# Communal Sensor Network for Adaptive Noise Reduction in Aircraft Engine Nacelles

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***Abstract*— Emergent behavior, a subject of much research in biology, sociology, and economics, is a foundational element of Complex Systems Science and is apropos in the design of sensor network systems. To demonstrate engineering for emergent behavior, a novel approach in the design of a sensor/actuator network is presented maintaining optimal noise attenuation as an adaptation to changing acoustic conditions. Rather than use the conventional approach where sensors are managed by a central controller, this new paradigm uses a biomimetic model where sensor/actuators cooperate as a community of autonomous organisms, sharing with neighbors to control impedance based on local information. From the combination of all individual actions, an optimal attenuation emerges for the global system.**

## I. INTRODUCTION

For centuries, emergent behavior has been observed in biological systems [1]. Observers have long marveled at the sophisticated organization and activity resulting in animal colonies from the interaction of thousands of relatively simple organisms (e.g., ants, bees, and termites). More recently, emergent behavior has been explored in sociological and economic systems. Although humans are highly cognitive compared with insects, they operate autonomously, cooperate with relatively few other people, and make decisions on a relatively small subset of total information, often subjectively. From the combination of all individual action, amazingly complex behavior emerges for the society (e.g., cities and stock markets). Although these complex systems are much researched, observations well documented, and theories postulated for how such complex behavior emerges from networks of simpler interacting agents, systems of electromechanical machines have yet to be designed demonstrating the sophistication of emergent behavior found in natural systems. What remains to be discovered are principles of *engineering for emergent behavior*.

Sensor networks represent and ideal architecture for emergent behavior. Current sensor/actuator *motes* (independent sensor/actuator devices) are by definition autonomous. They are distributed in an environment, can sense and/or act on the environment, have onboard computational capability with memory to make their own decisions, and communicate wirelessly only with other motes within a transmission range that is limited (i.e., a subset of the global community). As such, they are more analogous with organisms in an ecosystem than they are with computers connected in a network. By designing rules for behavior of individual motes, behavior that emerges from interaction of large numbers of motes may be directed: emergent behavior is engineered. The challenge is to engineer for *desired* emergent behavior while guaranteeing against *undesirable* behavior.

Towards that goal, a novel approach in design of a sensor/actuator network is presented maintaining optimal noise attenuation as an adaptation to changing acoustic conditions. Engine nacelles accomplish noise abatement typically with uniform liners comprised of large numbers of fixed impedance, homogeneous resonators compromised to provide acceptable noise attenuation throughout the flight regime. NASA has improved attenuation with heterogeneous resonators [2] and has developed adjustable resonators [3]. The challenge is to decide impedances to achieve optimal attenuation as acoustic conditions change. Rather than use a conventional approach where a central controller dictates impedances, this new paradigm uses a biomimetic model where sensor/actuators cooperate as autonomous organisms, sharing with neighbors to adjust impedance based local information. From the combination of actions of all sensor/actuators, an optimal attenuation emerges for the global system. This application serves as an example that organization and operation of sensor/actuator networks need not be limited to sensors and actuators acting as slaves to a central controller. Significant advantages can be attained, if the sensors and actuators function as autonomous entities, cooperating with others on relatively simple actions. From the combination of these actions, global behavior emerges. This eliminates single point of failure and facilitates robustness.

In Section II, emergent behavior is further defined providing direction in engineering for emergent behavior. In

Section III, current technology for noise reduction in aircraft engine nacelles is described and a system for noise abatement using a community of autonomous, yet cooperating sensor/actuators that are designed for desired emergent behavior is described. Space limitation prevents providing all details of the simulation of this system. The goal is to provide enough detail to demonstrate that system behavior emerges from the interaction of individual motes in adaptation to changing environment conditions. Section IV provides conclusions.

## II. ENGINEERING FOR EMERGENT BEHAVIOR

In Biology, an organism is an autonomous living entity. Organisms are autonomous in that they make their own decisions about interactions with their environment. However, they are not independent as they cooperate with other organisms. An ecosystem is defined as a community, a collection of organisms, interacting with one another and their environment and interconnected by an ongoing flow of material and information exchange. Organisms react to and operate on the environment autonomously and asynchronously, yet they can cooperate with local neighboring organisms. The amount of, sophistication of, and motivation for cooperation varies immensely from simple unicellular organisms up through multicellular organisms to populations that form great societies.

