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A dendritic cell mechanism for detection, identification, and evaluation of aircraft failures

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ABSTRACT

Successful fault-tolerant control strategies often require vital tools that can accurately detect the failure, identify its root cause, and evaluate its nature and severity. Most of the existing methodologies in the field of failure detection, identification, and evaluation are limited to few subsystems with reduced number of features. Due to the complexity and multidimensionality of the aircraft system, new methodologies that are robust, accurate, and fast enough need to be developed for such systems. The biological immune system is a natural system that possesses vigorous peculiarities in protecting the mammalian body from harmful intruders and, therefore, may represent a rich source of inspiration to solve anomaly problems. This paper presents a novel integrated scheme for aircraft sub-system failure detection, identification, and evaluation based on the functionality of the biological dendritic cells and their interactions with the various components of the immune system. The proposed approach relies on using the self/nonself discrimination principle with the hierarchical multiself strategy to overcome the multidimensionality issues. The information collected by the artificial dendritic cells is fused in a way that convert the identification and evaluation problem into a pattern recognition problem. The proposed scheme was successfully tested for a supersonic fighter aircraft in a motion-based flight simulator with high detection, identification, and evaluation rates and practically zero false alarms.

1. Introduction

The development of in-flight fault-tolerant control strategies has been an extensive research area in failure accommodation (Campbell, Kaneshige, Nguyen, & Krishnakumar, 2010; Nguyen & Krishnakumar, 2009; Zhang & Jiang, 2008). However, these techniques very often require triggering mechanisms that are sufficiently accurate in detecting the failure, identifying its source, and evaluating its type and severity as soon as it takes place. The failure detection, identification, and evaluation (FDIE) process can potentially provide critical information to the human and automatic pilot for increased situational awareness and abnormal condition (AC) compensation.

Several techniques have been proposed in the past two decades for failure detection and identification (FDI) (Hwang, Kim, Kim, & Seah, 2010; Venkatasubramanian et al., 2003a, 2003b). These techniques can be divided into two main categories: statistical and artificial-intelligence methodologies. Statistical methods are either model-based or non-model-based. Model-based statistical methods require understanding the physics of the system and rely on deriving functional relationships between the inputs and outputs of the system. Diagnostic observers, parity relations, Kalman filters, and parameter estimation are the mostly used model-based statistical methods for the purpose of FDI. On the other side, non-model-based methods do not require physical understanding of the system and rely on the availability of large amounts of data. Examples of these methods are trend analysis, statistical classifiers, and partial least squares. Artificial intelligence methods used for the purpose of FDI include digraphs, which are based on the cause-and-effect principle, logical fault trees, search techniques (such as lookup tables and hypothesis-and-test search), expert systems, and artificial neural networks. Depending on the technique used, these methods partially satisfy the FDI requirements of raising minimum false alarms under normal operating conditions, detecting and identifying all subsystem failures with high rates, adapting to system changes, exhibiting robustness to system disturbances and uncertainties, and being scalable to the complexity and dimensionality of the system.

Recent research studies (Belcastro, 2010a; Belcastro & Jacobson, 2010; Figueroa et al., 2009; Roemer et al., 2008) have acknowledged the need for an integrated and comprehensive solution to

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the problem of aircraft FDIE which takes into account the complexity and multidimensionality of aircraft system. Research investigations showed that the artificial immune system (AIS) paradigm, which has emerged in the last two to three decades, exhibits all these desired characteristics and can provide a platform to the sought solution.

Dasgupta et al. (2004) proposed an aircraft fault detection system to detect a broad spectrum of known as well as unforeseen faults based on a real-valued negative selection algorithm. Kaneshige and KrishnaKumar (2007) demonstrated the potential of using immunized maneuver selection in air combat maneuvers of an unmanned aerial vehicle (UAV) using a combination of genetic and evolutionary algorithms in emulating the adaptive capabilities of the biological immune system to construct the maneuvers that are necessary for responding to different air combat situations. Significant research efforts at West Virginia University (WVU) have been focused on AIS-based aircraft abnormal conditions' management. Perhinschi, Moncayo, and Davis (2010) proposed an integrated immunity-based framework for the detection, identification, and evaluation of a wide variety of failures of aircraft subsystems. Moncayo, Perhinschi, and Davis (2010, 2011a) developed an immunity-based aircraft failure detection and identification scheme. They proposed a hierarchical multiself (HMS) strategy where different self-configurations are selected for detection and identification of specific abnormal conditions. They have also proposed failure evaluation over extended flight envelope based on the AIS paradigm (Moncayo, Perhinschi, & Davis, 2011b). The potential of the artificial immune system to provide adaptive control of a UAV has been recently investigated by augmenting an immunity-based mechanism to the nonlinear dynamic inversion of the UAV in an attempt to provide adaptive control laws (Moncayo et al., 2012). An evolutionary algorithm has been developed for the generation and optimization of artificial immune system-based failure detectors using the negative selection strategy (Davis, 2010; Davis, Perhinschi, & Moncayo, 2010).

