Operational Synchronization

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1.0 Introduction

1.1 Scope

Complex systems incorporate many elements, links, and activities. This paper describes techniques for adaptive control within complex systems by stimulating coherent synchronization of component actions. This approach fuses concepts from complexity theory, network theory, and non-cooperative game theory.

1.2 Synchronization

Webster defines synchronize as: "To take place at the same time. To operate in unison. To cause to operate with exact coincidence in time or rate. To cause to coincide with an action." In military parlance synchronization is: "The arrangement of military actions in time, space, and purpose to produce maximum relative combat power at a decisive place and time." [DoD, JP 1-02] Neither are sufficient. This paper defines **coherent synchronization** as "the relative and absolute sequencing and adaptive re-sequencing of all relevant activities in time and space and continuous alignment of those actions with purposeful intent or objectives in a complex and dynamic environment."

2.0 Complexity

2.1 Emergent Behavior

Complex systems exhibit an array of behaviors. A wide range can emerge from simple interactions of system components. Emergent behavior can be simple (static, steady-state, regular harmonic…), complex, chaotic, or random. Many organizational concepts assume that only desired behaviors will emerge—a fallacy.

Most operational concepts recognize the need for synchronization of actions; some concepts assume synchronization results from improved information flows and shared situational awareness. Concept papers cite examples of coherent behavior in nature, but there are many counter-examples [Strogatz]. Advocates of emergent coherent behavior err with inductive arguments given abundant counter-examples [Stogratz].

Synchronization is one type of coherent behavior. Coherence may be externally induced or it may emerge because of direct interactions among elements. Emergent synchronization of coupled oscillators is possible – like fireflies flashing or clocks ticking in unison – and in special cases, it is certain [Stogratz]. Likewise, external action may yield coherent behavior – as an electric current induces a magnetic field. In complex systems, elements may align some attributes while other properties remain disordered. In these cases, the order is less apparent. Moreover, some elements may remain out of sync. Thus, synchronization is not universal and emergent sync in complex systems is not certain. [Manrubia]

Studies of complex systems conclude, "Individual processes in different parts of a system [must be] coordinated [to enable] the system to display coherent performance." [Manrubia, p1] Central coordination is not always required to gain coherent behaviors, but complex systems that display such coherent behavior exhibit organized complexity.

2.2 Organized Complexity

In the development of information theory, Charles Bennett identified two components of organized complexity. First, algorithmic complexity describes the minimal model, formula, program, or elements needed to support a result. Second, logical depth captures the processes needed to generate the result given the initial minimal program [Davies, 1992]. Complex systems exhibiting deep logical depth, like synchronization, arise after many cycles through the minimal program and thus they may appear to "emerge over time." However, the same logical depth derives more quickly by starting with complex formulae containing information otherwise reconstructed.

If synchronization is not certain to emerge from the cumulative interactions of independent agents (akin to minimal programs), then a structured program might generate the behavior. Simple agent interactions shape possible approaches.

2.3 Emergent Synchronization

Emergent synchronization in simple systems evolves after many cycles in a minimal program. For example, Thai fireflies developed an adaptive response to external flashes via genetic selection; the firefly adjusts the timing of its signal to achieve sync [Stogratz]. These synchronized oscillators demonstrate four elements: a coupling agent (signal), an adjustment process (minimal program), feedback or selection process (fitness), and computational cycles (evolutionary time). As a minimum, synchronization in complex systems will need these elements; all of them pose challenges.

Challenges: static guidance (intent) does not provide a dynamic coupling agent. Moreover, regional operations must sync globally distributed elements operating over vastly different time horizons; simple signals will not suffice. The activities of elements are complex, not simple threshold reactions like those evidenced in nature. A simple adjustment process may not suffice. Selection processes that operate for biological ecosystems are not available (mating behaviors) or desirable (predator-prey). Moreover, the time required for an emergent selection processes (biological computations) is not sufficiently responsive.

The implications are stark: coherent synchronization will not rapidly emerge and adapt without a foundation and emergent self-sync does not reliably provide requisite capability. Studies in other domains support this conclusion with the observation that "when adaptive speed is warranted, initial organizational structure is critical." [Manrubia] "It's a basic principle: Structure always affects function." [Strogatz]

Operational Synchronization provides this structure.

3.0 Response

3.1 Adaptive Synchronization

A software experiment developed and demonstrated a feasible approach to adaptive sync. It yielded a structural model embodied in a precursor experimental tool dubbed the *Synchronization, Adaptation, Coordination, and Assessment (SACA)* tool. The structure embodied in SACA and its performance provide direct evidence of the practical feasibility of this approach to adaptive synchronization.

