, and learning emerge from the interaction between systems, observers, and metasystems (Yolles, 2021). This forms a metasystem hierarchy where recursive metasystems are connected by causal-agents such as autopoiesis (operative intelligence, self-production) and autogenesis (figurative intelligence, self-creation; Schwarz, 2021; Yolles, 2021; Yolles & Frieden, 2021). At the lowest level, the operative system executes goal-directed behavior guided by cognitive and strategic-regulative metasystems through autopoietic feedback loops (Beer, 1979; Yolles, 2021; Yolles & Fink, 2015c). Higher-order metasystems (metametastystems) provide regulatory oversight, reducing uncertainty in the relationships and behaviors of lower-order systems, and generating meta-structures that guide adaptation, anticipation, and self-organization (Yolles, 2021; Yolles & Fink, 2015c). This metasystem hierarchy relates to the substructure and superstructure relationship from agency theory (Yolles, 2021).

Hadorn et al. (2015, p. 2) state that “different cybernetic orders have been defined to understand, describe, and model complex systems.” First-order cybernetics focuses on observed systems with external regulation, emphasizing positivist objectivity, automated feedback, and self-organization of structural components (Hadorn et al., 2015; Yolles, 2021; Yolles & Fink, 2015c). It treats systems as passive entities responding to perturbations from the environment (Yolles, 2021). Second-order cybernetics introduces the observer inside the system, emphasizing constructivist knowledge creation (Yolles & Fink, 2015b). The observer participates in feedback loops, reflecting on actions, interactions, and the system’s responses (Axelsson, 2025; Glanville, 2007; Hadorn et al., 2015; Yolles, 2021). Self-referentiality, reflexivity, and communication between agents enable the co-construction of meaning and adaptive learning (Axelsson, 2025). Regulatory control is now internally derived, allowing systems to adapt and self-organize in a social or living context (Yolles, 2021). Third-order and higher cybernetics address anticipation, unresolved undecidabilities, and paradigm shifts (Yolles & Fink, 2015c). These orders incorporate metasystems and meta-metasystems, providing higher-order regulatory capacity, promoting novel adaptation, and enabling self-creation (Yolles, 2021). They form a metasystemic hierarchy, where each higher order elaborates on and stabilizes lower orders while introducing requisite variety to manage uncertainty and complexity (Yolles, 2021).

Mission Engineering

Mission Engineering “is an interdisciplinary process encompassing the entire technical effort to analyze, design, and integrate current and emerging operational needs and capabilities to achieve desired mission outcomes” (OUSD R&E, 2023, p.3). Mission Engineering focuses on



breaking the end-to-end mission into parts to understand and evaluate how everything interacts. Gaps, risks, and opportunities are identified to evaluate solution spaces (OUSD R&E, 2023). Mission measures and metrics are established to assess the outcomes of a given mission approach and the associated elements. Three measures and forms of metrics are “selected from repeatable and unambiguous objective values and threshold values, which most directly inform the investigative questions and decisions to be addressed by the purpose statement” (OUSD R&E, 2023). Measures of Success (MOSs) are “measurable attributes or target values for success within the overall mission in an operational environment that are typically driven by the mission objectives of the blue force” (OUSD R&E, 2023). Measures of Effectiveness (MOEs) are “measurable military effects or target values for success that come from executing tasks and activities to achieve the MOS” (OUSD R&E, 2023). Measures of Performance (MOPs) are “measurable performance characteristics or target parameters of systems or actors used to carry out the mission tasks or military effect” (OUSD R&E, 2023). Collectively, MOPs, MOEs, and MOSs link system-level performance to operational effects and strategic stress criteria. This framework supports informed decision-making by emphasizing how individual components contribute to overall mission outcomes.

Discussion

Theoretical Framework for Recursion in Complex System Governance

The theoretical framework for recursion is comprised of six interacting theoretical pillars, collectively termed the RMGF. These six pillars are theorized to interoperate to employ weak anticipation (Yolles & Fink, 2014, 2015c; Yolles & Frieden, 2021), enabling the metasystem to stimulate additional knowledge generation through additional levels of recursion in support of proactive adaptation for sustained system viability. The RMGF conceptualizes complex system governance as a third-order cybernetic system in which governance, operations, intelligence, and control are recursively coupled, and governance itself becomes a reflexively governed process.

