Resilience of a Network Service System: Its Definition and Measurement

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***Abstract*— Modern human society relies on different critical service systems. One important feature of these systems is that they work in a network manner. Thus, they could also be called networked service systems. Resilience is a necessary property of systems; in particular, the networked service systems should meet customers' demands facing various uncertainties. However, the understanding of resilience, especially in the context of service system, is still not very clear; the concept of resilience was confused with other similar safety concepts, such as reliability and robustness in the current literature. In this paper, we present a definition of resilience in the context of networked service system. Furthermore, some criteria of resilience measurement following this definition are also proposed. Two particular measurement models focusing on the different measurement criteria are presented with two simple examples to show how the proposed models work.**

***Keywords-resilience; measurement; networked service system; rebalance*.**

I. INTRODUCTION

Modern human society relies on different critical service systems, such as transportation system, power grid system, communication system and so on. One important feature of these system is that they work in a networked manner. Thus, they could also be called networked service systems. The networked service systems are complex socio-tech systems. It is unfortunate that today's networked service systems face serious safety issues. Here are two very recent examples. The breakdown of the power supply system in the north India happened in July 2012 led one-half of the country into serious trouble, which further caused the failure of other critical service systems, such as transportation system, financial system, water supply system, and hospital system [1]. Hurricane Sandy in late October 2012 killed at least 199 people in seven countries and half of New York lost the functions of almost all the service systems [2]. To address such safety challenges, the concept of resilience was introduced into safety engineering and used to describe the system's safety property [3].

From the safety engineering perspective, the resilience concept has been investigated by different researchers [3]-[6]; particularly, there are three categories of understanding of resilience. The first category mixed up resilience with other safety concepts, such as reliability and robustness [7], [8]. The second category focused on the system's recovery ability from partially damage [5]. The third category viewed resilience as in intrinsic ability to adjust its functioning prior to, during, or following changes and disturbances under both expected and unexpected conditions [12]. The three categories of definitions can not well reflect the features of the service systems. Therefore, the objectives of this paper are to (1) clarify the concept of resilience by giving a definition of resilience in the context of networked service systems, and (2) propose resilience measures based on the definition.

The organization of the remainder of this paper is as follows. Section II proposes a new definition of resilience concept. Section III presents the criteria of the resilience measurement and two particular measurement models, as well as simple examples. Section IV discusses the conclusions and future work.

II. RESILIENCE DEFINITION FOR SERVICE SYSTEMS

A. *Resilience Definitions in the Literature*

Resilience is a popular term in material science [9], medicine [10] and ecology [11]. This concept was introduced into engineering field to understand safety as the ability to succeed under varying conditions [3], [12]. Two typical definitions of resilience from engineering perspective are given here. Zhang defined resilience as the ability of a system to recover to meet the demand from a partial damage [5]. Another well-known definition viewed resilience as the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances so that the system can sustain required operations under both expected and unexpected conditions [12]. This definition actually covers the traditional concepts of safety, reliability and robustness, and makes further extension; in particular, resilience concept deals with the damaged situation – a point of resilience stressed by Zhang [5]. However, these definitions and understandings do not well describe the safety features of the networked service systems.

B. *Definition of Service System*

To facilitate the further discussion, the concepts of service and service system we proposed elsewhere [13] are given below.

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"A service is a function that is achieved by an interaction between a human and an entity under a protocol [13]."

"A service system consists of three subsystems: (i) an infrastructure, (ii) a substance, and (iii) a management to directly meet demands of humans who are defined as consumers. The infrastructure is of network, and substance “flows” over the infrastructure. The management plays the roles such as coordinating, leading, planning and controlling, which are applied to both the infrastructure and substance systems [13]."

The substance in a service system may refer to: material, human or animal, energy, data or signal [13]. It is noted that a service system, in this paper, is also called a networked service system, as it has networked feature as mentioned in Introduction.

Following the definitions above, we may have two important understandings: (1) a service system has different functions to meet human's different demands; in particular, a service system with only one function could be viewed as a special case, and (2) relationships between the multiple demands and the multiple supplies determine the safety performance of a service system; furthermore, the relationships are dynamic.

