Engineering Applications of Artificial Intelligence 26 (2013) 24–34

Contents lists available at SciVerse ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

How to learn from the resilience of Human–Machine Systems?

Kiswendsida Abel Ouedraogo [a,b,c], Simon Enjalbert [a,b,c,*], Frédéric Vanderhaegen [a,b,c]

[a] Université Lille Nord de France, F-59000 Lille, France
[b] UVHC, LAMIH, F-59313 Valenciennes, France
[c] CNRS, FRE 3304, F-59313 Valenciennes, France

ARTICLE INFO

Article history:
Received 4 June 2011
Received in revised form
7 March 2012
Accepted 7 March 2012
Available online 30 March 2012

Keywords:
Human–Machine Systems
Resilience
Learning process
Feedback/feedforward control

ABSTRACT

This paper proposes a functional architecture to learn from resilience. First, it defines the concept of resilience applied to Human–Machine System (HMS) in terms of safety management for perturbations and proposes some indicators to assess this resilience. Local and global indicators for evaluating human–machine resilience are used for several criteria. A multi-criteria resilience approach is then developed in order to monitor the evolution of local and global resilience. The resilience indicators are the possible inputs of a learning system that is capable of producing several outputs, such as predictions of the possible evolutions of the system's resilience and possible alternatives for human operators to control resilience. Our system has a feedback–feedforward architecture and is capable of learning from the resilience indicators. A practical example is explained in detail to illustrate the feasibility of such prediction.

1. Introduction

Resilience is related to the ability of a material to recover from a shock or disturbance. Resilience is a relatively new field of research, although the concept has been used in physics for Charpy impact tests throughout nearly all of the XXth century. The concept of resilience has also been developed in the field of ecology and is used to characterise natural systems that tend to maintain their integrity when subjected to disturbances (Ludwig et al., 1997). It has generated a lot of interest in different scientific communities and has been applied to psychology, psychiatry (Goussé, 2005), sociology, economy, biology (Orwin and Wardle, 2004; Pérez-España and Sánchez, 2001), computer sciences (Chen et al., 2007; Nakayama et al., 2007; Luo and Yang, 2002), and automation (Tianfield and Unland, 2004; Neema et al., 2004; Numanoglu et al., 2006).

Psychological resilience is linked to the invulnerability theory (*i.e.*, the positive capacity of people to cope with trauma and to bounce back). Biological or ecological resilience is based on the theory of viability (*i.e.*, the ability for an organism to survive after disruption). The resilience of industrial systems is linked to on-line safety management, faced with known or unknown situations. It differs from the traditional off-line safety analysis process, which aims at foreseeing undesirable situations and proposing schemes to avoid their occurrence or protect the system from their consequences. From the organisational and safety management viewpoints, resilience is the capacity of a system to survive, adapt and face unforeseen changes, even catastrophic incidents. There are many formal definitions of resilience, but most of them suppose the existence of functional capacities in order to make a system resilient: the capacity to recognise, adapt to, and absorb changes.

When a Human–Machine System (HMS) does not have sufficient resources or competences to control such functions, it cannot be resilient, or its resilience may be managed by another HMS. Another strategy can be applied: learning to face new or unknown situations. HMS decision-makers have to make sense of these kinds of situations and identify alternatives to control them. When the management of these situations is successful, the HMS is resilient.

This paper focuses on the positive control of new, unknown, unexpected or surprising situations and on the possibility of learning from resilience. It proposes a functional architecture for learning from resilience indicators and their evolution. An example applied to a cockpit and its four-person flight crew illustrates the feasibility of such learning.

The rest of this paper is organised as follows. Section 2 focuses on the concept of resilience applied to HMS and the indicators for assessing it. Section 3 presents an original method to learn from other resilience indicators. Section 4 provides an example of learning from resilience. Section 5 offers our conclusions and prospects for future research.

* Corresponding author at: UVHC, LAMIH, Le Mont Houy, F-59313 Valenciennes, France.
E-mail addresses: kiswendsidaabel.ouedraogo@univ-valenciennes.fr (K.A. Ouedraogo), simon.enjalbert@univ-valenciennes.fr (S. Enjalbert), frederic.vanderhaegen@univ-valenciennes.fr (F. Vanderhaegen).

0952-1976/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engappai.2012.03.007

2. Pending issues about resilient HMS

One of the first substantive publications on resilience as applied to engineering was ''Resilience Engineering: Concepts and Precepts'' (Hollnagel et al., 2006). The basic concepts behind resilience engineering are developed, but at the present stage, resilience engineering has several fundamental problems: (1) there is no appropriate definition of resilience, and (2) the differences between resilience and other similar concepts (*e.g.*, robustness, reliability) are not clarified. These problems need to be addressed in order to advance resilience engineering and transform a theoretical concept into an applied science by defining a quantitative method that can measure system resilience.

