The Open Cybernetics & Systemics Journal

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The Open Cybernetics & Systemics Journal, Volume 9, 2015

ISSN: 1874-110X
DOI: 10.2174/1874110X20150610E006

Article Type: Research Article

Received: April 17, 2015
Revised: April 22, 2015
Accepted: April 27, 2015

Provisional PDF Publication Date: June 10, 2015

Analyzing Ballistic Missile Defense System Effectiveness Based on Functional Dependency Network Analysis

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Abstract: Recent engineering experiences highlight the Ballistic Missile Defense System (BMDS) as a System of Systems (SoS), and traditional probability models were limited in capturing the complex interactions between component systems. A novel approach was proposed to evaluate the effectiveness of the whole BMDS from the aspect of functional interactions, rather than the functions of components. First, Functional Dependency Network Analysis (FDNA) was introduced to build the analysis model through integrating the component systems in multi-layered kill chains of BMDS. The key metrics were proposed to measure the effectiveness from both probability of raid annihilation and system response time. Finally, the application of this method was demonstrated through a case study, and the result shown the holistic characters of BMDS at SoS level. The case shown that FDNA was a promising way to analyze SoS at high level.

Keywords: Functional dependency network analysis, Ballistic Missile Defense System, Effectiveness analysis, System of systems.

1. INTRODUCTION

Ballistic Missile Defense System (BMDS) being developed, tested and deployed by the United States provides initial capability to counter ballistic missiles in multi-layers, other countries(e.g., Russian and China) also achieve great progress in missile defense capability.

Traditionally, the effectiveness analysis of BMDS was based on the simplified probability models of both intercept missiles and support sensors [1-3]. With continued attention to architecture integration of sensors with shooters, specifically to implement launch-on-remote (LOR) and engage-on-remote (EOR) firing doctrines [4], recent engineering experiences focus on the numerous interactions between component systems of the BMDS in the view of system of systems(SoS) [5,6].

The most critical interactions in SoS are functional dependencies between component systems, as the mission of SoS is completed by the whole not a single or several component systems, that functional dependencies integrate the components as a whole. Therefore, it is necessary to evaluate the effectiveness of BMDS from the aspect of functional dependencies.

To assess the effectiveness of BMDS at the level of SoS, we built the functional dependency network (FDN) of BMDS through integrating the kill chains in the multi-layered defense system, and make the metrics to assess and measure the effectiveness of BMDS.

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The paper is organized as follows: in section 2, we review the current practice in the effectiveness analysis of BMDS. In Sections 3, functional dependency analysis model of BMDS is proposed. In section 4, a case study is presented to show how the outputs of the method can be used to quantify metrics of effectiveness in BMDS. In section 5, we draw the conclusions and give recommendations for applications and future work.

2. RELATED WORK

2.1 BMDS Overview

The BMDS consists of a network of satellites, radars, Aegis ships, missile launchers and missiles, and provides intercepting capabilities in three phases of flight: boost phase, midcourse phase, and terminal phase, that performances multi-layered missile defense [4]. Whereas the currently deployed BMDS performs missile defense with elements acting independently, the next generation BMDS focuses on the capability of distributed engagements: EOR and LOR [4]. LOR concept, the missile launching ship receives sensor input from off-board sensors (for example, land-based AN/TPY-2 radar) of sufficient quality to launch an interceptor and does not need to acquire the target track on its on-board sensors at the time of launch. EOR is an extension of LOR, that the interceptor can be launched using any available target track and engagement is controlled from in-flight target updates that can be provided to the interceptor missile from any Aegis AN/SPY-1 or AN/TYP-2 radar [5].

2.2 BMDS Effectiveness Analysis

Probabilistic model is widely applied in the analysis the effectiveness of BMDS from the aspects of configuration and doctrine [3]. Menq introduced a discrete time Markov process model to multi-layered BMD system [1]. Wilkening proposed a simple Bernoulli trials model to determine the size of required BMDS [2]. The effectiveness of BMDS was presented by the probability distribution of the number of penetrating warheads, and optimal fire doctrines were proposed based on these models. Probabilistic model focused on the capability of interceptor, however, the support systems (e.g. radar sensors, communications networks) were ignored or simplified, and failed to capture the internal dependency between component systems.

Due to the complexity of BMDS, system of systems engineering is applied to study the effectiveness [6]. Tommer built surrogate models of components in BMDS, and provided an M&S environment for real-time, high-level BMDS architecture trade studies at the SoS level [7]. Garrett proposed a SoS framework to managing the interstitials, in which Graph Theory was applied to analysis information flowing between component systems [5]. Agent Based Modeling (ABM) was proposed to as a technique to explore and quantify the interstitial behaviors [8]. Most of system of systems engineering adopted M&S approach to model the complex interactions and focused on high-fidelity component models. However, interaction as a key factor to form SoS capability was not studied independently at high level.