C. *Definitions of Resilience*

From the perspective of functions, the output of a service system are different functions, which are defined as supply functions, which are represented as $F_i^S, 1 \le i \le m$ where *m* is the number of supply functions. The demands from the customers are also expressed as functions, which are defined as demand functions, which are represented as $F_i^D, 1 \le i \le m$. The relationships between the supply functions and demand functions, balance and imbalance, are defined as follows. Balance between the supply functions and the demand functions is defined as the relationship between the supply functions and demand functions which satisfies the conditions: $F_i^S = F_i^D, 1 \le i \le m$. **Imbalance** between the supply functions and the demand functions is defined as the relationship between the supply functions and demand functions which satisfies the conditions: $\exists i, F_i^S < F_i^D, 1 \le i \le m$. The situations of balance and imbalance may be transferable; a service system may be rebalanced. **Rebalance** is defined a process that a service system transfers from an imbalance situation to a balance situation. Thus, **safety** of a service system is defined as the dynamic balance between the multiple supply functions and the multiple demand functions. Such a definition of safety is quite different from traditional definition of safety. The traditional understanding of safety implies that if a system is not safe, there must be something wrong. However, the proposed definition above indicates that even there is nothing wrong in the system, it may be still not safe, as it may not meet the customers' demands. For example, a large athletic meeting leads to the demand of wireless communication in a particular area much larger than the supply provided by the regular wireless communication system. There are no damages in such a situation; however, the wireless communication system is not safe, as it could not meet the customers' demand.

The definition of safety above has shown that an unsafe service system is not necessarily damaged. Thus, the resilience definitions discussed in Section II do not well reflect the features of a service system, as they are related with partial damage situations. Our definition is given below.

The **resilience** of a service system is defined as a property that allows the system rebalance the supply functions and demand functions from imbalance situations. Four remarks are given below for further explanation on this definition.

Remark 1: According to the definition of safety above, imbalance situation means unsafe situation.

Remark 2: A service could be examined through different perspectives, such as state, structure, functions and so on. The proposed definition of resilience implies that the resilience property should be examined from the perspective of function.

Remark 3: Resilience does not aim at returning to the original states, or structure or functions of the system; it aims at making the supply functions meet the demand functions.

Remark 4: The imbalance situation implies that the supply functions are less than the demand functions. Therefore, the key ability of resilience is to respond to the imbalance situation and to improve the supply functions to meet the demand functions.

The proposed definition of resilience is different from other three categories of definitions of resilience introduced in Section I. According to the new definition of safety in this paper, category I is related to the balance situation of a service system. Category II could be viewed as a special case of the new definition, as it focuses on the imbalance situations of partially damage. Category III is an all-inclusive definition and covers the scope of the new definition.

III. RESILIENCE MEASUREMENT FOR SERVICE SYSTEM

A. *Criteria of Resilience Measurement*

Following the proposed definition in Section II, the resilience can be measured through the maximization of imbalance situation, which can be rebalanced with the bounded time and cost (or resources). Four important corollaries could be derived from the definition as the criteria of resilience measurement.

Criterion 1: The resilience of a system is only measured in terms of particular imbalance situations.

Criterion 2: A system which can rebalance the supply functions and demand functions from larger imbalance situation is more resilient.

Criterion 3: A system which can rebalance the supply functions and demand functions from the imbalance situation with less time is more resilient.

Criterion 4: A system which can rebalance the supply functions and demand functions from the imbalance situation with less cost (or resources) is more resilient.

Based on these measurement criteria, it is obvious that there are three important factors affecting resilience performance: (1) rebalance solutions, (2) rebalance time, and

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(3) rebalance cost. For a networked service system under a particular imbalance situation, there may be different rebalance solutions and the best solution will determine the resilience performance of the system. The rebalance solutions certainly depend on the available rebalance time and resources. The criteria actually imply that given different conditions, there may be different measurements. For example, given rebalance time and cost, the measurement is maximization of imbalance situation. Given imbalance situation and available rebalance cost, the measurement is minimization of rebalance time. Next, two measures following Criterion 2 and Criterion 3 are expressed respectively.

B. Resilience measurement following Criterion 2

Criterion 2 is the main concern of resilience measurement. Based on Criterion 2, the following model is proposed to measure the resilience of a service system.

1) Variable Definition

m : the total number of functions;

n : the category number of resources;

w_i : weight of function i, $i = 1, 2, \cdots, m$, $\sum_{i=1}^{m} w_i = 1$;

$r_{i,j}^t$: the number of resource j needed by function i at time t, $i = 1, 2, \cdots, m$, $j = 1, 2, \cdots, n$;

R_j : the total number of resource j, $j = 1, 2, \cdots, n$;

$D_i^t(x)$: the demand function i at time t with rebalance solution x, $i = 1, 2, \cdots, m$;

$S_i^t(x)$: the supply function i at time t with rebalance solution x, $i = 1, 2, \cdots, m$;

T_i : the demand time for the rebalance of function i, $i = 1, 2, \cdots, m$;

x : rebalance solution

2) Objective Function and Constraints

$$\text{Max } \sum_{i=1}^{m} w_i \frac{D_i^0(x) - S_i^0(x)}{D_i^0(x)} \quad (1)$$

$$\text{s.t. } S_i^t(x) \geq D_i^t(x), t \geq T_i \quad (2)$$

$$\sum_{i=1}^{m} r_{i,j}^t \leq R_j, \ j = 1, 2, \cdots, n, t \leq \max\left\{T_i \middle| i = 1, 2, \cdots, m\right\} \quad (3)$$

In the above, formula (1) represents the imbalance situation at beginning; formula (2) represents the constraint of rebalance time for different functions; formula (3) represents the resource constraints.

