Summary: The brief review of the state of the art of System of Systems (SoS) concept application is presented, based on selected published papers and collected information about running and past research projects. First various applications of the SoS concept are presented focused on applications in aeronautics. Based on the open source literature review, the definition of SoS is formulated, underlining the differences between the Large Scale Systems (LSS) and the SoS concept. Next the short review of the methods used in SoS optimization is presented. The review of applications and mathematical / numerical methods formed a background for formulating SoS architecture for the search and rescue mission performed by a group of UAVs.

**Keywords:** System of System, optimization, aeronautics

1. INTRODUCTION

Nowadays progress in computer technology allows to model and to analyze effectively very complex systems for optimization performance and/or specialized missions. As a result it is possible to formulate more stringent requirements for large, complex systems, which components (subsystems) have already been optimized for their individual qualities. These led to a concept of System of Systems, in which the individual systems are embedded. The SoS concept recently drew attention of many researchers in various fields of science and technology, due to its generality and applicability. The main driving factor for concept investigation and development is an increasing computation ability of affordable hardware, which allows to solve in a reasonable time very complex numerical tasks for simulation or performance optimization. It is possible to approach complex problems in a more comprehensive way, which in term leads to increasing complexity of the models used. The integration of multiobject systems, which are composed of many independently operated subsystems, complicates their analysis. It is intuitively clear that a special numerical approach is needed to analyze the SoS at the global level, due to the fact that optimization done for each of subsystems separately may not result in optimality of their collaboration.
The paper summarizes briefly the results of preliminary studies of performance of SoS composed of Unmanned Aerial Vehicles (UAVs) collaborating for various tasks. The available literature was analyzed to elaborate definition of SoS adequate to the selected case of application. Methods applied in similar cases were identified and solutions in aeronautic were reviewed to formulate mission, to be studied and methods to be used in the project.

2. CONCEPT APPLICATION

The System of System approach is applied in various fields of science and technology like military, security, aerospace, manufacturing, transport, environment systems, and disaster management. In the next chapter, selected application SoS concept is presented, focused on aeronautics.

2.1. SPACE, MILITARY AND RESCUE

The SoS application in space and military operations including Search & Rescue (S&R) missions.

In paper [Jamshidi M.] (Global Earth Observation System of Systems) the objective of the research was to respond the need for timely, quality, long-term, global information required for decision making. The objective was to exchange data from observations recorded by aircraft and satellite networks with minimum time delay and cost.

In paper [Barritt B., Bhasin K.] network architecture of space communication and navigation services was investigated for future space exploration missions. New techniques of defining and analyzing network architectures were developed to improve accessibility, flexibility, and interoperability. It allowed to facilitate high-level decision-making, reduce costs and increase reliability.

In [Hayden J., Jeffries A.] a flexible Joint Polar Satellite System (JPSS) was developed performing telemetry, tracking & command (TT&C), data acquisition, routing and data processing services for a variable fleet of satellites to support weather prediction and climate modeling.

In [Nanayakkara T., Jamshidi M.] a system for Future Combat Missions (FCM) was developed to improve national security. The research objective was to provide a system of manned and unmanned combat systems. This Future Force system should be strategically responsive and dominant within wide spectrum of operations from nonlethal activity to full-scale conflict participation. Applying SoS approach resulted in “significant capability enhancements; allowing for multiple state-of-the-art technology options for mission tailoring and performance enhancements; development of a common, relevant operating picture and achievement of battle space situational understanding.”

In [fig. 1] from [Bociaga Michael L., Crossley W.] results of US Coast Guard Integrated Deepwater System Program are illustrated. The objective of the research was to take
advantage of all the necessary assets at disposal (helicopters, aircrafts, cutters, satellite (GPS), ground stations, people, computers, etc.) integrated together to react unforeseen circumstances to secure the coastal borders of the south-eastern United States. The result of applying SoS approach allowed to improve the operational capabilities of legacy cutters and aircraft; ability to interoperate among all Coast Guard mission assets.