3. FUNCTIONAL DEPENDENCY NETWORK OF BMDS

3.1 Basic of FDNA

Functional Dependency Network Analysis (FDNA) was originally formulated by Garvey [9], who applied it to capability portfolio analysis and risk assessment. FDNA has been applied in SoS analysis for wide domains. Guariniello extended FDNA in both operational and development networks to analysis the complex dependencies between systems and capabilities in SoS, which is applied in the aerospace SoS design and architecture [10]. Drabble [11] applied the dependency network analysis to identify the key dependent nodes and conduits within the information propagation network for emergency response. Wang [12] and Zhang [13] analyzed the SoS security of Global Navigation Satellite Systems (GNSS) based on FDNA technique.

Accordingly [9,10], in the FDN, the nodes represent systems or capabilities, while the links represent the operational dependencies between the systems or between the capabilities. Each dependency is characterized by strength (Strength of Dependency, SoD) and criticality (Criticality of Dependency, CoD), that affect the behavior of the whole SoS in different ways. As in the SoS, CoD quantifies the operational independence of the components, while SoD represents the effect of interactions between components. Those inputs can come from expert judgment and evaluation, or the result of statistics of simulations and experiments. The formation of FDN is given as follows:

Define 1. A Functional Dependency Network (FDN) is a tuple <V, E, C, OE>, with G = (V, E) representing a directed-acyclic graph, Where

V : set of nodes representing either the component systems or the capability to be acquired,

E : set of edges representing the operational dependencies between nodes,

C : represents the dependencies attributes : $E \rightarrow \{\text{SoD}, \text{CoD}\}$, $\text{SoD} \in [0,1]$ is the strength of dependency fraction, $\text{CoD} \in [0,100]$ is the criticality of dependency constraint.

OE : represents the operate effectiveness level: $\text{CoD} \rightarrow [0,100]$

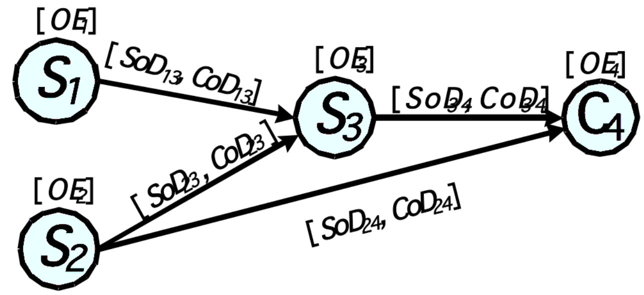

Fig. (1), An Example of Functional Dependency Network.

We presented an Breadth-First-Search algorithm to solve the FDNA, and the detail calculation on the FDNA, which can be found in [9], was also in the algorithm.

Algorithm 1 FDNA algorithm

Procedure FDNA<*V, E, C, OE*>

  Function Analysis(V)

    while $V \neq \varnothing$ **do**

      for all $v_i \in V$ **do**

        if $\mathrm{P}(v_i) = \varnothing$ **then**

          $V = V - v_i$

          // $\mathrm{P}(v_i)$ *is the parent nodes set of* v_i

        else if $\mathrm{P}(v_i) \cap V = \varnothing$ **then**

          Analysis ($\mathrm{P}(v_i) \cap V$)

        else

$$SoD\_P_i = \frac{1}{K} \sum_{v_k \in P(v_i)} (SoD_{ki} * OE_k + (1 - SoD_{ki}) * OE_i$$

$$CoD\_P_i = \underset{v_k \in P(v_i)}{Min} (CoD_{ki} + OE_i)$$

$$OE_i = Min(SoD\_P_i, CoD\_P_i)$$

          //K is the number of nodes in $\mathrm{P}(v_i)$

        end if

      end for

    end while

  end Function

end Procedure

3.1 Integrate BMDS Kill Chains into FDN

As our study focuses on the effectiveness of the whole system of systems, we built the FDN of BMDS through integrating multi-layered kill chains. In our FDNA model, the components in BMDS were represented as nodes while the links in C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, Reconnaissance) were represented as edges. In BMDS, most component systems are able to work independently, however the function dependency further exploit the capabilities of the components. For an instance, data from SBIRS relieves AN/TYP-2 of unnecessary volume or fan search, and free the fire control radars to focus on tracking and discrimination at longer distance and get ready for the launch against time-sensitive targets.

For the SoS of BMDS, probability of raid annihilation (P_{RA}) is the final Measure of Effectiveness (MoE). The capability of interceptors was defined as probability of kill, while that of sensor was defined as the time to detect the target.