Figure 1 depicts one recursive instantiation of the RMGF. The six theoretical pillars are designated by color in the figure, with the red outer boundary depicting the Recursive Structure and Communications Infrastructure (TP3), which represents the invariant framework within which all recursive operations of the RMGF exist. This diagram distinguishes two forms of Process Intelligence (PI) that interconnect levels of recursive governance. PI, according to Yolles (2021, p. 15), “is a network of information processes that act as conduits to connect the various internal systems,” that has the task of “manifesting information from its source system to its receiving system.” PI of the first order is designated PI(1), which is a network of first-order processes that can create improvements within the confines of existing system structure. This is shown as the blue dotted arrow between Metasystem Duality & Cohesion (TP2) and System Operations & Cybernetic Control (TP4). PI of the second order is designated PI(2) and is defined as a network of second order processes that permits “novel forms of adaptation to occur through processes of learning that allow for adaptation or creativity” (Yolles, 2021, p. 23). This is shown as the blue dotted arrow between Metasystem Hierarchy (TP1) and PI(1).

The orange oval situated at the bottom right of the diagram represents Recursive Operations and Cybernetic Control (TP4). This is a whole system-metasystem couple, or holonic entity, that is responsible for operating within a local environment to fulfill all or part of the system’s purpose. The TP4 is closely aligned with the System 1 from the Viable System Model.

The green oval in the middle of the diagram represents Metasystem Duality & Cohesion (TP2). Its primary purpose is governance of TP4 operations, and as such is closely aligned with the VSM metasystem. The traditional VSM has several connections between the System 1 and



the Metasystem; in this diagram those are collectively represented by the PI(1) Autopoietic Couple via the blue curved arrow connecting TP2 to TP4 (Yolles, 2021).

The blue oval that intersects both Recursive Operations and Cybernetic Control (TP4) and Metasystem Duality & Cohesion (TP2) is Recursive Intelligence (TP5). This is a recursive function that integrates environmental signals and internal feedback into cognitive maps through assimilation and accommodation, enabling weak anticipation of processes and operations. A key aspect of Recursive Intelligence (TP5) is a Reflexive Recursion Gatekeeper (TP6), which samples the PI couples and provides feedback to stimulate adaptation. Recursive Intelligence (TP5) and the Reflexive Recursion Gatekeeper (TP6) are shown twice on the diagram, once between Metasystem Duality & Cohesion (TP2) and Recursive Operations & Cybernetic Control (TP4), then again between the Metasystem Hierarchy (TP1) and Metasystem Duality & Cohesion (TP2). These Recursive Intelligences are sampling their respective environments along with PI(1) and PI(2). This sampling enables evaluation of governance performance and stimulation additional recursions for complexity reduction.

The red oval at the top left represents the Metasystem Hierarchy (TP1), which provides oversight of governance operations. The connections between the Metasystem Hierarchy (TP1) and Metasystem Duality & Cohesion (TP2) is collectively represented by the PI(2) Autogenetic Couple via the blue curved arrow connecting TP1 to TP2 (Yolles, 2021). The Metasystem Hierarchy (TP1) can also be termed the metametasystem in relation to the metasystem, and as such monitors the execution of metasystem governance operations and monitors how metasystem governance decisions are being made. This monitoring is represented by the Recursive Intelligence (TP5) oval intersecting Metasystem Governance (TP1) and Metasystem Duality & Cohesion (TP2). This level of Recursive Intelligence (TP5) is structurally the same as that discussed earlier. In this instantiation, Recursive Intelligence is monitoring a higher-level environment, sampling PI(1) and PI(2), and providing the Metasystem Hierarchy and Metasystem Duality & Cohesion with intelligence findings. Embedded within Recursive Intelligence (TP5) is the Reflexive Recursion Gatekeeper (TP6), which is monitoring governance decisions by sampling PI(1) and stimulating recursive actions as needed to reduce governance complexity. At this level, the TP6 can stimulate a governance paradigm shift when existing modeling, interpretations, and actions are not improving governance or operations. The Metasystem Hierarchy (TP1) would then work to stimulate a reframing of the interpretive lens of the Metasystem Duality & Cohesion (TP2). This corresponds to “novel forms of adaptation to occur through processes of learning that allow for adaptation or creativity and incorporates” (Yolles, 2021, p. 23).



