Chapter 1

INTRODUCTION

There is notably a growing interest in System of Systems (SoS) concepts and strategies. The performance optimization among groups of heterogeneous systems to realize a common goal has become the focus of various application areas including military, security, aerospace, and disaster management. There is particular interest in achieving synergy between these independent systems to enable the desired overall system performance. In the literature, researchers have begun to address the issue of coordination and interoperability in a SoS pointing to the emergence of the concept of system of systems engineering (SoSE). SoSE presents new challenges that are related to, but distinct from, systems engineering (SE) challenges. By understanding these differences, appropriate methods, tools, and standards, a SoSE approach may be crafted in an intelligent manner to architect and control seemingly amorphous systems.

1.1 Introduction and Overview

The engineering and control of emergent capabilities of large complex systems comprised of numerous seemingly unplanned contributing systems has been an unattainable goal of technologists and social infrastructure planners. Similarly described as an "invisible hand" in the published work of the Scottish philosopher Adam Smith in Book IV of the "Wealth of Nations" whereby economic processes, acting as individual agents to maximize their own well being, affect other processes without due intent (Smith, 1776). The invisible hand metaphor is intended to explain that actions have unintended consequences, are not controlled by a central command authority, and have an observable and patterned effect on the process and systems. The cooperative systems' architecture, design, and control are characterized by a set of interconnected systems with a common goal. The real-time cooperative control is not well understood let alone intentionally designed (Cloutier, DiMario, & Polzer, 2009; Tien, 2009). To possess the methodology to direct and control similar examples such as the U.S. health care system, world political systems, the effects of an economic recession, and a global shipping system is a study of complex systems.

Many complex systems are a SoS that comprise numerous constituent interdependent systems and have been described as an integration of complex metasystems — defined as a group of systems that have an interrelationship (Keating *et al.*, 2003). This system description supposes that the systems are autonomous and heterogeneous forming partnerships whereby their interoperability relationship produces capabilities or unintended consequences because of emergent behavior. The emergent behavior does not originate from any single individual constituent system nor deduced by properties of the collective constituent systems. The interoperability relationships of the constituent systems create new behaviors of the holistic system.

General Systems Theory (GST) introduces the holistic concept of systems as a science of wholeness whereby there are general systems laws, which apply to any system of a certain type independent of its properties, classified as summative and constitutive. The summative system owes its capabilities to the summation of the characteristics and sub capabilities of its elements. The properties of the elements are universally the same in all environments and have no relationships. The constitutive system has capabilities that are greater than the summation of its elements because the effects are dependent upon the context of their properties and their relationships (Bertalanffy, 1969). Kenneth Boulding a general systems theorist, described this concept as a SoS which may perform the function of a *gestalt*, which is a pattern so unified as a whole that its properties cannot be derived from its parts (Boulding, 1956).

This thesis discusses a constitutive SoS framework in regard to new behaviors that emerge as a result of a mechanism of collaboration that is architected to affect a holistic capability. The management and design of SoS architectures are of great interest as individual systems become ever more interoperable with other systems (U.S. Department of Defense, 2008). The ability to design and control a SoS architecture to elicit capabilities not germane to any one individual system becomes paramount (DiMario, Cloutier, & Verma, 2008). SoS architecture management and development of such structures, as well as the discipline of SoS, is of great interest with many avenues to explore as well as its foundational engineering science discussed further in Appendix C (DeLaurentis *et al.*, 2007).

1.2 Problem Statement and Research Hypothesis

A description of an approach of a mechanism framework whereby the paradox of autonomous and yet cooperative systems may be architected to elicit SoS capabilities is lacking. A methodology and framework to architect systems that may influence other systems in collaboration is absent in the systems literature as well as literature in support of systems that naturally interoperate but were not presciently designed to do so. The research hypothesis is a system of systems (an SoS), as distinct from a system of parts, is a system comprised of pre-existing autonomous systems that choose to belong to the dynamically forming SoS, and interoperate together in spite of their evident diversity, is a result of changes in the autonomous systems' environment or their own utility resulting in capabilities of the SoS not presciently designed.

1.3 Research Objectives

The research objectives are to describe the influence of SoS characteristics that demarcate a class of systems defined as constituent — design-time SoS, and run-time SoS. This includes a description of how constituent systems may cooperate through the characteristic of belonging creating value of the SoS as a constitutive mechanism. This is done via design rules or a social function that balances the SoS characteristics of autonomy and belonging. SoS run-time and design-time are uniquely assembled by interoperability at various levels and define system's belonging.

1.4 Uniqueness of this Research

This research addresses the autonomy of systems, managed independently, to make independent choices of collaboration. However, the SoS cannot exist physically if not for constituent systems agreeing to be "integrated" and having a sense of belonging. For an SoS, the hypothesis of this thesis is a mechanism that allows systems to be integrated at a holistic level that are either designed, referred to as design-time, or occur naturally via self-organization and referred to as run-time. Examples are:

- Al-Qaeda: Run-time SoS;
- Health care: Run-time SoS;
- USN Battle Group: Design-time and run-time SoS;
- National Transportation: Run-time SoS;

- Coast Guard Deepwater Program: Design-time SoS at end of the program or T_0; Expected run-time at later epochs or T_1.

The constitutive mechanism defines the levels of belonging as a design for influence approach defines the design rules or rules naturally evolve as an "invisible hand" or amorphous via self-organization.

1.5 Dissertation Organization and Structure

This chapter provides an introduction and context for this research. Chapter two highlights the relevant literature of SoS and an esemplastic, a union of ideas giving way to new concepts, approach to the problems presented. Chapter three discusses the research approach. Chapter four discusses the results of the research and findings. Chapter five discusses the validation of the research as a case study approach of low-constraint methods and the case study data. Chapter six highlights the research conclusions and next logical research steps. The remainder of the dissertation consists of appendices of published or to be published papers, additional research supporting material, and dissertation references.