The structural foundation for adaptive, dynamic synchronization evolved during spiral development efforts. This framework, threaded synchronization, extends beyond time to align a wealth of activities along the three axes:

- Vertical (motivation) – cascading objectives
- Horizontal (association) – interrelationships between objectives
- Temporal-spatial (location) – physical scheduling of activities

The vertical axis aligns objectives and end states with missions and actions. These links correspond to mission threads expanded to include intent, constraints, priorities, limits, and resources. Initial branching of threads leads to a traditional, decision tree structure tied to cascading objectives, goals, and tasks [Keeney]. A more complex structure proves more robust and allows multiple links to merge and diverge at successive levels. This construct eliminates the assumption of vertical linearity of cascading objectives or horizontal independence between objectives at the same level. Thus, complex relationships between successive and supportive objectives force structural use of a network of objective nodes and associative links. This approach retains lineage and exposes the impacts of linked actions with complex, multiple inheritance.

The horizontal axis links nodes of related activities – a cluster of activity nodes. These core clusters enable the dynamic, adaptive use of assets as envisioned by network-centric warfare concept [Cares]. Horizontal links provide structure to fuse and align activities that precede, support, reinforce, or follow primary actions. They capture inter-dependencies between objectives at the same level of organization or between the subsequent activities. These connections represent physical or logical ties between elements independent of subsequent scheduling of activities – a precursor vice result of the derived schedule. These activities extend to reach across domains and incorporate all elements of national power. Horizontal links may incorporate Boolean logic.

In military operations, horizontal links represent a group of aircraft containing strike aircraft, reconnaissance aircraft, unmanned vehicles, electronic warfare assets, and control aircraft. On the ground, similar relationships bind a maneuver force, its screening force, and its supporting fires. In the commercial sector, horizontal sets may include regional flights into a hub that feeds long-haul air routes.

The third axis, location, encompasses space and time. This axis schedules blocks or sets of activities sequenced and emplaced in space-time: defined as **action frames**. The organizational separation between the previous horizontal axis (associations) and this sequencing is critical – it enables adaptive scheduling and dynamic rescheduling.

Diverging from a traditional command-directed approach (command economy), the third axis envisions (but does not require) the formulation of a marketplace of options that might be combined with other activities in the selection and scheduling process: a free market. This approach expands terminating activities from "decision leaves" in a directed decision tree structure into a small world network of nodes to deliver a rich, dynamic array of options. This richness provides adaptive depth and robustness.

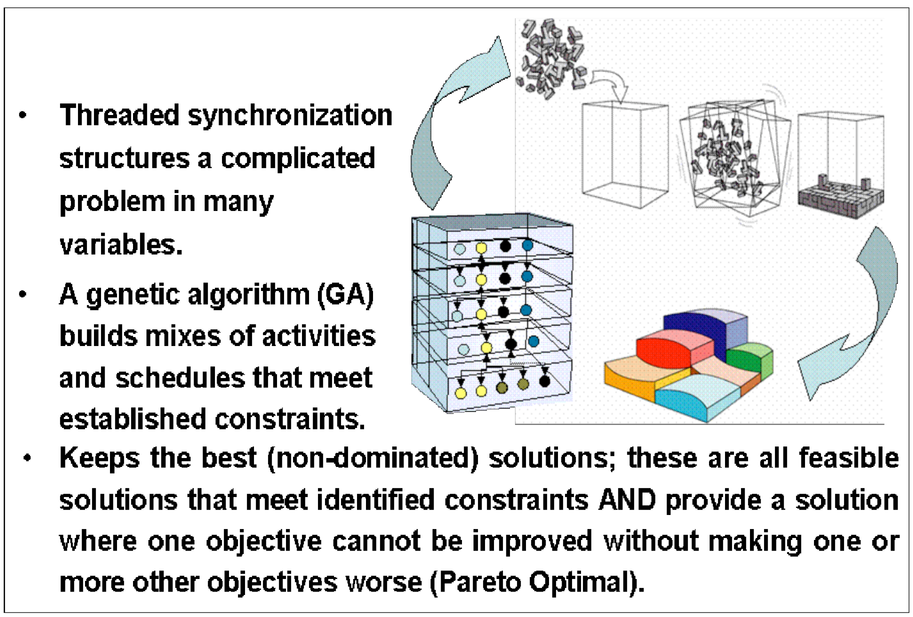

Figure 1. Threaded Synchronization Process

The experimental synchronization tool, SACA, established the feasibility of the **threaded synchronization** process. It developed and used a constrained, sorting genetic algorithm (GA) to construct and select action frames. SACA demonstrated the practicality of structured synchronization by constructing hundreds of alternative action frames that incorporate activities across all elements of the marketplace of national power and are ALL equally feasible (but not all equally desirable). Each block of action frames represents an alternative schedule-set of viable actions [Ritter]. [Figure 1]