Fig. 1. Example of SoS application

2.2. AERONAUTICS, UAV

The objective of the research presented in [DeLaurentis D., Crossley W.] was to create concurrent aircraft design and resource allocation in a new aircraft being designed (‘yet-to-be designed aircraft’) for airline operations. The main task of the project was “to determine the characteristics of a new aircraft for allocation along with an airline existing fleet to meet passenger demand”. The slight different task was "to determine the characteristics of a new aircraft for allocation, when the demand is uncertain and it is expressed as a probability distribution of trips between city pairs.” Applying SoS approach resulted in “an aircraft design that directly impacted costs related to the FMC (Fractional Management Company) operations and identification of operational changes to take advantage of the new aircraft characteristics.”

In Air Traffic System-of-Systems investigated in [Conway S.] the objective was to: improve the aviation infrastructure in order to increase its capacity and flexibility. In [Mane M., Crossley W.] the objective was to allocate existing and yet-to-be designed systems to provide an operational capability. Optimization methods were applied to reduce the costs of operating fleet and to meet the passenger demands, which resulted in the improvement of global system-of-systems performance.

In research presented in [Nanayakkara T., Jamshidi M.] the objective was to develop a strategy and a technical architecture to facilitate making the airplane (Boeing 787)
manufacturing network-aware and capable of leveraging computing and network advances. As a result of applying SoS approach the costs of production, operations, and maintenance for both Boeing and the airline customers were reduced.

In [Francis M. S.] the Unmanned Combat Air System (UCAS) was investigated to create an efficient, flexible and affordable system of unmanned aerial vehicles capable of performing different mission scenarios assuming mutual communication between unmanned aircrafts (fix- and rotary-wing), satellites and ground stations. Application of SoS approach resulted in shared situation awareness due to sensor data exchange between system members, offering comprehensive image of the battlefield to the ground operator, which may be beneficial in the decision making process.

The results of research cited above prove benefits of SoS concept application.

3. SYSTEM OF SYSTEMS DEFINITION

A SoS concept is a relatively new approach to solving existing and emerging problems of many collaborating subsystems. Due to various fields and objectives of applications, there is no commonly accepted "definition" of SoS. Various researchers emphasize different features, as particular to SoS. In this chapter an attempt was undertaken to construct the definition suitable for further research area of the project using literature references. The reviewed definitions were divided into two categories. The first group of the references stresses only the general system features, and the second one is more detailed.

3.1. STRUCTURE OF SYSTEM

In this chapter the general approach to SoS concept definition is reviewed.

What all definitions have in common is that SoS consists of many elements (subsystems) collaborating / interacting to gain new capabilities. The subsystems are considered as operating independently. Comparing to Large Scale Systems (LSS) analysis SoS approach seeks synergy effect of systems interactions [Nanayakkara T., Jamshidi M.]. The SoS appears [DeLaurentis] when a set of sub-systems cooperates to achieve new functionalities. Constituent sub-systems possess various, different features, but collaborating may perform tasks that are unavailable by each individual.

According to [DoD, Mayers] is a “A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities”. Similar definition is presented in [Sobieszczanski-Sobieski]: “An assemblage of interacting components, the components themselves exhibiting the internal structure of interacting elements”. In [Taylor] “Systems of systems are collections of systems (such as air vehicles) that can operate independently, but deliver more value when designed and operated as a coordinated ensemble”. These definitions are in line with [Baldwin] “a set or arrangement of systems that results when independent and useful systems are integrated
into a larger system that delivers unique capabilities”. Similar definition is presented in [Mane]: “[...] “system-of-systems” describes a large system of multiple systems, each capable of independent operation, which have been brought together to provide capabilities beyond those of each individual constituent system.” and in [Stanley]: “System-of-systems is a pervasive concept within the Sensor Webs paradigm. Elements can be bound together for the benefit of another, more overarching system. Each system has a particular task, or set of tasks, that it can perform. By combining the outputs or results from several systems, new products can be derived.”