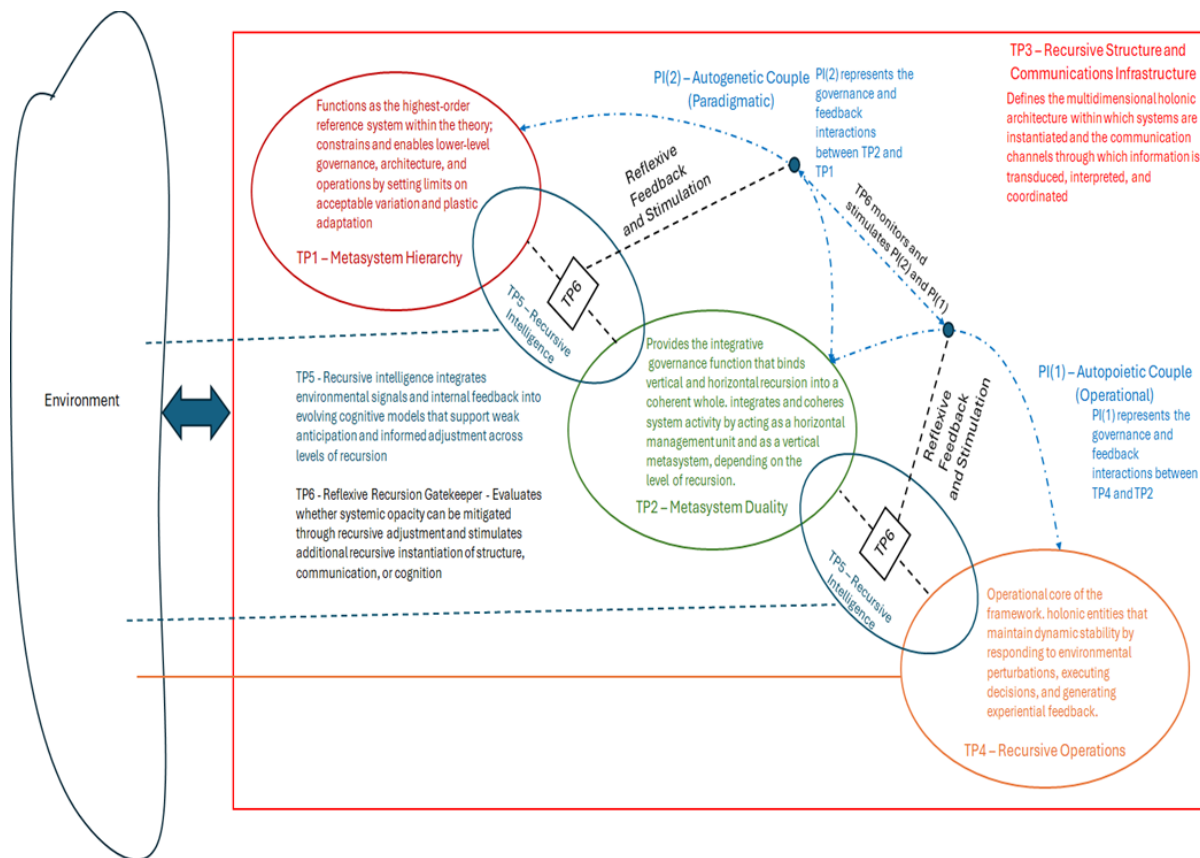


Figure 1. Recursive Metasystem Governance Framework Depiction (Goddin, 2026)