Each action frame thus represents an option, a branch, a course of action, or a segment of a larger, connected, continuous storyboard. If one computes the number of options of an unstructured set of activity nodes, one quickly reaches a point where the number of options is quite large and intractable. By structuring the activities in objective-goal-action threads and bounding the range of options to feasible and desirable regions, the constrained-sorting genetic algorithm used for scheduling quickly converges on optimal solutions. This approach does NOT generate a single point optimum; it returns the Pareto Optimal solutions.

One such action frame could encompass an effects tasking order or an air tasking order. In entertainment, a set could include all television broadcasts in a region over the span of a day or might sequence different segments of a film into alternate storylines. In the commercial realm, these blocks could represent a market portfolio of stocks or commercial transportation assets (air, land, or sea).

The performance of the software using this approach exceeded initial expectations. The process developed Pareto optimal solution sets for 10,000 activities within 15 minutes. A dynamic re-planning test held most activities constant and forced 300 activities into adaptive rescheduling; the computation converged in 15 seconds. These initial tests of the SACA tool used a 1.5 GHz single-processor workstation running Linux. Retested on a 12-node cluster, the runtime for 10,000 actions dropped to under a minute.

Implications reach beyond the rapid production of activity schedules to the core processes for course-of-action development and decision analysis. SACA enabled dynamic synchronization for tactical actions. **Threaded synchronization** alone falls short of providing the same capability to leaders at operational and strategic levels. They need a viable process that enables coherent adaptation of the **action frames** – to sequence and shape subordinate actions and supporting plans and operations.

Operational Synchronization (OpSync) answers that requirement by incorporating threaded synchronization along its three axes and extending the dynamic to a fourth.

The **threaded synchronization** process produces a wealth of **action frames** that can be ordered, reordered, edited, cut, or augmented to concurrently evolve multiple options or approaches toward achieving strategic objectives and shifting end states. Combining and sequencing action frames on a storyboard will produce a series of alternative pathways. Each path embodies a coherent, feasible campaign plan with branches and junctions. However, simply having more alternatives does not provide adaptation if each path is rigid. Hence, branches in paths may spawn alternative paths; separate routes may merge to share a series of action frames before splitting apart again; and completely separate paths may use unique action frames. However, continuity is required; paths may change direction or terminate but discontinuous leaps between pathways cannot occur. The reason for this constraint ties back to the thread that provides resource, action, and intent traceability.

While this framework is new, the results are familiar. OpSync is a manifestation of an idealized wargame. For example, in the classic movie **"*WarGames*,"** [Badham, 1:46:25-1:48:59] the WOPR computer simultaneously constructs [in OpSync terms] multiple action frames along derivative paths to explore and evaluate alternative war scenarios and develop a winning strategy.

Derivative paths have a characteristic not immediately evident from these examples.

The various strategies represented by these paths need not be concurrent (synchronous in time) except (possibly) at junctions of two or more paths. As an example, one approach might embody mostly economic actions that lead to the goal over years while another military or diplomatic approach might reach the same goal in days. It should be evident that the concept permits the concurrent pursuit of multiple strategies in a single, coherent framework.

In summary, **operational synchronization** extends **threaded synchronization** to align activities concurrently along four axes:

- Vertical (motivation) – mission threads
- Horizontal (association) – mission sets
- Temporal-spatial (time & space) – action frames
- Derivative (alternate strategies) – ordered frames

4.0 Conceptual Applications

The SACA experiment developed a conceptual architecture to use the tool in a control system. Details are beyond the scope of this paper, but the collaborative structure and control feedback envisioned by that framework hold promise.

4.1 Modulated Self-Synchronization

In a push to empower users, a network of OpSync hubs could produce and transmit a global sync signal. Akin to the Global Positioning System signals or cellular networks, distributed users could receive wireless OpSync signals on a personal handset or **OpSync watch** – a logical extension of today's wristwatches [Clark]. These devices would provide time, location, orientation within current frames, and alignment on derivative paths. Armed with this data, users could conform their actions to an adaptive execution scheme AND input local status and intended actions for integration into OpSync action frames. In this vein, modulated self-synchronization is practicable.