The most important characteristic feature stemming from many approaches is that system composed of many systems provides new capabilities and functionalities [Mayers], not achievable individually. The range, efficiency and operability of SoS is higher than individual systems, and this result cannot be achieved simply by connecting subsystems together.

### 3.2. SoS AS SET OF FEATURES

In some definitions a typical features of SoS are stated explicitly. According to [Sage and Cuppan] “SoS exist when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behavior, and evolutionary development”. Similar approach is presented in [Pei] “SoS integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios.”

Principal characteristics that make the system family designation appropriate [Nanayakkara T., Jamshidi M] are:

- operational independence of the individual systems;
- managerial independence of the systems;
- often large geographic and temporal distribution of the individual systems;
- emergent behavior, in which the system family performs functions and carries out purposes that do not reside uniquely in any of the constituent systems. It may evolve over time in an adaptive manner. In [Meyers C., Smith J. D, Capell P, Place P] again operational independence of the systems, managerial independence of the systems, evolutionary development and emergent behavior are pointed out.

Some Authors [Manthorpe Jr W.H] consider as the most important feature of the SoS is interoperability and ability of cooperation. In [DoD]: “The ability of systems to provide data, information, materiel, and services to, and accept the same from, other systems and to use the data, information, material and services so exchanged to enable them to operate effectively together.” The same feature is indicated in [Jamshidi] “Systems of systems are large-scale integrated systems which are heterogeneous and independently operable on their own, but are networked together for a common goal to enhance the overall robustness, lower the cost of operation, and increase the reliability of the overall complex (SoS) system.”

Because the constituent systems are capable of independent operation, they can not only cooperate but also compete for subtasks within the system. The SoS is a dynamic entity as new systems are added and current systems are replaced or removed [Crossley W.A.].
3.3. DEFINITION SUMMARY

To summarize the main features, the SoS consists of a number of independently – operating subsystems and provides new functionalities and capabilities. As a result of operation it generates values and qualities that are unachievable by subsystems operating independently, without cooperation. The comprehensive definition was proposed by [Crossley W.A and Nanayakkara T., Jamshidi M] “The emerging system of systems context arises when a need or set of needs are met with a mix of multiple systems, each of which are capable of independent operation but must interact with each other in order to fulfill the global mission or missions. The mix of systems may include existing and yet-to-be-designed aircraft, satellites, ground vehicles, ground equipment, and other independent systems”.

4. OPTIMIZATION METHODS

Optimization is a key for improving operations of complex systems. In all optimization methods the common feature is an optimized cost function (quality index) concept. Applications differ by objective (cost) functions formulations and decision variables changed to obtain cost function extremum.

It is intuitively clear that for particular cost function, the optimization methods should be properly adjusted to obtain effective solution. Each of the mathematical method / algorithm has also various limitations, which are the main criterions in the selection of the best method for considered problems. The modeling and solutions depend on the complexity of the problem to be solved. In a case of need various methods can be combined, for instance less numerical expensive algorithms for solution prediction and more powerful for subsequent and more detailed computation. The short literature review below enumerates some commonly used well established methods (tab. 1), as well as a new ones and their main features as given in literature.