In the combat field, assume P_i is the probability of kill for interceptor P_i at ideal situation that the operate effectiveness is 100, however, the P_i is effected by many extra factors such as the quality of track data and the level of the training. Thus, the actual kill probability is $P_{Ki} = OE_i * P_i / 100$, then P_{RA} is

$$P_{RA} = 1 - \prod_{i=1}^{n} (1 - P_{Ki}) \quad (1)$$

System response time is also suggested by the authors as a MoE in the time-sensitive intercept task. Assume sensor s to detect the target within T_s at the effectiveness of 100, given the actual OE_s, the response time is modified as $T_s = 100 * T_s / OE_s$, the response time of the first shoot is

$$T_r = \min T_s \quad (2)$$

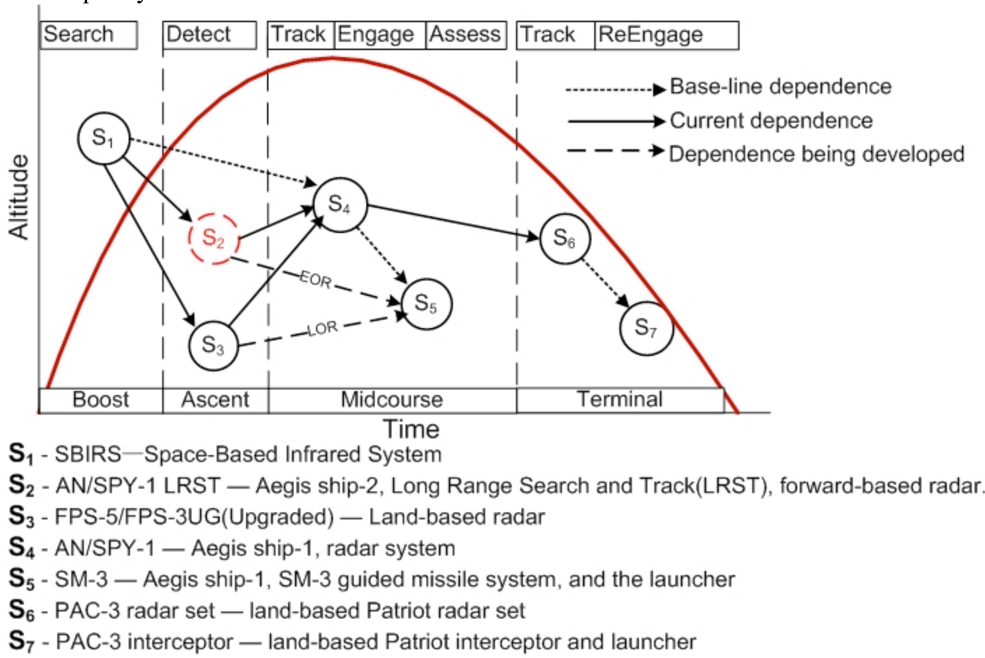

Fig. (2), Multi-Layered Kill Chains in BMDS

Table 2. Parameters of the functional dependency

Systems	S1	S2	S3	S4	S5	S6	S7
S1	\	(0.3,80)[a]	(0.4,60)	(0.3,60)	\	\	\
S2	\	\	\	(0.4,60)	\	(0.7,0)	\
S3	\	\	\	(0.3,50)	\	(0.8,0)	\
S4	\	\	\	\	(0.6,80)	(0.9,0)	\
S5	\	\	\	\	\	\	(0.9,0)

[a]. (SoD_{ij}, CoD_{ij}) and "\"represents no functional dependency

4. CASE STUDY

To test the applicability of our method, three notional BMDS architectures were built which took the US and Japanese BMDS as a reference [16]. Although these data were notional, the general principles and trends reflect those of reality, the notional BMDS was shown in Fig.2. *Arct* A is the base-line architecture that an Aegis destroyer and a PAC-

3 battery worked independently without support from other systems. *Arct* B is the current architecture, while *Arct* C is the architecture updated based on *Arct* B with AN/TPY-2 radar being added to form the capabilities of EOR and LOR.

In Table 1, the independent operational effectiveness means the system works without the support from others, and max capability for the sensors means the least time to acquire a track with full support, which for interceptors means the highest probability of kill with high quality track. The functional dependency networks of BMDS architectures were presented in Fig.2, and the notional values of SoD and CoD were given in Table 2.

