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Predictive maintenance for the heated hold-up tank

Benoîte de Saporta [a,b,c,*], Huilong Zhang [b,c]

[a] University of Bordeaux, CNRS GREThA, UMR 5113, F-33600 Pessac, France
[b] University of Bordeaux, CNRS IMB, UMR 5251, F-33400 Talence, France
[c] INRIA Bordeaux Sud-Ouest, team CQFD, F-33400 Talence, France

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ABSTRACT

We present a numerical method to compute an optimal maintenance date for the test case of the heated hold-up tank. The system consists of a tank containing a fluid whose level is controlled by three components: two inlet pumps and one outlet valve. A thermal power source heats up the fluid. The failure rates of the components depends on the temperature, the position of the three components monitors the liquid level in the tank and the liquid level determines the temperature. Therefore, this system can be modeled by a hybrid process where the discrete (components) and continuous (level, temperature) parts interact in a closed loop. We model the system by a piecewise deterministic Markov process, propose and implement a numerical method to compute the optimal maintenance date to repair the components before the total failure of the system.

1. Introduction

A complex system is inherently sensitive to failures of its components. One must therefore determine maintenance policies in order to maintain an acceptable operating condition. Optimizing the maintenance is a very important problem in the analysis of complex systems. It determines when it is best that maintenance tasks should be performed on the system in order to optimize a cost function: either maximize a performance function or conversely minimize a loss function. Moreover, this optimization must take into account the random nature of failures and random evolution and dynamics of the system.

The example considered here is the maintenance of the heated hold-up tank, a well know test case for dynamic reliability, see e.g. [1–4]. The system consists of a tank containing a fluid whose level is controlled by three components: two inlet pumps and one outlet valve. A thermal power source heats up the fluid. The failure rate of the components depends on the temperature, the position of the three components monitors the liquid level in the tank, and in turn, the liquid level determines the temperature. The main characteristic of this system is that it can be modeled by a stochastic hybrid process, where the discrete and continuous parts interact in a closed loop. As a consequence, simulating this process and computing related reliability index has been a challenge for the dynamic reliability community. To our best knowledge, optimization of maintenance policies for the heated hold-up tank has not been addressed yet in the literature.

The only maintenance operation considered here is the complete replacement of all the failed components and the system restarts in its initial equilibrium state. Partial repairs are not allowed. Mathematically, this problem of preventive maintenance corresponds to a stochastic optimal stopping problem as explained by example in the book of Aven and Jensen [5]. It is a difficult problem because of the closed loop interactions between the state of the components and the liquid level and temperature. A classical approach consists in using condition-based maintenance (CBM) to act on the system based on its current state and before its failure. One can for example calculate the remaining useful life (RUL) of the system and the preventive replacement is carried out when the deterioration level exceeds a certain threshold or enters in a certain state [6,7]. Our approach also takes into account the current state of the process, but our decision rule is not based on damage accumulation nor does it correspond to hitting some threshold. Instead, it involves a performance function that reflects that the longer the system is in a functioning state the better.

The dynamics of the heated hold-up tank can be modeled by a piecewise deterministic Markov process (PDMP), see [4]. Therefore, our maintenance problem boils down to an optimal stopping problem for PDMP's. PDMP's are a class of stochastic hybrid processes that has been introduced by Davis [8] in the 1980s. These processes have two components: a Euclidean component that represents the physical system (e.g. temperature, pressure, …) and a discrete component that describes its regime of operation

* Corresponding author at: INRIA Bordeaux Sud-Ouest, team CQFD, F-33400 Talence, France. Tel.: +33 524574169.
E-mail address: saporta@math.u-bordeaux1.fr (B. de Saporta).

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and/or its environment. Starting from a state x and mode m at the initial time, the process follows a deterministic trajectory given by the laws of physics until a jump time that can be either random (e.g. it corresponds to a component failure or a change of environment) or deterministic (when a magnitude reaches a certain physical threshold, for example the pressure reaches a critical value that triggers a valve). The process restarts from a new state and a new mode of operation, and so on. This defines a Markov process. Such processes can naturally take into account the dynamic and uncertain aspects of the evolution of the system. A subclass of these processes has been introduced by Devooght [1] for an application in the nuclear field. The general model has been introduced in dynamic reliability by Dutuit and Dufour [9].

The objective and originality of this paper is twofold. First, we propose an optimization procedure for a well-known benchmark in the dynamic reliability literature. The tank model was first introduced by [12] where only one continuous variable (liquid level) is taken into account, and then in [13,2] where the second variable (temperature) is introduced. They have tested various Monte Carlo approaches to simulate the process to compute reliability and safety indices. In [14], the authors have used the same system to present continuous cell-to-cell mapping Markovian approach (CCCMT) still to simulate the process. The simulation of the holdup tank example has been and is still widely studied in the literature (not exhaustive) [15–19,11]. Here we go one step further and not only propose to simulate the tank process but also we optimize it.