2.1. Definition of HMS resilience

Wreathall (2006) defined resilience as ''the ability of an organisation (system) to keep, or recover quickly to, a stable state, allowing it to continue operations during and after a major mishap or in the presence of continuous significant stresses''. As a resilience definition, Wreathall's definition lacks a distinction of resilience from robustness (Zhang and Lin, 2010; Wang et al., 2010). Both terms are related to the ability of a system to keep functioning faced with disturbances.

Zhang and Lin (2010) further defined resilience as a system property about how the system can still function to the desired level when it suffers from partial damage. This definition was able to distinguish resilience from robustness: for a robust system, the physical structure of the system is still intact, whereas for resilient system, the physical structure is damaged (Gao, 2010). This definition sees resilience as a system's post-damage property (*i.e.*, the system's ability to recover its functions faced with damage). In essence, a resilient system contains characteristics of a robust system in that it is the magnitude of the disturbance that differentiates resilient system from robust one.

We aim to apply the resilience concept to HMS, with human operators as an unpredictable source of both reliability and errors. We distinguish a robust system from resilient one, based on the nature or typology of the threats/disturbances, as defined by Westrum (2006): robust systems deal with regular and, at a certain level, irregular threats, whereas resilient systems manage unknown situations (*e.g.*, unexpected or unprecedented disturbances).

Assuming that optimal performance level exists (*i.e.*, an initial nominal HMS state or a baseline), after any disturbance, either internal disturbance (*e.g.*, human errors or technical failures) or external disturbances (*e.g.*, environmental events), the HMS performance may be degraded. Several scenarios can be envisioned:

- If the HMS is capable of returning to the initial nominal performance (*i.e.*, known disturbance situations), the system can be defined as resistant.
- If the HMS is capable of recovering from a disturbance and stabilizing at another ''acceptable'' performance level, which is an unoptimal performance due to controlling unknown situations (*e.g.*, unexpected or unprecedented disturbances), the system can be defined as resilient.
- If the HMS is not capable of recovering from a disturbance (*i.e.*, not an acceptable performance) or stabilizing itself, the system is neither resistant nor resilient.

Human operators and machines in the HMS cooperate to ensure an optimal operation, and they are potentially available resources to make the HMS resilient. These resources need particular capacities, and some methods exist to make a system resilient. One of these methods is related to the learning process.

2.2. Resilience and methods

In order to be resilient, a system or an organisation required the following four qualities (Steen and Aven, 2011):

- the ability to anticipate risk events;
- the ability to monitor what is going on, including its own performance;
- the ability to respond to unplanned events (regular, irregular or unprecedented) in a robust or flexible manner; and
- the ability to learn from experience.

Resilient systems are supposed to adapt to unplanned events with their ability to anticipate failures, to control disturbances, to react and to recover from these events (Fig. 1). The system also has the possibility of learning from its reactions to unplanned events (*i.e.*, successes and failures). Thus, the design of resilient systems can be based on some principles, such as the five principles defined by Zhang and Lin (2010), which mainly highlight the need of

- a certain degree of functional redundancy,
- a controller for redundancy and learning management,
- a sensor for monitoring the whole system's performance,
- a predictor for predicting potential threats or analysing potential vulnerabilities of the system, and
- an ''actuator'' for implementing changes or training.

A non-resilient system cannot continue to operate correctly after a major mishap or in presence of continuous stress. Many methods or mechanisms can be used to recover from such situations, such as

- Using non-affected elements to compensate and accomplish the functions of the affected or degraded parts (Chen et al., 2007; Nakayama et al., 2007; Numanoglu et al., 2006), with what works compensating for what does not work.
- Maintaining the system between the minimum and maximum thresholds of acceptability or perturbation management instead of a stable point or value (Martin, 2005).
- Putting critical elements in redundancy (Luo and Yang, 2002), with the affected elements no longer being solicited and being replaced by redundant components.
- Optimising the mitigation of the perturbations when the redundancy strategy is too expensive (Neema et al., 2004; Tianfield and Unland, 2004), thus developing fault resilient systems.
- Applying the principles of cooperation (Vanderhaegen, 1997, 1999a; Hsieh, 2009; Zieba et al., 2009), with cooperation between humans and/or artificial agents facilitating the problem-solving for new situations.

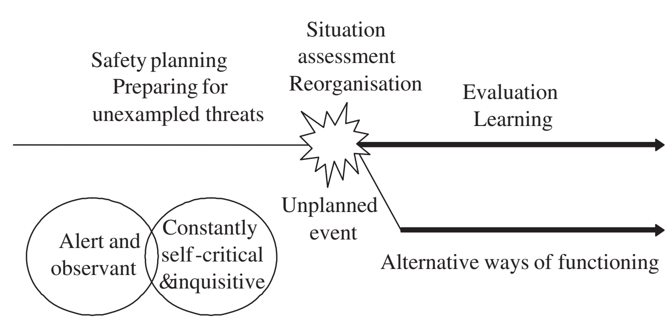

Fig. 1. Resilient organisation.
Hollnagel, 2006.