Model-Predictive Controllers for Performance Management of Composable Conveyor Systems

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***Abstract*—Composable Conveyors expose fundamental new problems that must be addressed as the nation transforms its advanced manufacturing infrastructure. Unanticipated fluctuations in workloads caused by the increasingly open and interconnected advanced manufacturing systems makes it significantly challenging to appropriately configure and adapt the operating parameters of conveyor systems that are deployed at individual plants such that reliability and desired quality-of-service (QoS) requirements are met. Moreover, these must not be tightly coupled to a single layout but work seamlessly after the conveyor layouts change. To address such challenges, this paper describes different controller design strategies and compares each approach against a baseline system without any controller.**

***Index Terms*—Composable conveyors, controller design**

I. Introduction

Material handling and packaging systems are excellent examples of widely-used engineered systems that embody many characteristics of cyber physical systems (CPS). Such systems have applications in warehouses, manufacturing plants, package sorting facilities (e.g., FedEx and UPS), and even in front-line logistics for military deployments. Composable conveyor systems (CCS) provide composable and reconfigurability in the layout of an assembly or material handling plant that makes them attractive in application scenarios because they can adapt to changing process and environmental demands – an emerging need for advanced manufacturing systems that aspire seamless interconnection across the supply chain and the plant floor [1].

CCS, like other automation systems, are becoming increasingly open and more connected to the supply chain. Workloads in the system can fluctuate substantially; e.g., holiday season may experience dramatic increase in packages that must be sorted and shipped to their destinations. In such situations, statically-defined preset speeds for the entities of the CCS may not be sufficient to effectively operate the system. Similarly, unforeseen disruptions in the supply chain can make any fixed schedule ineffective. Plant operators are thus faced with the task of addressing at least two key challenges.

- First, they must be able to dynamically adapt the operation of their plant to maximize the throughput and minimize energy consumption while adapting to the unanicipated workload fluctuations.
- Second, these dynamic adaptation capabilities must remain available when the conveyor topology or layout of the plant floor undergoes change due to business specific and other logistical reasons.

Our prior work for CCS has explored the use of model driven engineering tools to reason about different properties of CCS conveyor layouts prior to their actual deployment [2]. More recently we adapted the classical priority inheritance protocol to resolve priority inversions in CCS [3]. None of these efforts investigated the use of model predictive control. On the other hand, we have designed a model-predictive, two-level controller for the adaptive performance management of computing systems, however, this solution was applied to a purely cyber-only system [4]. In the current work we focus on cyber physical systems and account for both the physical dynamics and the cyber interactions of these sysetms. To that end we are exploring three alternative model predictive approaches to controller design for CCS. The rest of this paper provides the status of our ongoing work.

II. Alternate Designs of Model Predictive Controllers for CCS

A. Controller Design

System Model: The composable conveyor systems (CCS) we consider for our research comprises multiple instances of two kinds of units, namely, Segment and Turn. A Segment has a belt whose speed and direction can be controlled. A Turn is a reconfigurable merger/splitter unit that can be juxtaposed with upto four Segment instances. These conveyor systems can be controlled by regulating the speed of the belt on the individual Segment units. The load in the system, i.e., the number of packages handled by different units in the system can be regulated by dynamically routing the packages over different end-to-end paths in the system. Configuring and synchronizing the speeds of the Segments is unlikely to be scalable if the decisions are made in a central location. The speeds must also be adjusted in response to variabilities in the arrival rates of the packages at the different inputs to the system.

Our current work focuses on addressing the first challenge, i.e., predict unforeseen workload and autonomically configure the minimum belt speed needed for energy conservation and maintaining the maximum throughput. In our design, we allow six speed levels for the belts: two levels for low, two for medium, and two for high. For our ongoing work, the conveyor topology is fixed. Figure 1 and the logistics are predefined. I1 and I2 denote input bins, S1,S2, ..., S8 represent segment belts; T1, ..., T4 are switch turns; and O1 and O2 are output bins. Two flows are fixed for the incoming workloads according to the arrow directions shown in Figure 1

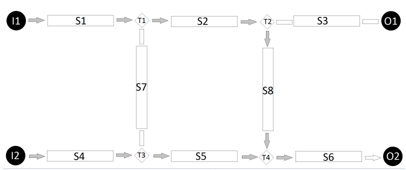

Fig. 1. MainTopology

We use an ARIMA model to make the estimation and adjust the parameter based on the patterns of arrival. The local controller is a limited look-ahead controller (LLC). We also define a cost function to measure the QoS. This function takes into account the cost of the control inputs themselves and their change. It is also possible to consider transient costs as part of the operating requirements, expressing the fact that certain trajectories towards the desired state are preferred over others in terms of their cost or utility to the system.

In short, the LLC controller predicts for the next time step the package arrival rate, traverse all 6 possible speed values (in two-level controller, it has a difference that is explained later), and calculate cost function, and finally choose the speed which can make the next cost function minimum and achieve energy saving. Energy consumption is directly related to belt speed. The following four strategies are designed:

(1) No controller (NC): The systems units (conveyor belts) have fixed speed. The system uses maximum speed to make sure no package is dropped.

(2) Totally decentralized controllers (TD): Each unit has a local LLC controller and predicts arrival rates independently of each other. This approach is easy to extend but lacks precision and incurs unstability with large variability in arrival rate.

(3) Partially decentralized controllers (PD): Each unit has a local LLC controller but it predicts the arrival rate taking into account the speed of the preceding unit. This is more accurate than the previous approach but requires additional communication.

(4) Two-level global controller (GC): This approach is based on a completely decentralized controller design, where the individual controllers at the first level make short-term predictions of workloads. These controllers are in turn managed by a second level controller that makes longer-term forecasts of expected workloads and fine tunes the performance of the system. The global controller decides for the next 60 time units the speed level so that the system can only traverse limited times of speed level. The two level controller can reduce the space complexity from $O(n^2) \rightarrow O(n)$.

B. Preliminary Results

We present preliminary results of simulation experiments we performed. To compare the strategies, we apply the same topology and the same package arrival rate at the input bins.

Prediction evaluation: Figure 2 presents prediction behavior of a segment S1 in our topology using a ARIMA model. The green line is estimation error, and the average estimation accuracy rate is 88.13%. If the package workload changes dramatically, we observe larger error differences because incoming package arriving rate is sharply different from previous workload.

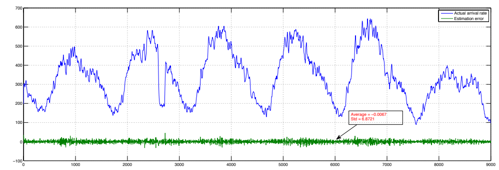

Fig. 2. Belt S1's Prediction Evaluation in TD

Energy Conservation: Table I summarizes the energy conserved by the three strategies when compared against the no controller strategy.

TABLE I
ENERGY CONSERVATION EVALUATION

Simulation	Energy Conservation%
TD	83.62
PD	83.95
GC	74.39

III. CONCLUDING REMARKS

Our current work focuses on developing controllers for autonomic performance management of composable conveyor systems used in advanced manufacturing. This work presented preliminary results on performance and energy savings accrued using three different model predictive controller designs. Our ongoing work is evaluating the designs on different conveyor topologies and workload arrivals based on real-world workloads. All simulations are available for download from https://github.com/onealbao/Composable_Predictable_Controller

ACKNOWLEDGMENTS

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