Organisms may simplistically be modeled as finite state machines whose genetic material defines an initial state and rules for interaction with other organisms and the environment. State conditions and/or the rules may or may not change as the organism interacts with the environment and neighboring organisms. An organism may "learn" by remembering its interaction with the environment in a local memory. This learning implies some level of cognitive capability.

Biological ecosystems provide excellent examples of how global behavior of a large, complex community can emerge from the combined behavior of individual community members. It is important to note that the behavior of individuals occurs without those individuals knowing all information available within the community and the individuals may not be aware of any goal of the community or the resulting global behavior. That is, there is no central control of individual behavior and there may not be any global awareness on the part of the individual.

Cognitive science, the interdisciplinary study of mind, intelligence and behavior, has lately recognized the importance of interaction with the environment and behavior emerging from the combined interactions of component subsystems. Pfeifer and Scheier [4] promote a new model of learning they call, *embodied cognitive science* where behavior emerges from the interaction of an organism with its environment. There is general agreement among biologists and researchers of complex systems in the concept of emergent behavior: that in complex systems, global behavior of a system results, or emerges, from evolution and interaction of their constituent parts. The behavior of an individual, driven by feedback from the local environment and interactions with numbers of other individuals, produce a system-wide behavior not predictable from the individual behaviors.

The rule sets by which individuals operate in an emergent system may be viewed on a continuum of increasing cognition. On the lower end of the continuum are *automated* individuals: they operate by a fixed rule set that cannot change and therefore, cannot adapt to unforeseen environmental conditions. On the high end of the continuum are highly cognitive individuals that, through perception, memory, learning, and reasoning, are able to modify innate rules and create new rules of operation in response to changing environmental stimuli. In the progression up the continuum, adaptability improves with increasing ability to adjust rules and create new rules of behavior.

The magic of emergent systems is that high levels of cognition in individuals are not required to produce apparent intelligence in the global community. Social homeostasis [5], hive-minds [6], swarming and similar behavior associated with large communities of social insects share a common thread: the intelligence that these behaviors seem to exhibit is not the result of a cognitive process within individual members of the community. The intelligence of the swarm emerges from the interactions of many thousands of autonomous individuals. Each individual follows its own set of rules and reacts to local state information. Individuals are connected within their immediate neighborhood and share information, but they do not have a central controller with which to communicate.

Although there is agreement on what emergent behavior is, there are significant differences in opinions on how to engineer complex systems for desirable emergent behavior. Behavior will emerge when massive numbers of agents are released to follow simple rules, regardless of how the rules are formulated. But the debate is on how to develop interactions among components to produce desirable behavior from complex systems. How can a designer anticipate, predict, and control emergent behavior? That is, how does one *engineer* for emergent behavior.

Most research in embodied cognitive science and emergent behavior is related to intelligence in robotics and autonomous systems. Sensor network research is, for the most part, ignoring the application of this research, choosing rather to treat sensor networks as conventional computer networks with special constraints. However, sensor networks, with massive numbers of autonomous components interacting directly with their environment and confined to direct communication only with neighbors, is a powerful application that can benefit from the concepts of embodied cognitive science and emergent behavior. In the following section, such an application is described.

## III. A COMMUNAL SYSTEM FOR NOISE REDUCTION

Aircraft engine nacelles accomplish noise abatement through a liner in the nacelle comprised of a massive number of Helmholtz resonators [7]. Typically, the liner is *uniform* with all resonators of fixed and homogeneous impedance. The impedance is designed as a compromise to provide tolerable noise attenuation throughout the flight regime (e.g., take off, cruise, and landing). NASA has proven that a liner comprised of patches of resonators, differing in impedance, can achieve better attenuation than any uniform liner [2]. An adjustable resonator has been designed that can change its impedance and, thus, its ability to abate sound [3]. A liner designed with patches of adjustable impedance can be adapted to optimal attenuation as acoustic conditions change. The challenge is how to determine the correct impedance for each patch to attain optimal attenuation. A conventional approach is to predetermine impedance values for anticipated acoustic conditions in each of the different conditions of the flight regime and have these values dictated to actuators by a central controller as the flight progresses. An alternate approach described below has the sensor/actuators determine impedance from local conditions, cooperate with neighbors, and adjust impedances for all patches adapting for exact conditions *in situ* and without a central controller. This eliminates the single point of failure of the central controller while providing a more accurate response to changing conditions.