3)A Simple Example of Transportation System: A very simple transportation system example is given to show how the model work. In this example, we only consider the maximum imbalance situation that the system can rebalance and the rebalance time and cost are ignored. Fig. 1 is an original transportation system with only two nodes. Two edges link the two nodes. The travel time and edge capacity are as shown in the figure. Suppose that the unit of travel time is minute. In this example, we consider the imbalance situation is that the transportation demand from A to B is increased to 15 per 2 minutes due to some reason. The rebalance solution is contraflow approach, namely reverse and edge from B to A, as shown in Fig. 2.

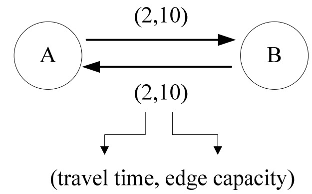

Figure 1. Original transportation system with only two nodes.

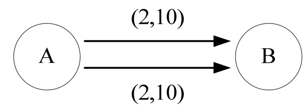

Figure 2. Rebalance solution.

With the rebalance solution in Fig.2, the maximum transportation ability from A to B is 20 per minutes. Therefore, the largest imbalance situation that can be rebalanced is that the transportation demand from A to B increased to 20 and the imbalance degree is (20-10)/20=50%. Thus, the resilience of this transportation system facing the particular imbalance situation of increased transportation demand from A to B is 50%.

C. Resilience measurement following Criterion 3

Criterion 3 implies that given the same imbalance situation that could be rebalanced, the minimization of the rebalance time could be used to measure the resilience of a service system.

1) Variable Definition:

The variable definition is given below.

m : the total number of functions;

n : the category number of resources;

w_i : weight of function i, $i = 1, 2, \cdots, m$, $\sum_{i=1}^{m} w_i = 1$;

$r_{i,j}^t$: the number of resource j needed by function i at time t, $i = 1, 2, \cdots, m$, $j = 1, 2, \cdots, n$;

R_j : the total number of resource j, $j = 1, 2, \cdots, n$;

$c_i(x)$: the completion time for the rebalance of function i, $i = 1, 2, \cdots, m$;

T_i : the demand time for the rebalance of function i, $i = 1, 2, \cdots, m$;

2) Objective Function and Constraints

The objective function and constraints are given below.

$$\text{Max } \sum_{i=1}^{m} w_i \frac{c_i(x)}{T_i} \quad (4)$$

$$\text{s.t. } \sum_{i=1}^{m} r_{i,j}^t \leq R_j, \ j = 1, 2, \cdots, n, t \leq \max\left\{T_i \middle| i = 1, 2, \cdots, m\right\} \quad (5)$$

$$c_{(i)}(x) \leq T_i, i = 1, 2, \cdots, m \quad (6)$$

In the above, formula (4) represents the resilience of the system; formula (5) represents the resource constraints; formula (6) represents the constraint of rebalance time.

3)An Example of Enterprise Information System: A simple example of enterprise information system is employed to show how the model works. An enterprise information system is a very special service system in that such a system usually has backup and could be rebalanced from even 100% lost of functions. We consider a scenario that an enterprise information system is fully damaged. There are two functions in this system, which are totally lost. There are two categories of resources. The total number of resource 1 is 2; the total number of resource 2 is 4. All the functions are treated with the same importance and the weight for each function is 0.5. Due to the limitation of resources, the two functions can not be rebalanced synchronously. This implies that a rebalance solution needs to choose a particular order among a set of rebalance tasks.

TABLE I. REBALANCE PARAMETERS

Function	Resource 1 $r_{i,1}$	Resource 2 $r_{i,2}$	p_i (min)	T_i (min)
i=1	2	3	2	2
i=2	2	4	5	8

The information of rebalance solutions is given in Table 1. p_i is the process time for the recovery of function *i*. Obviously, the optimum solution for this problem is with the order of [1,2]. The fitness value is 0.857, which implies that the system could be rebalanced a little earlier than the demand recovery time.

IV. CONCLUSION AND FUTURE WORK

This paper proposes a new definition of resilience for the networked service system by considering its important safety features. Furthermore, the measurement criteria of resilience are discussed. Following these criteria, two particular measures are presented with two simple examples to show how the measures work.

This work describes only very preliminary results with the two models. As future work, realistic examples of networked service systems will be adopted to validate the proposed measures.

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