<table>
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<tr>
<th>№</th>
<th>Method name</th>
<th>Disadvantages</th>
<th>Ref.</th>
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| 1  | Linear Programming   | • Absence of risk assessment (assumption that expectations adequately capture risk)  
• Restriction to linear objective functions  
• Appropriate reduction of the world to a set of linear equations is usually very difficult | Belegundu D., Tirupathi R. |
| 2  | Non linear Programming | • Most algorithms cannot guarantee convergence to the global minimum.  
• Limited applicability – developed only for some particular sort of problems.  
• General-purpose software is less effective because the nonlinear paradigm encompasses a wide range of problems with a great number of potential pathologies and eccentricities.  
• Some of the codes treat the derivative matrices as dense, which means that the maximum dimension of the problems they can handle is somewhat limited. | Bradley S., Hax A |
| 3 | Gradient | • Do not handle non-differentiable problems.  
• Often slow and very dependent on scaling.  
• If the objective function or the constraint functions are numerically noisy can be inaccurate. | Alison |
|---|---|---|---|
| 4 | Gradient free | • Excessive function evaluation requirements.  
• Lack of optimality conditions - except in special cases, a solution cannot be proven to be an optimum when a gradient free algorithm is employed | Alison |
| 5 | Probabilistic approach | • Computational inefficiency – probabilistic algorithms are inherently less efficient than non-probabilistic ones, due to the fact that they consider entire probability densities  
• Necessity of approximation – arises from the fact that most robot worlds are continuous. Computing exact posterior distributions is typically infeasible, since distributions over the continuum possess infinitely many dimensions | Thrun S., Burgard W |
| 6 | Neural Network | • The neural network needs training to operate.  
• The architecture of a neural network is different from the architecture of microprocessors therefore needs to be emulated.  
• Requires high processing time for large neural networks.  
• Neural networks cannot be retrained | Nanayakkara T., Jamshidi M. |
| 7 | Evolutionary Algorithms | • No guarantee for finding optimal solutions in a finite amount of time (however, asymptotic convergence proofs are available).  
• Parameter tuning mostly by trial-and-error (self-adaptation as a remedy).  
• Population approach may be expensive (parallel implementation as a remedy). | Narzisi G. |
| 8 | Fuzzy Logic | • Formulation of the task can be very tedious  
• Membership functions can be difficult to find  
• Multiple ways for combining evidence  
• Problems with long inference chains  
• Inefficiency for complex tasks  
• There are many ways of interpreting fuzzy rules, combining the Fuzzy Logic, Sets and Systems outputs of several fuzzy rules and defuzzifying the output | Nanayakkara T., Jamshidi M. |
| 9 | Swarm algorithms | • Simple rules do not always lead to complex structures.  
• Non-optimal – they are redundant and have no central control, so that swarm systems are inefficient.  
• Non-controllable – guiding a swarm system can only be done as a shepherd would drive a herd  
• Non-immediate – simple collective systems can be awakened simply, but complex swarm systems with rich hierarchies take time to boot up | Ahmed H., Glasgow J. |
| 10 | Multi-objective Optimization | • For mixed optimization problems (min-max), it is necessary to convert all the objectives into one type.  
• Uniformly distributed set of weights does not guarantee a uniformly distributed set of Pareto-optimal solutions.  
• Two different set of weight vectors not necessarily lead to two different Pareto-optimal solutions.  
• There may exists multiple minimum solutions for a specific weight vector that represents different solutions in the Pareto-optimal front (wasting the search effort).  
• The solution to the problem largely depends on the selection of the \( c \) vector. In particular, it must be chosen such that it lies between the minimum and maximum value of each objective function  
• As the number of objectives increase more information from the user is required | Alison, Narzisi G. |
Heuristic optimization methods

- Rely on experimental data or empirical models with no or weak foundation in theory
- may take more serial CPU time and give a less accurate answer for problems that satisfy the assumptions of other algorithms
- Although aiming at high quality solution, they cannot pretend to produce the exact solution in every case with certainty

Maringer D.

5. SoS AT WUT

Presented literature review was done to form the background for “System of Systems Force Structure Research” project performed at Warsaw University of Technology. The next step will be formulation of the problem and method selection for SoS analysis.

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**PRZEGŁĄD ZAGADNIEŃ SYSTEMU SYSTEMÓW I ICH ZASTOSOWAŃ W LOTNICTWIE**


**Słowa kluczowe:** System systemów, optymalizacja, lotnictwo