Applying Bayesian Networks for Intelligent Adaptable Printing Systems*†

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Abstract

Adaptable systems are difficult to control as they have to dynamically adjust themselves at runtime to a changing environment, which is usually uncertain. Moreover, there is uncertainty about the underlying physical model of the system, which poses a problem for modelling the system's behaviour. In this paper, we propose to model the system using a Bayesian network, that can be learned, or tuned, from data. We demonstrate the usefulness of Bayesian networks for control by a case study in the area of adaptable printing systems and compare the approach with a classic PID controller.

1 Introduction

Many complex systems such as printers are required to make dynamic in-product trade-offs between various qualities of operation at the system level, which can be viewed as the capability to adapt. In printing systems, system-wide qualities include the power division, the speed of printing, the power consumption, etc. Such trade-offs heavily depend on the system's environment, e.g., humidity, temperature, available power, etc. Failure to adapt adequately to the environment might result in faults or suboptimal behaviour.

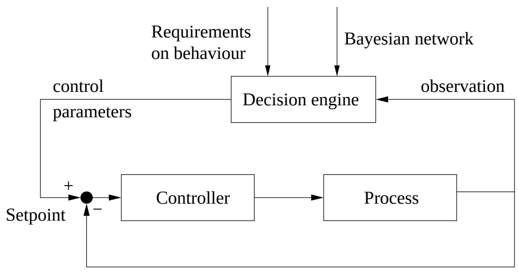

Figure 1: Block diagram of an adaptive controller using a Bayesian network.

The purpose of the paper is to convey some of our experience in building controllers based on Bayesian networks [3] in the area of adaptive printing systems, which can be looked upon as special stochastic controllers [1, 2]. A schema of this system is illustrated in Figure 1. In our view, as systems get more and more complex, the embedded software will need to be equipped with such reasoning capabilities for making sound decisions.

2 Case study: dynamic speed adjustment

The productivity of printers is limited to the amount of power available, in particular in environments which depend on weak mains. If there is insufficient power available, then temperature setpoints cannot be reached, which causes bad print quality. To overcome this problem, it is either possible to decide to always print at

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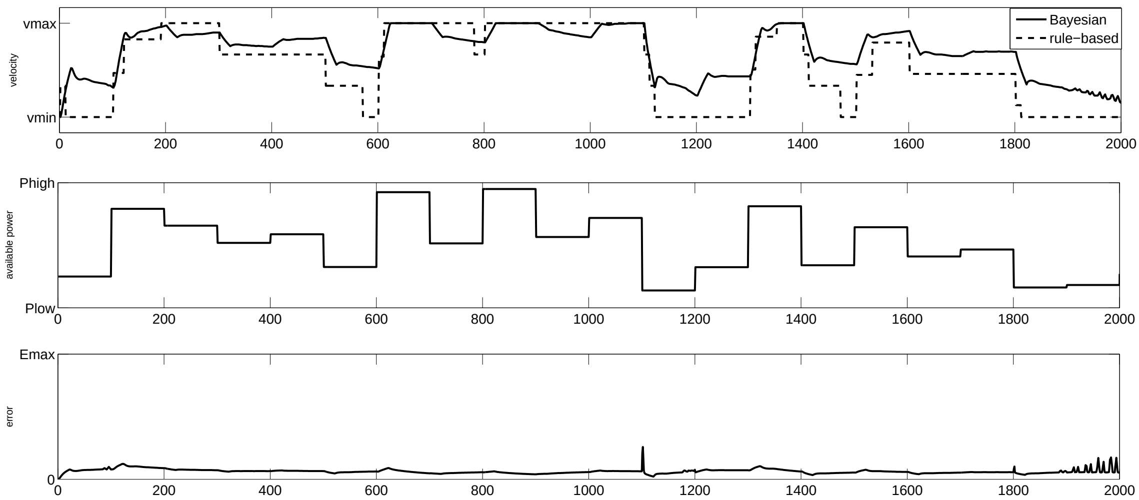

Figure 2: In the centre figure, the available power is plotted, which is fluctuating. at the top, we compare the velocity of the engine which is controlled by a rule-based system and by a Bayesian network. Below, we present the error that the controller based on the Bayesian network yields, which is within the required limit, i.e., below $E_{\max}$.

lower speeds or to adapt to the available power dynamically. The structure of a Bayesian network was elicited from a domain expert and parameters were learned using simulation data. The resulting network was used for controlling the velocity of the machine.

The print quality cannot be measured during runtime, but is related to observations about the available power and power requested from low-level controllers. The highest velocity is chosen such that the variable that determines the print quality does not deviate from printing norms with high certainty. We compared the productivity of the resulting network with a rule-based approach that incorporates heuristics for choosing the right velocity, which is shown in Figure 2. Compared to the rule-based approach, the Bayesian network improves roughly 9% in productivity while keeping the error within an acceptable range. While it could certainly be the case that the rules could be improved and optimised, the point is that the logic underlying the controller does not have to be designed. The model was estimated from data and a probabilistic criterion was defined which can be inferred during runtime. This is considered a significant advantage compared to the manually designed controller.

3 Conclusions

Bayesian inference is well-known for its estimation of hidden states in a dynamic model. In this paper, we go one step further, namely to use an understandable Bayesian network for estimations of setpoints, such as the velocity of the machine. Bayesian networks have drawn attention in many different application areas, such as psychology, biomedicine, and finance. Results of this paper provide evidence that explicit Bayesian networks can also be useful for the development of adaptive control systems.

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