4.2 Decision Support

Generally, people make decisions based on either instinctive analysis or structured analysis [Jones]. Instinctive decisions are marked by their rapidity and by identification and execution of a single satisfactory solution: "It's good enough!" The instinctive process works well when the problems are straightforward and immediate response is critical. This "single track" approach frequently leads to sub-optimal or partial solutions to complex problems or to even larger blunders [Horgan]. Structured analysis takes longer, but considers more factors and more options.

Structured analysis begins with the identification of the problem(s) and the major factors and issues: decision variables. Next, a divergent process, brainstorming, yields an array of possible solutions. Generally, as many as three "different" courses are considered. In practice, however, the differences between these courses may not be very great. Finally, a convergent process reduces the number to a single preferred solution. A structured process helps the mind cope with complexity.

"We settle for partial solutions because our minds simply can't digest or cope with all of the intricacies of complex problems …" [Jones, p xii-xiii]

OpSync is structured analysis on steroids. The four-axis structure identifies problems and decision variables being resolved. The genetic algorithm produces massive options in an unequalled, divergent process that then converges from millions of considered options to tens of non-dominated solutions. The final selection of the specific solution(s) resides with the operational decision maker, who is thus empowered to see multiple options within the context of operational level decision factors.

Liberated from the tyranny of building schedules, decision makers can refocus time and attention on higher-level decision factors that rightfully should dominate their thinking and shape the conflict space. By mapping decision attributes into multi-dimensional decisonscapes, the decision maker can see the topography of the complex environment. Using visual or analytic clues, a commander may be able to avoid cusps or boundaries where phase changes abound and chaos reigns. [Casti]

5.0 Mathematical Foundations

5.1 Current Constraints

Most synchronization techniques use one of three general approaches.

1. "Post and avoid" strategies dominate efforts to deconflict actions. For example, operators post actions on a sync matrix (or activity board) aligned within a desired timeframe and then manually check for conflicts. Planners avoid new conflicts as they add more actions. This method is "tried and true;" but it fails. It is slow (the process is labor intensive and cumbersome), constrained (produces only one option), fragile (cannot easily respond to changes in requirements or dynamic environments), and vulnerable (a limited failure can eliminate the node hosting the sync matrix).

2. Automated linear programs find favor in some areas since they reduce process times and produce the "optimum" solution. However, most operational schedules are not linear. For example, some material capabilities (i.e., sensors) may constrain actions to a defined period (i.e., daylight) that is cyclical vice linear. A few-minutes delay can mean failure while a delay of 20 hours may not have the same consequence. Linear arrays do not capture these realities. Other conditions can be more problematic.

3. A few "advanced tools" use non-linear gradient search techniques to optimize non-linear schedules. These search techniques use complex algorithms that posit solutions lie in a convex set. Operational experience, empirical evidence, and complexity science suggest that solutions may be in regions with sharp discontinuities and cusp geometries. [Casti, p59bis] Hence, the basic conditions required for the direct use of gradient search techniques are not satisfied.

5.2 Threaded Synchronization

Threaded synchronization uses approaches from three fields of study: network science, non-linear algorithms, and multi-player non-cooperative game theory.

Mission threads link objective (end state) nodes with activity nodes in a regular lattice structure (network). Objectives: (a) tie to multiple activities; (b) set constraints and bounds for supporting activities; and (c) allocate resources to supporting activities. Activities can link to and receive resource allocations from multiple objectives. Each activity must link to at least one objective. Intermediate layers in the lattice establish hubs and form the backbone of the network. Thus, mathematical models of networks provide a foundation for these mission threads and networked interactions support the required dynamic adaptation.

The non-linear search technique uses a constrained, sorting GA to construct, assess, and evolve feasible solutions. This approach makes no *a priori* assumptions about the shape of the solution space. Other search techniques may be feasible. Note that GA searches may not produce the same answers each time and may not "discover" the optimal solution (schedule), but in practice, the results are robust and responsive. Moreover, variation in answer sets should contribute to surprise and operational security.

Objective functions for the GAs stem from the linked objectives (end states) and not directly from the attributes of individual activities. Sets of all possible activity schedules thus constitute alternative strategies in a theoretical multi-player game with competing objectives being the "players." Thus, the dominant options found will approach the idealized points predicted by the Nash equilibrium [Kuhn].

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