In simulation, a liner is divided into 16 axial patches on one side of a rectangular duct (Fig. 1 and top of Fig. 2), each which can be adjusted to an impedance value. Impedance is represented as an imaginary number, comprised of resistance ($R_s$) and reactance ($R_a$). Patches are adjusted to an impedance value from a domain of possible values (depicted in Fig. 3). Initially, all patches are adjusted to an impedance value (e.g., $R_s$ = 0.6, $R_a$ = -0.8). Patch, $P_0$, as the initial *leader* patch coordinates with $P_{15}$ to determine the local pressure for this impedance. In turn, it adjusts its impedance to each of the 8 neighboring values of the domain (depicted in gray in Fig. 3), instructs all other patches to adjust to this value, and reassesses local pressure. From these assessments, it selects the impedance producing the optimal pressure and communicates this value to be set by all other patches. This impedance becomes the center of a new neighborhood of the impedance domain. It repeats this process until its impedance is optimal among the neighborhood of values in the domain. At optimal impedance, $P_0$ freezes at this impedance and renders leadership to $P_1$ to repeat this process. When all segments have frozen, optimal attenuation is achieved with impedances as depicted in Fig. 2. Fig. 4 plots this repetitive process as attenuation increases from initial to optimal attenuation, exceeding the best uniform liner early in the adaptation and far exceeding it before completion.

When $P_0$ freezes at impedance 1 ($R_s$ = 1.3, $R_a$ = -1.1 – see Fig. 2) and sets all other patches to this impedance, the liner attains the best attenuation for a uniform liner. But it then renders leadership to $P_1$. As $P_1$ freezes at impedance 2 ($R_s$ = 1.3, $R_a$ = -1.3) and sets all patches except the frozen patch, $P_0$, to this impedance, global attenuation surpasses that of the best uniform liner. As leadership is passed and the process continues, attenuation continues to improve. While it is possible that an acoustics designer could derive the final configuration depicted in Fig. 2., the sensor network determines this arrangement by applying simple rules in the presence of changing environmental stimuli: optimal global attenuation emerges from individual action and cooperation.

Fig. 5 depicts adaptation to 4 frequencies that achieves optimal attenuation for each frequency as the patches adjust impedance. In each case, attenuation initially drops as the frequency changes. The optimal liner for the previous frequency is not optimal for the current frequency but quickly, the liner adjusts to an attenuation much better than that attainable from the best uniform liner.

What is significant is that this method achieves optimal attenuation by cooperation of autonomous sensor/actuator systems using only local information with no central controller. While information is shared among patches, no patch knows global information (e.g., global attenuation or pressure at all patches). All decisions are made on the basis of local observations and information obtained from a small subset of others. No patch understands the goal of optimal attenuation or monitors its progress as adaptation proceeds. The patches simply follow their rule set in response to environmental stimuli.

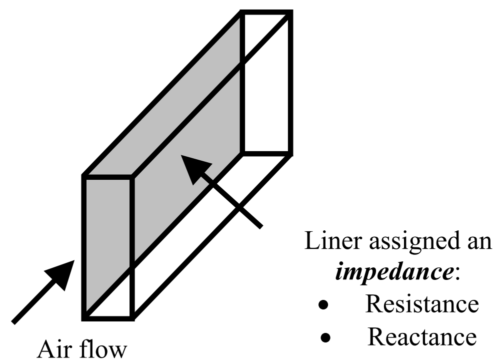


Figure 1. Rectangular duct for simulation, 15” x 6”