Dendritic cells (DCs) are important cell populations in the biological immune system. They belong to the innate immune system (i.e., peripheral tissues) which forms the first line of defense against the intruders. When an antigen enters the body, the DC engulfs it, breaks it up into its constituent molecules, and transports subsets of these molecules to the cell surface. The DC then migrates to the lymph nodes (the home of other immunity cells that form the adaptive immune system) to present the processed antigen molecules to the T-cells, which will proliferate and differentiate into helper T-cells and memory T-cells.

Memory T-cells remain in the body for years to provide faster response when the same antigen infects the body again. While some helper T-cells bind to a special type of T-cells (called the cytotoxic T-cells) that bind to infected cells so that they self-destruct through a certain cell suicide mechanism, other helper T-cells bind to B-cells to produce "antibodies" that are *specific* to the antigen molecules presented by the DCs, such that they can bind to the same antigens to mark them for attack by other DCs.

Depending on the molecules of the foreign bodies they carry on their outer surfaces, the migrated DCs have two functionalities in the adaptive immune system: they either stimulate the production of cytotoxic T-cells and antibodies when they carry "harmful" antigen molecules or activate the production of the suppressor T-cells when they carry molecules of foreign "safe" bodies, such as food and molecules released from self-cells that died due to the programmatic "healthy" death. These suppressor T-cells will eventually regulate the production of cytotoxic T-cells and antibodies. Thus, the functionality of the DCs and their interaction with the different cells in the adaptive immune system play an important vital role in determining the resulting immune response. The interaction between the innate and adaptive immune systems is illustrated in Fig. 1. More details about this process can be found in Janeway, Travers, Walport, and Shlomchik (2005), Steinman and Cohn (1973), Steinman (2015), Banchereau and Steinman (1998), and Pletinckx et al. (2011).

Despite their success in some application domains, the dendritic cell algorithm (DCA) proposed by Greensmith (2007) and its variants (Chelly & Elouedi, 2010; Greensmith & Aickelin, 2008; Mokhtar et al., 2009) relies on the mapping of their input signals to the appropriate parameters of the particular application. This mapping becomes extremely difficult, if not impossible, in complex and multidimensional systems such as the aircraft. The DCA was based on the behavior of the DCs that are part of the innate immune system, whereas the principle of self/non-self discrimination was based on the functionality of the antibodies in the adaptive immune system.

The artificial DC mechanism has been recently proposed (Al Azzawi, 2014; Al Azzawi, Perhinschi, & Moncayo, 2013, 2014a 2014b) to solve the aircraft FDI problem within an integrated immunity-based framework developed at WVU (Perhinschi, Moncayo, & Al Azzawi,

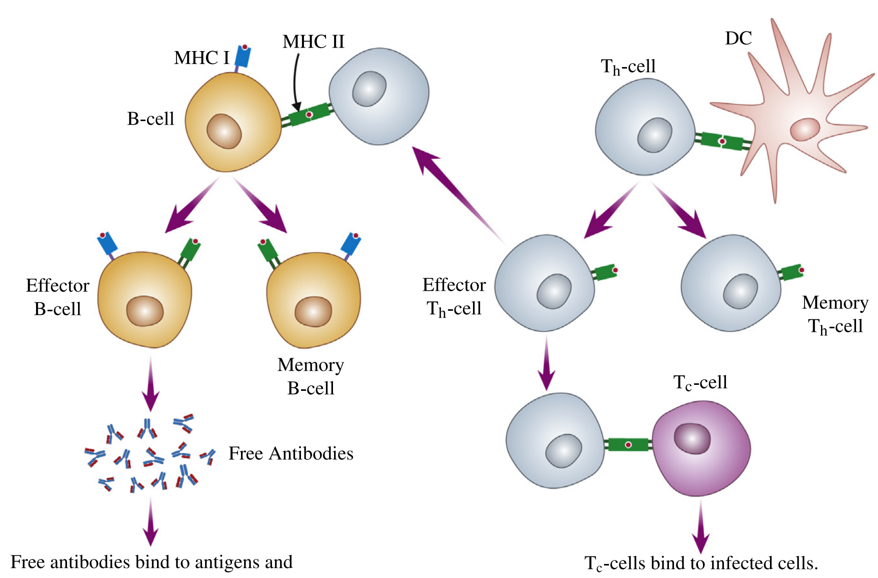

Fig. 1. Production of cytotoxic T-cells and antibodies governed by dendritic cells (Al Azzawi, 2014).