The RMGF concept has been leveraged as a foundation for system of systems modeling and analysis of naval missions. This framework employs modeling and analysis at three different levels, coincident with the governance levels of the RMGF. The lowest level represents platform-level analysis underpinned by physics-based and parametric models of the individual constituent systems. This level of modeling is primarily conducted by combat system programs of record. This level of modeling is currently segmented by combat system variant across the surface Navy to include the Ship Self-Defense System (SSDS) for large deck aircraft carriers and amphibious ships, and the Aegis Combat System for guided missile Destroyers. Both of these combat systems provide command and control across mission areas, including maintaining situational awareness; providing ship self-defense against air, surface, and subsurface threats; protecting high-value assets from ballistic missile attack; executing strike operations; and providing air control, among many others.

The next higher level of analysis focuses on mission execution across platforms. This level of analysis uses measures of success as a metric to evaluate multiple platforms acting as a larger system of systems to execute operational scenarios across one or more mission areas. This analysis makes use of constituent system and platform modeling results to create models for the system of systems boundary. It is in this phase of modeling where mission gaps emerge and need to be filled by additional systems, using existing systems differently, integrating new technology, or procuring upgrades. This level of analysis is key because there are three methods of defining a system of systems—self-organization, accretion, or purposeful design (Keating, 2022). Accretion is a process where systems are added piecemeal to fill perceived gaps. This often results in a fragmented system of systems where identity is unclear, and operations are not cohesive (Keating, 2022). Self-organization involves allowing the system



structure to evolve based on environmental perturbations with minimal higher-level oversight. The results may or may not be consistent with desired performance when observed at the system of systems level (Keating, 2022). System of systems evolution through accretion and self-organization alone often result in systems that do not meet performance expectations (Keating, 2022; Keating & Katina, 2019). Evolution using these methods is not purposeful from the holistic system of systems perspective, and results in a condition referred to as “system drift” (Keating, 2022). System drift refers to a system “that is subject to the unintended consequences that accrue in the absence of a purposefully executed design” (Keating, 2022, p.153). Purposeful design is the development and evolution of a system of systems through rigorous examination based on a set of systemic lenses (Keating, 2022). These lenses are underpinned by the seven axioms of systems theory.

The top-most level of analysis seeks to fill observed operational gaps through the integration of new technologies or by identifying novel operational uses of existing system capabilities. This is a forward-looking set of analyses that focuses on the “what-if.” This level of analysis employs models and model results from the mission-based analysis, then augments them with possibilities that surpass current program of record design and operation. The focus here is the effectiveness and performance of the overall system of systems. This level of analysis provides recommendations for acquisition of new capabilities, for new technology transition, for new system of systems capabilities through the novel employment of existing constituent capabilities, and for the initiation of new technology investigation and experimentation. The hierarchical mission engineering and analysis framework based on the RMGF is depicted in Figure 2.