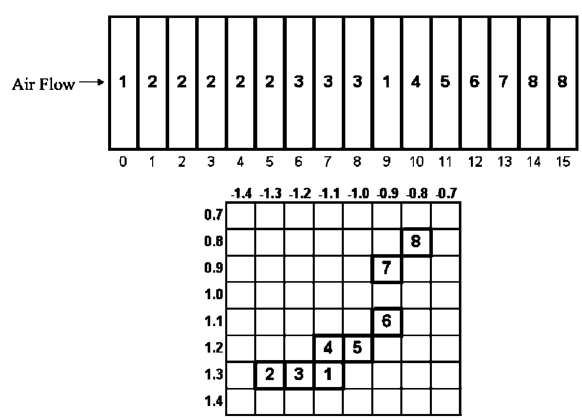


Figure 2. Optimal Segmented Liner for 1500 Hz

| Rs \ Ra | -1 | -0.9 | -0.8 | -0.7 | -0.6 |
|---|---|---|---|---|---|
| 0.5 | 10.96 | 11.54 | 11.86 | 11.83 | 11.38 |
| 0.6 | 13.65 | 14.56 | 15.17 | 15.21 | 14.52 |
| 0.7 | 16.44 | 17.87 | 19.06 | 19.43 | 18.24 |
| 0.8 | 36.00 | 41.96 | 23.66 | 25.73 | 22.74 |
| 0.9 | 33.75 | 39.52 | 42.70 | 33.54 | 25.50 |
| 1 | 30.13 | 32.69 | 32.90 | 29.39 | 24.77 |
| 1.1 | 26.62 | 27.76 | 27.55 | 25.71 | 22.98 |
| 1.2 | 23.70 | 24.27 | 24.01 | 22.87 | 21.11 |
| 1.3 | 21.34 | 21.65 | 21.42 | 20.63 | 19.42 |

Figure 3. Impedance domain

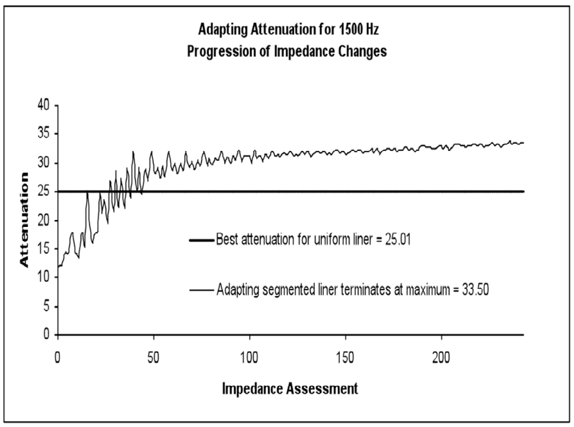


Figure 4. Adapting Attenuation for 1500 Hz

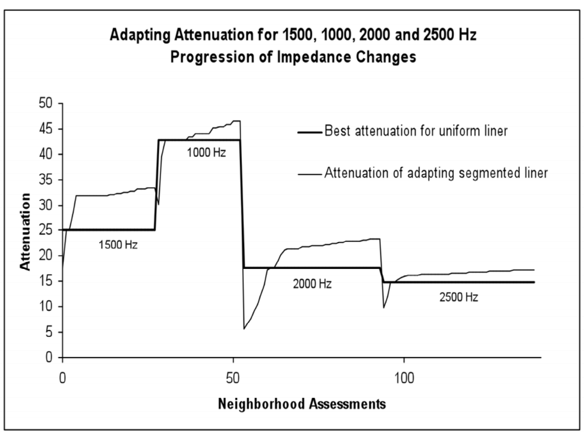


Figure 5. Adapting Attenuation for 1500, 1000, 2000, and 2500 Hz

## IV. Conclusions

Since their inception, sensor networks have been designed as computer networks with motes viewed as computers connected with other computers passing data among nodes. Most architectures are designed from a *sense and send* model: sensor motes function only to acquire data from the environment and periodically send that data via a network to a central controller where all decisions are made. Herein, the concept is presented, that a better architectural paradigm is modeled after a biological ecosystem where sensor/actuator motes exist as organisms, autonomously interacting with the environment and each other. Motes make local observations, share these with a subset of neighboring motes, make autonomous decisions, and take local actions. No mote knows all global knowledge and there is no central controller. From the combination of these individual actions, global behavior of the system emerges. The challenge is to design individual behavior such that only desired global behavior emerges.

Such an architecture is presented for noise reduction in aircraft engine nacelles. Sensor/actuators are arranged in patches on the liner. Motes sense local acoustic conditions and communicate this information to a subset of neighbors. Local decisions are made and communicated to a subset of neighbors. No mote knows global conditions or global goals and no central controller exists. From the combination of these local observations, decisions, and actions, optimal global behavior emerges. While decisions are not cognitive, the system goes well beyond an automated system as it is adapting to changes in the environment that are not and need not be predetermined. Thus, the system is engineered for desired emergent behavior.

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