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Multi-objective switching controller for cloud computing systems

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ABSTRACT

This paper presents the performance management of a web-server hosted on a private cloud (the target system). Based upon an identified linear switched model with workload arrival rate as the switching signal, the paper presents a new algorithm to develop a multi-objective switching controller to ensure asymptotic stability with pole placement in convex regions called the $\mathcal{D}_R$-regions in the complex plane. These results are applied to the target system for performance guarantees in terms of the client perceived response time under changing workload conditions. The identification, validation and real-time control experiments are demonstrated on the open source Eucalyptus cloud platform.

1. Introduction

Cloud computing is a model for enabling ubiquitous network access to a shared pool of computing and storage resources as a service. The cloud has essential characteristics such as on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service (http://csrc.nist.gov/publications/nistpubs/). Various services such as web-servers, email, e-commerce and video streaming are migrated to the cloud due to low cost and high scalability. Cloud is operational in three different forms: public cloud, private cloud, and hybrid cloud (http://aws.amazon.com/ec2/, http://aws.amazon.com/ec2/) with virtualization (Barham et al., 2003) as the key enabling technology. This allows partitioning of the physical machines into multiple computing devices called virtual machines (VMs).

A physical machine after virtualization is called the virtualized physical machine (VPM). The virtual machine manager or the hypervisor manages the sharing of the available hardware resources among different VMs to independently execute their own operating system with the hosted applications. A detailed description of the cloud terminology with hosted web-server is provided in Section 6 of this paper and can also be found in earlier work by the authors (Saikrishna, Chandrasekar, & Pasumarthy, 2015; Saikrishna, Bhatt, & Pasumarthy, 2015; Saikrishna, Pasumarthy, & Kruthika, 2015).

Modeling and Control of Cloud computing systems: As cloud is a heterogeneous and large scale distributed system, hence the management of its resources is indeed a challenging task. Feedback control theory provides well established tools for modeling and performance management of such complex systems. In this direction, this paper presents a systematic approach for modeling and performance control for supporting applications such as SaaS (Software as a Service) on the cloud.

One of the widely used SaaS on the cloud is a web-server. It delivers information by means of a web-page to the clients using the Hypertext Transfer Protocol (HTTP). The performance of the hosted web-server hosted (henceforth called the target system) is evaluated by modeling it as a switched linear system. The constituent MIMO (multi-input multi-output) state space models are obtained at several well defined operating regions by grey-box identification technique. More details on modeling is presented in Section 3.

Switched systems and pole placement: Switched systems are an important class of hybrid systems which consist of continuous or discrete-time sub-systems and a rule to orchestrate switching between them (Daafouz, Riedinger, & Iung, 2002). A switched linear system alternates among different linear modes of operation. In this work, arbitrary switching between linear discrete-time sub-systems of the target system is considered. The desired performance specifications like settling time and damping in each mode of the switched system translate to placing the poles of the closed-loop system at the corresponding locations in the complex plane via an appropriate state feedback. This technique is usually referred to as pole placement (Hellerstein, Diao, Parekh, & Tilbury, 2004).

Due to the wide range of applications of pole placement techniques, extensions of Ackermanns explicit formula (Ackermann, 1972) and various numerical algorithms such as (Kautsky, Nichols,

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& Van Dooren, 1985; Valášek & Olgac, 1995; Varga, 1981) were developed for exact pole placement. However, when the modeled system has uncertainties, a strict pole placement in the desirable locations is no longer valid. Therefore, a non-strict placement in a region of the complex plane is preferred. Since a slight migration of the closed loop poles around desirable pole location may not significantly effect the transient response and therefore the robust performance of the system can be assured.

The results pertaining to the switched systems with pole placement in this paper can be viewed as an extension of recent work by Daafouz, Riedinger, and Iung (2004, 2002), Daafouz and Bernussou (2001), Peaucelle, Arzelier, Bachelier, and Bernussou (2000) and Montagner, Leite, and Peres (2003) to ensure switching stability with regional pole placement in the desirable sub-regions of the z-plane. To the best of authors knowledge, there are very few techniques in literature to accomplish such a design objective.

2. Related work on control of computing systems

For physical systems, fairly accurate models can be derived from first-principles. Some of the prominent work in the first-principles approach for computing systems were fluid approximation based models of server systems presented in Misra, Gong, and Towsley (2000) for modeling relationship between TCP/IP window size and router queue length, Malrait, Bouchenak, and Marchand (2011) for modeling the allocation of storage to cache memory pools. Although these attempts and some others such as Abdelzaher, Lu, Zhang, and Henriksson (2004) and Kihl, Robertsson, and Wittenmark (2003) are indicative of success in the first-principles approach, they also suggest a considerable increase in sophistication required for modeling. Therefore, deriving an analytical model using first-principles for a complex computing system like the cloud would be extremely difficult (Hellerstein et al., 2004). Queing theory based models are also widely used for the performance measurement of computing systems, see for example, Ardagna, Casale, Ciavotta, Pérez, and Wang (2014) and references therein. However, they are only suitable for steady state analysis with open loop control (Qin & Wang, 2007; Hellerstein et al., 2004).