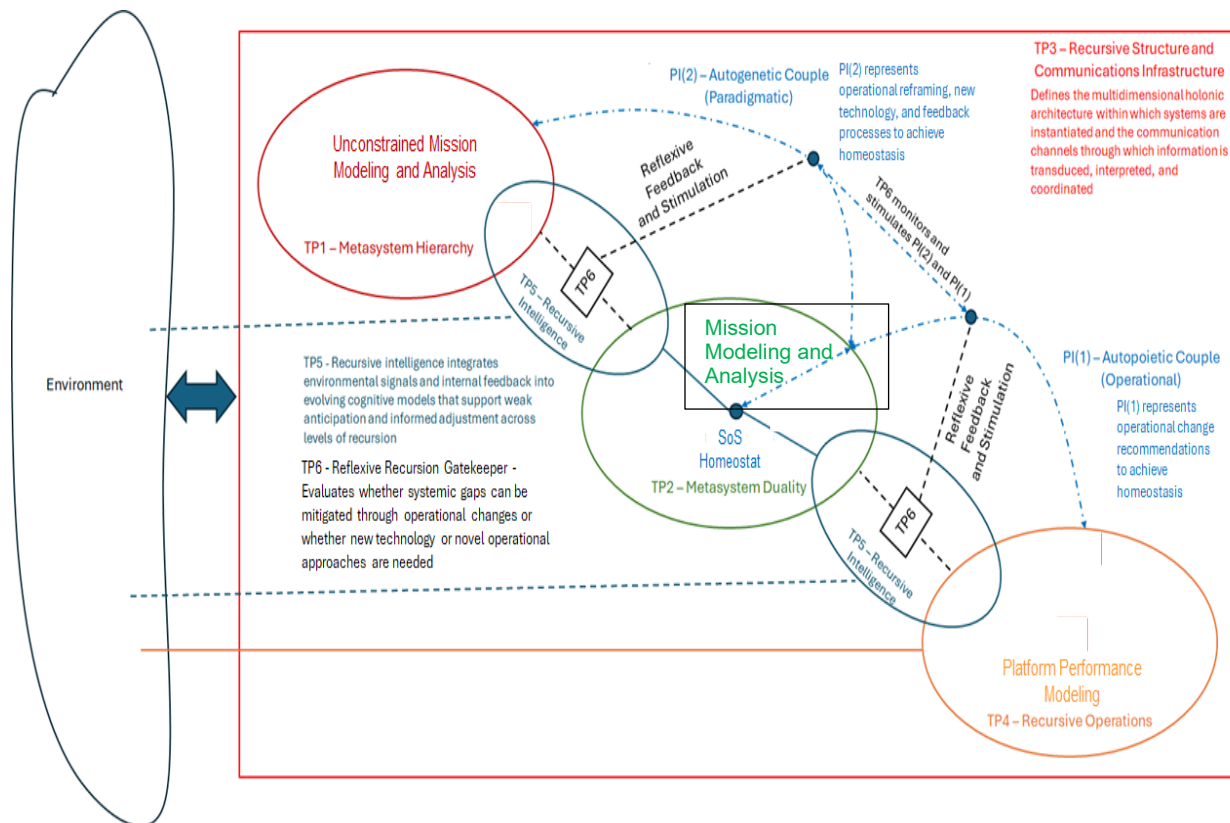


Figure 2. Framework for Cybernetic Modeling and Analysis of Naval System of Systems

This hierarchical approach to modeling and analysis employs aspects of cybernetics, metacybernetics, systems theory, and agency theory, and integrates them with mission engineering. From a systems theory perspective, the seven axioms become paramount in understanding communicating the system of systems aspects of mission execution. Relevant systems principle from five of the seven axioms are provided in Table 1 as they apply to this level of mission modeling and analysis.

Table 1. Relevant System Axioms and Principles

System Axiom	Axiom Definition	Systems Principle	Principle Applicability
Centrality	Central to all systems are two pairs of propositions: emergence and hierarchy and communication and control. (Adams et al., 2014; Keating & Katina, 2019; Whitney et al., 2015)	Hierarchy: Entities meaningfully treated as wholes are built up of smaller entities which are themselves, wholes. In a hierarchy, emergent properties denote the levels	This approach introduces a hierarchy of modeling and analysis, where each level represents a whole comprised of smaller entities, which are themselves wholes.
Contextual	System meaning is informed by the circumstances and factors that surround the system (Whitney et al., 2015)	Boundary: The abstract, semi-permeable perimeter of the system defines the components that make up the system, segregating it from its environmental factors	Analysis boundaries shift between constituent systems, platforms, missions, and campaigns. Each boundary introduces a new set of circumstances and factors that must be considered
		Holism: A system must be considered as a whole, rather than a sum of its parts	The increasing boundaries from constituent systems to platforms to missions means that maintaining the holistic perspective becomes increasingly important for overall performance assessment
Design	System Design is a purposeful imbalance of resources and relationships (Whitney et al., 2015)	Requisite Saliency: The factors that will be considered in a system design are seldom of equal importance.	The balance of resources and relationships is dictated by the measures of effectiveness and measures of success of the overall system of systems