Table 1. Parameters of the component systems

Systems	S1	S2	S3	S4	S5	S6	S7
Independent *OE*	90	80	60	70	0	60	0
Max Capability	80s	160s	120s	220s	0.8	360s	0.7

4.1 Effectiveness Analysis

First, initial *OE* of systems and dependency parameters were fed into the FDN to compute the actual OE of each system. Fig.3. showed the improvement in component OE due to the functional dependencies, especially in detect and track systems. With the support of sensors, interceptors came into work ($OE_i \neq 0$). Due to the networked sensor architecture, in *Arct* B the P_{RA} increased by 24.2%, while T_r was almost the same at about 224s, as the AN/SPY-1 was the key sensor to launch SM-3.

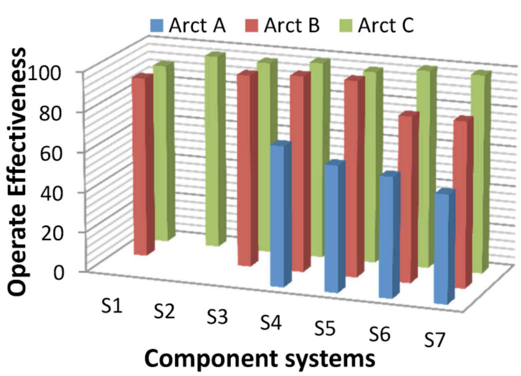

Fig. (3), Operational Effectiveness of Component Systems

In *Arct* C the land-based AN/TPY-2 was integrated in the SOS to provide the EOR and the FPS-3 radars was updated with LOR. The BMDS made a great improvement with two intercept opportunities at 123s with probability of 61% and at 166s with 54%, as was shown in Fig.4.

4.1 System Degradation Analysis

In the battle field, the adversary would destroy or disable the components in the BMDS, for example, the anti-satellite weapons to destroy the SBIRS. On the other hand, operational effectiveness might decrease due to the bad environment. Therefore, it is meaningful to analysis the effectiveness of BMDS under attack and system degradation.

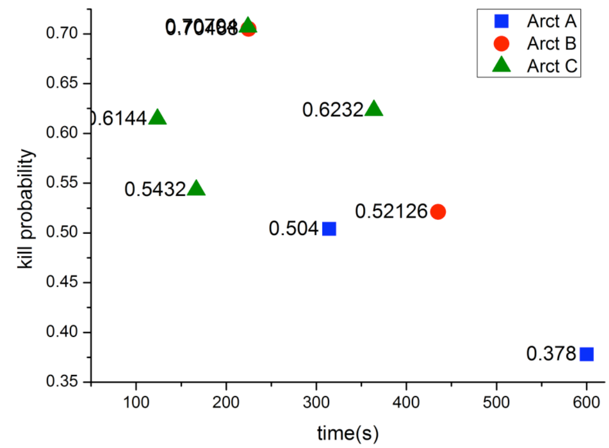

Fig. (4), Intercept Opportunities

A serious scenario was that the SBIRS being disabled by anti-satellite weapons, other scenarios considered the degradation of AN/SPY-1 at three levels -30%, -50%, -70%. The P_{RA} and T_r were compared between *Arct* B and *Arct* C. The result was shown in Table 3, the SBIRS contributed lots to T_r, while made few effect on P_{RA}, only about 10%. The early warning was critical to EOR engagement conducted by AN/TPY-2, as the T_r increased by 23.9% (*Arct* B) and 38.9% (*Arct* C). For the degradation of AN/SPY-1, *Arct* C worked more effectively than *Arct* B both in P_{RA} and T_r . *Arct* C was not affected at 30% degradation of AN/SPY-1, because the land based AN/TPY-2 shared the workload of AN/SPY-1.

Table 3. Parameters of the component systems

Situation	Metric for BMDS			
	Arct B		*Arct* C	
	P_{RA}	Tr	P_{RA}	Tr
SBIRS (-100%)	-11.2%	23.9%	-9.3%	38.9%
AN/SPY-1 (-30%)	-7.9%	18.2%	0	0
AN/SPY-1 (-50%)	-13.5%	19.3%	-5.3%	9.7%
AN/SPY-1 (-70%)	-25.5%	22.3%	-7.3%	12.3%

5. CONCLUSION AND FUTURE WORKS

We proposed a new approach based on the functional dependency network to analysis the effectiveness of BMDS in the view of system of systems. Our approach overcomes the limits of traditional probability models and simulations by the analysis on the functional dependences between the components which built up the multi-layered kill chains. The notional case study demonstrated that it was a useful approach to assess the BMDS under different scenarios.

The future works would focus on the methods to form the parameters of functional dependency which represent the effectiveness of the C4ISR, and an explorer analysis would be made to get a full knowledge of the BMDS in different situations.

CONFLICT OF INTEREST

The author confirms that this article content has no conflict of interest.

ACKNOWLEDGEMENTS

The research was supported in part by the National Natural Science Foundation of China through Grant Number (61273198, 91024015).

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