Data driven approaches to modeling such as black-box and grey-box models (Ljung, 1987) offer a possible alternative to the first-principles approach especially for systems for which physical laws governing the dynamics are not readily available. These models help in deriving the relationship between input–output variables by applying estimation techniques to the data collected from the target system at various operating regions. In computing systems, since the workload characteristics (the workload arrival rate λ and the service rate μ) also affect the performance metrics apart from the control inputs. The effect of control inputs is considered in the presence of representative workloads (Hellerstein et al., 2004) and the developed models are often described as the workload based models. In this paper, we present workload based model for the target system with the data-driven approach.

The rest of the paper is organized as follows: Section 3 describes the problem formulation, while Section 4 describes the main results. Section 5 describes the algorithm for multi-objective switching controller. Section 6 describes the experimental environment of the Eucalyptus private cloud, while Section 7 presents the system identification technique to develop MIMO LTI models of the target system followed by model validations. Section 8 presents the real time evaluation of switching controller performance. Finally the concluding remarks and future work are presented in Section 9.

3. Problem formulation

The first objective of the present work is to develop a linear switched model for the target system using system identification technique. The second objective is to develop a control strategy to ensure quality of service (QoS) (i.e. the response time below certain set value under changing workload conditions with minimal use of virtual machines) in addition to ensuring stability of the target system. This objective translates to placing poles of the target system at desired regions in the complex plane called the $\mathcal{D}_R$-regions. The aim is to accomplish this goal by successive partial pole placement of a subset of poles in the $\mathcal{D}_R$-region by using an aggregation technique (described later in the paper). This leads to solving a multi-objective problem to ensure switching stability with pole placement in distinct sub-regions of the $\mathcal{D}_R$ regions.

State space model of the hosted web-server: The state variables chosen for the target system are the average CPU utilization $CPU(k)$ (of all the running VMs on a VPM), the response time $RT(k)$ and the throughput $TP(k)$ are represented as $x_1(k)$, $x_2(k)$ and $x_3(k)$ respectively. The control inputs are the admission control and the VM control denoted by $u_{adm}(k)$ and $u_{vm}(k)$ respectively. The admission control is used for regulating the workload whereas the VM control input is used to modulate the number of running VMs serving the workload. The requests served by the hosted web-server, denoted by $u_{req}(k)$ is chosen as the exogenous input to the model. This is because, the serviced requests affect the dynamics of the state variables apart from the control inputs. Consequently, all the state variables at any instant would also depend on the exogenous input. As the CPU is the available computing resource, the response time and throughput depend on the state $CPU(k)$. Hence, the MIMO LTI model over an operating region can be written as:

$$\begin{aligned} CPU(k+1) &= a_1 CPU(k) + b_1 u_{adm}(k) + b_2 u_{vm}(k) \\ &\quad + b_3 u_{req}(k) \\ RT(k+1) &= a_2 CPU(k) + a_3 RT(k) + b_4 u_{adm}(k) \\ &\quad + b_5 u_{vm}(k) + b_6 u_{req}(k) \\ TP(k+1) &= a_4 CPU(k) + a_5 TP(k) + b_7 u_{adm}(k) \\ &\quad + b_8 u_{vm}(k) + b_9 u_{req}(k) \end{aligned} \tag{1}$$

The exogenous input u_{req} is decoupled from (1) to differentiate it from the control inputs u_{adm} and u_{vm}. The modified MIMO LTI model may be written as:

$$\begin{bmatrix} CPU(k+1) \\ RT(k+1) \\ TP(k+1) \end{bmatrix} = \begin{bmatrix} a_1 & 0 & 0 \\ a_2 & a_3 & 0 \\ a_4 & 0 & a_5 \end{bmatrix} \begin{bmatrix} CPU(k) \\ RT(k) \\ TP(k) \end{bmatrix} + \begin{bmatrix} b_1 & b_2 \\ b_4 & b_5 \\ b_7 & b_8 \end{bmatrix} \begin{bmatrix} u_{adm}(k) \\ u_{vm}(k) \end{bmatrix} + \begin{bmatrix} b_3 \\ b_6 \\ b_9 \end{bmatrix} u_{req}(k) \tag{2}$$

The proposed model is often described as the workload based model as it considers the workload characteristic i.e. the service rate (μ) or u_{req} (in the present model) as the exogenous input. It is obtained by using input-output data by exciting the target system with the representative workload or arrival rate (λ) while altering the control inputs. Ten such MIMO LTI models are obtained using system identification technique. The arrival rate (λ) of the workload is used as a switching signal to switch between operating regions of the target system. Therefore the linear switched system representing the target system is of the form:

$$x(k+1) = A_\alpha x(k) + (B_1)_\alpha u_1(k) + (B_2)_\alpha u_2(k) \tag{3}$$