System Axiom	Axiom Definition	Systems Principle	Principle Applicability
Goal	Systems achieve goals through purposeful behavior using pathways and means	Purposive Behavior: Denotes that the act or behavior may be interpreted as directed to the attainment of a goal	The goals for each level of modeling shift based on the overall measures of effectiveness and measures of success of the overall mission, not of the individual constituent systems acting independently
Operational	Systems must be addressed in situ, where the system is exhibiting purposeful behavior	Homeostasis: The property of an open system to regulate its internal environment so as to maintain a stable condition, by means of multiple dynamic equilibrium adjustments controlled by interrelated regulation mechanisms	Homeostasis for this framework focused on the mission and campaign level measures of success. Adjustments are evaluated at the platform and constituent system level
		Sub-Optimization: If each subsystem, regarded separately, is made to operate with maximum efficiency, the system as a whole will not operate with utmost efficiency.	Each platform is operating as part of a larger system of systems, and as such cannot be optimized independently of the other platforms. The holistic mission-level measures of success indicate overall optimization standards, with constituent systems being sub-optimized accordingly.

This approach also leverages aspects of cybernetics, metacybernetics, and agency theory. Cybernetics focuses on regulation, communication, and feedback to maintain control. Beer (1979) derived the viable system model through the convergence of systems theory and cybernetics. The viable system model specifies the necessary and sufficient functions required for system viability in dynamic environments. Yolles and Fink (2011, 2014) extended Beer's viable system model with agency theory and then metacybernetics, emphasizing internal modeling, interpretation, and recursive intelligence. Their work reframed viable systems modeling from structural to reflexively cognitive, introducing the capability of adapting governing assumptions. They incorporated concepts such as autopoiesis (self-production) and autogenesis (self-creation) to define how systems reproduce and, when necessary, transform the rules under which that reproduction occurs. This recursive intelligence is formalized through



a metasystem hierarchy, with each higher level offering a new way of “seeing” the problem space to offer resources, control, or a reframed interpretation of the gathered intelligence. This framework adopts these aspects through the three levels of modeling and analysis, each with a different focus. Each level of analysis is interconnected with the levels above and below, providing recommendations based on analysis results and receiving feedback for incorporation into subsequent analysis efforts. These interconnections represent a second-order learning cycle, where first-order learning is behavioral, and the second order is cognitive. Finally, agency theory incorporates living systems theory, specifically the exploration of autonomous living systems and their capacity to behave and change (Yolles & Fink, 2014). Agency theory defines higher levels of agency consciousness through processes of assimilation, accommodation, and internalization (Yolles & Fink, 2011). Agency theory is a metamodel defined through a superstructure and a substructure, where superstructure is related to uncertainty reduction through vertical recursion, and substructure relates to system stability through horizontal recursion. Further discussion of vertical and horizontal cybernetic recursion is beyond the scope of this paper.

The cybernetics, metacybernetics, and agency theory foundations of the proposed mission analysis framework are evident through its hierarchical structure, recursive operations, and semi-autonomous operation for adaptation and change. Each successively higher level of modeling provides constraint to the lower levels, but only as required for coherency and optimization at the overall system of systems level. The top-most level of the framework represents the superstructure from agency theory, providing a different way of looking at the problem space by removing constraints, introducing new technology solutions, or using existing systems in unconventional ways. This represents the Potentiality aspect from Beer’s viable system model. The middle and bottom level of the analysis hierarchy constitutes the substructure, where operational systems integrate to form systems of systems to satisfy measures of success and measures of effectiveness across mission areas. This represents what-if analysis based on existing constraints, or using Beer’s terms, remaining within the Actuality and Capability bounds of the constituent systems.

The final section carries the proposed framework through a use case to explain the activities at each analysis level and the interdependencies across levels. This represents interim results as this framework is still a work in progress.