Second, even though PDMP's have been recognized as a powerful modeling tool for dynamic reliability problems [1,9], there are very few numerical tools adapted to these processes. Our aim is to further demonstrate the high practical power of the theoretical methodology described in [10], by applying it to the tank benchmark. In [10], the authors have proposed a numerical algorithm to optimize PDMP's and have studied its theoretical properties. This optimization procedure was first applied to an example of maintenance of a metallic structure subject to corrosion, without closed loop interactions or deterministic jumps. In addition, the system has only one continuous variable and the cost function is simple and does not depend on time, see [11]. In this paper, we adapt the numerical procedure proposed in [10] to the more challenging heated hold-up tank problem with two continuous variables, deterministic jumps when these variables hit some given boundaries and closed loop interactions between continuous and discrete variables. Furthermore, we consider a cost function that depends on both continuous variables as well as on the running time.

The remainder of this paper is organized as follows. In Section 2, the dynamics of the heated hold-up tank is presented with more details as well as the framework of PDMP's. In Section 3 the formulation of the optimal stopping problem for PDMP's and its theoretical solution are briefly recalled and the four main steps of the algorithm are detailed. In Section 4 the numerical results obtained on the example of the tank are presented and discussed. Finally, in Section 5 a conclusion and perspectives are presented.

2. Model

We are interested in the maintenance of a heated hold-up tank. The dynamics of the tank can be modeled by a piecewise deterministic Markov process (PDMP). We first describe with more details the dynamics of the tank, then we recall the definition and some basic properties of PDMP's. The tank model is a well known benchmark in dynamic reliability. It was first introduced by [12] where only one continuous variable (liquid level) is taken into account, and then in [13,2] where the second variable (temperature) is introduced. We have kept the values of the parameters defined in those papers.

2.1. The heated hold-up tank

The system is represented in Fig. 1. It consists of a tank containing a fluid whose level is controlled by three components: two inlet pumps (units 1 and 2) and one outlet valve (unit 3). A thermal power source heats up the fluid. The variables of interest are the liquid level h, the liquid temperature θ and the state of the three components and the controller. Each component has four states: ON, OFF, Stuck ON or Stuck OFF. Once a unit is stuck (either on or off) it cannot change state. The possible transitions between these four states are given in Fig. 2. Thus, by a random transition a working unit can only become stuck (either on or off). The initial state of the components is ON for units 1 and 3 and OFF for unit 2. The intensity of jumps λ^i for unit i depends on the temperature through the equation $\lambda^i = a(\theta) l^i$ with $a(\theta)$ given in Eq. (1), see [13,2]

$$a(\theta) = \frac{b_1 \exp(b_c(\theta - 20)) + b_2 \exp(-b_d(\theta - 20))}{b_1 + b_2}. \quad (1)$$

Function $a(\theta)$ is represented in Fig. 3 and the various parameters come from the literature, see [13,2], and are given in Table 1. The special form of the failure rate λ^i as a product of a constant depending on i and a function of the temperature allows for all three units to have failure rates with the same dependence on the temperature, but different scaling parameters. Indeed, at the reference temperature of 20 °C, the mean time to failure of unit 1 is 438 h, for unit 2, it is 350 h and for unit 3 it is 640 h.

In addition, the shape for function $a(\theta)$ was chosen in the original benchmark so that there is a very high failure rate when the temperature is high. More specifically, the parameters are

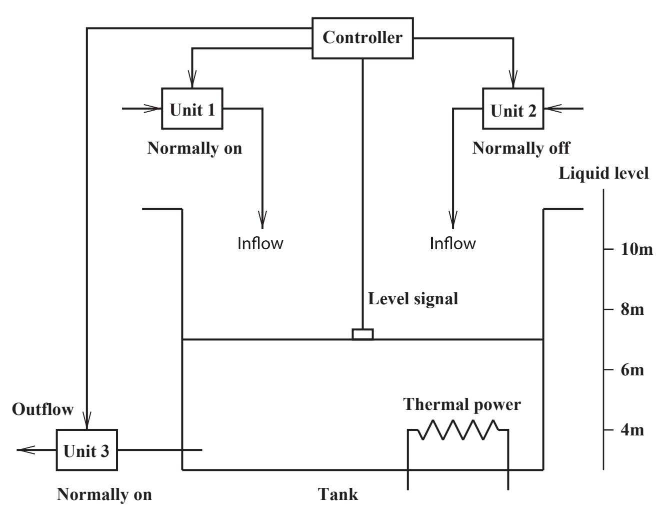

Fig. 1. The heated hold-up tank.

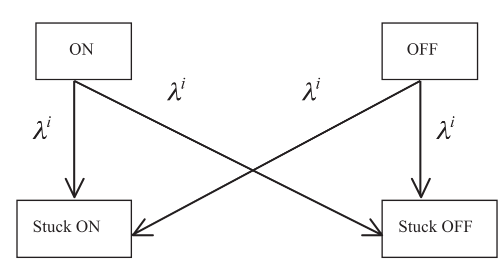

Fig. 2. Transitions for unit i.