Cybernetic Framework for Mission Engineering and Analysis

Figure 2 provided a high-level depiction of the cybernetic framework for mission engineering and analysis. A more detailed block diagram of this framework is depicted in Figure 3. Figures 2 and 3 illustrate a continuous and multi-level process. Within the process, system operations generate data that is recursively interpreted, evaluated, and executed across levels of governance. As operations unfold, outputs are translated through PI pathways into higher-level assessments of performance relative to mission objectives, while recursive intelligence functions integrate environmental signals and internal feedback to support anticipation and learning. Feedback mechanisms initiate a range of responses when deltas emerge. The responses could be low-level local adjustments within existing structures, up to reconsideration of governing assumptions. Over time, this process enables stability maintenance within the system under nominal conditions while still adapting. Thus, allowing performance to be sustained even as conditions evolve through second-level learning.

This second-order learning cycle is operationalized through a homeostatic mechanism embedded in the framework, with Measure of Success serving as its indicator of its regulatory behavior. This homeostat represents the set of feedback relationships that continuously regulate system behavior by comparing observed outcomes to desired conditions and also initiating



corrective adjustments. Within Figure 3, the homeostat links the three levels of analysis, enabling operational stability while supporting adaptation when deviations persist or exceed current bounds as threats evolve. Ongoing work is focused on quantifying the homeostat, with an emphasis on the development of measurable indicators aligned with regulatory effectiveness and adaptive capacity. A description of the framework block diagram is provided below.

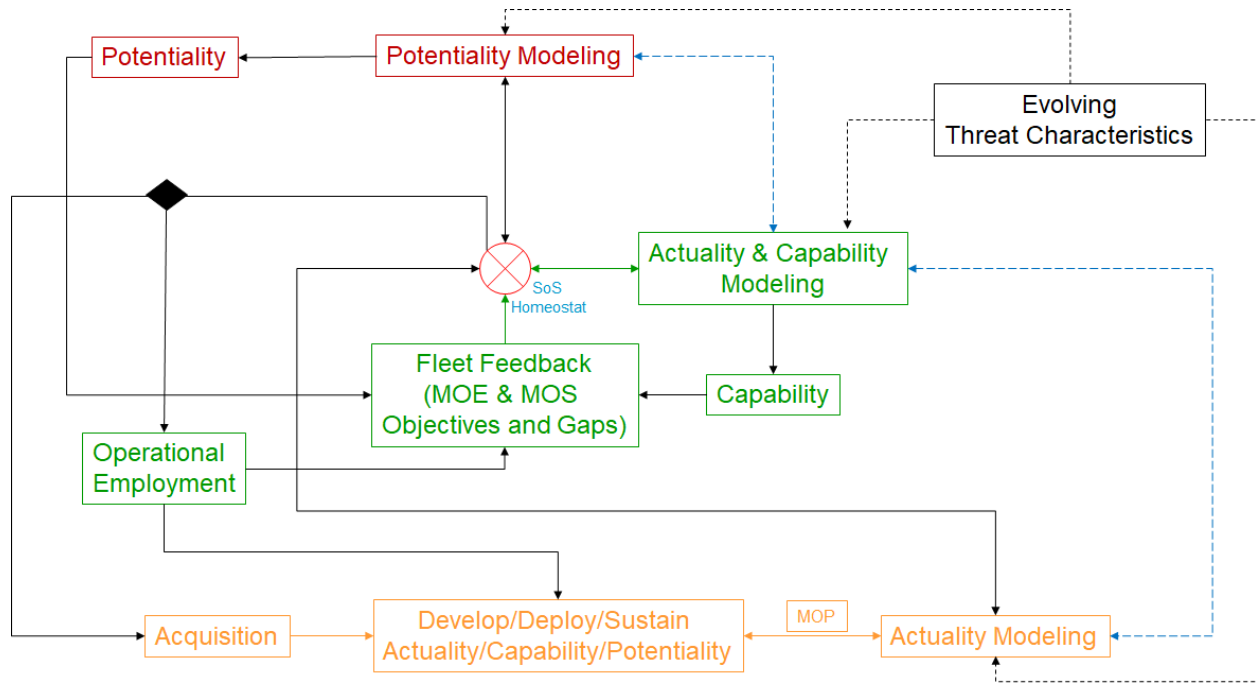


Figure 3. Framework Block Diagram for Cybernetic Mission Modeling and Analysis

The three levels of engineering and analysis in Figure 3 are indicated by the colors from Figure 2. Orange represents platform performance modeling, green represents mission modeling and analysis within existing performance and operational bounds, and red represents unconstrained mission modeling and analysis to close operational gaps with new technology or novel ways of using existing weapon systems. The key terms from the viable system model (Actuality, Capability, and Potentiality) are used to describe the modeling and analysis scope performed within each level. In this framework, Actuality modeling focuses on modeling the existing platform capabilities using physics-based design and specification models. Actuality & Capability modeling focuses on behavior modeling informed by the results from physics-based Actuality modeling to construct and model multiple platforms operating together towards a common mission-oriented goal defined by measures of effectiveness and measures of success. In this framework, additional performance information or operational understanding of platform systems is obtained through additional Actuality modeling. Potentiality modeling employs a combination of behavior and physics-based modeling to examine potential new technology solutions and to model their potential impact on mission-level measures of effectiveness and measures of success. Potentiality modeling also performs novel what-if performance-informed behavior analysis to determine whether existing systems can be employed in new and nontraditional ways to satisfy mission needs. The modeling at each level incorporates measures of performance as well as the evolving threat characteristics to inform up-to-date mission effectiveness assessments.

Key to the framework is the system of systems homeostat, which enables decision making for operational employment and the introduction of new technology or capability



improvements into the acquisition cycle. This homeostat resides in the middle level of the framework but intersects with all three levels. From the perspective of Figure 2, the system of systems homeostat is evaluating the balance of two sets of modeling and analysis efforts, both of which are resident in the Recursive Intelligence ovals. The blue dotted lines between Potentiality Modeling and Actuality & Capability Modeling, and between Actuality & Capability Modeling and Actuality Modeling indicate process intelligences for the framework, which provides cross-level analysis and learning that is essential for regulating the system of systems homeostat. These are each evaluating two dimensions of modeling—platform effectiveness operating individually vs multiple platforms operating as a cohesive whole as a mission-focused system of systems, and the capability limits of multiple platform integration vs. the introduction of new technology or the novel employment of existing systems.

The controls for the homeostat are provided by fleet needs, specifically by mission-level measures of success and measures of performance. Mission-level modeling results, both at the Capability and Potentiality levels, are operationally evaluated to gain fleet feedback for the homeostat. This essentially closes the loop on fleet needs and fleet acceptance of potential solutions and is key to the decision emanating from the system of systems homeostat for operational employment alternatives or new acquisition requirements. The continuous operation of this hierarchical system of systems modeling and analysis framework, using the system of systems homeostat as a measure of suitability for decision making, enables innovation results to be rapidly employed or fed into the acquisition cycle.

Summary

This paper introduced a cybernetic, systems theory–based framework for mission engineering and system of systems analysis to address the increasing complexity and dynamic operational demands of naval missions. The RMGF integrates six theoretical foundations into a unified approach for recursive governance. This approach allows operations, intelligence, and control to be coordinated across hierarchical levels. Analysis is structured through interconnected levels tied to MOSs, MOPs, and MOEs, which establishes a traceable link between system behavior, mission execution, and strategic outcomes. The connection of traceable links extends traditional models by including recursive intelligence and reflexive governance, allowing for continuous reassessment and adaptation of the assumptions that guide system behavior.

By the RMGF being applied within a naval system of system context, a continuous, multi-level process is supported to translate operational data into actionable insight, which results in real-time adjustment and forward-looking decision making. The integration of process intelligence and recursive intelligence facilitates anticipation, prediction, and learning guided by responses driven by feedback mechanisms ranging from local corrections to reframing strategy. Regulation through a homeostatic structure enables the system to maintain stability and adapt to evolving conditions. The resulting framework provides a foundation for intentional system evolution, mitigating and supporting informed technology insertion, acquisition, and capability development. Through ongoing efforts to quantify the homeostatic mechanisms, the framework's ability to guide adaptive mission engineering in complex operational environments will continue to strengthen.

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