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Real-Time Manufacturing Machine and System Performance Monitoring Using Internet of Things

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***Abstract*—This paper introduces a framework to assess the performance of manufacturing systems using hybrid simulation in real time. Continuous and discrete variables of different machines are monitored to analyze performance using a virtual environment running synchronous to plant floor equipment as a reference. Data are extracted from machines using industrial Internet of Things solutions. Productivity and reliability of a physical system are compared in real time with data from a hybrid simulation. The simulation uses discrete-event systems to estimate performance metrics at a system level, and continuous dynamics at a machine level to monitor input and output variables. Simulation outputs are used as a reference to detect abnormal conditions based on deviations of real outputs in different stages of the process. This monitoring method is implemented in a fully automated manufacturing system testbed with robots and CNC machines. Machines are integrated on an Ethernet/IP control network using a programmable logic controller to coordinate actions and transfer data. Results demonstrated the capacity to perform real-time monitoring and capture performance errors within confidence intervals.**

***Note to Practitioners*—Estimating expected performance of a manufacturing system processing different parts across multiple machines is a complex problem due to the lack of closed-form equations. Existing solutions focus on monitoring stochastic variables such as production or failure rate, or machine dynamics in separate environments often running asynchronous to the real system. This paper addresses the problem of monitoring and assessing the performance of complex manufacturing systems in real time. The proposed framework uses a real-time hybrid simulation of manufacturing at a machine and system level. The hybrid approach is based on a discrete and continuous model of manufacturing equipment integrated to run synchronously with the real plant floor operation. Data from both the virtual and real environments are merged to assess performance. Deviations from expected values represent an error that can trigger a warning signal to production, maintenance, and/or manufacturing personnel at the plant regarding health and productivity of plant operations.**

***Index Terms*—Cyber-physical systems, discrete-event systems (DES), manufacturing automation and control, real-time hybrid simulation.**

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NOMENCLATURE

Discrete

Machine Level:

H	Atomic model.
U	Set of inputs.
Y	Set of outputs.
S	Set of states.
δ_{int}	Internal transition function.
δ_{ext}	External transition function.
Δ	Set of transitions functions.
λ	Output function.
t_{adv}	Set of transition times.
e_i	Input event.
e_o	Output event.
s_j	State.
τ_j	Transition time.
w	Buffer occupancy.

System Level:

G	Coupled model.
$\boldsymbol{U}, \boldsymbol{U}^*$	Set of inputs, Kleene closure of set of inputs.
$\boldsymbol{Y}, \boldsymbol{Y}^*$	Set of outputs, Kleene closure of set of outputs.
$\boldsymbol{M}$	Set of atomic models.
EIC	External input coupling.
EOC	External output coupling.
IC	Internal coupling.
Select	Tie-breaker function.
E_i	String of input events.
E_o	String of output events.
N_i	Number of arrivals.
N_o	Number of departures.
Λ	Arrival rate.
μ	Throughput.
β	Work-in-process.
Ψ	Vector of cycle times.

Continuous

$x(k)$	State-variable in discrete time.
$y(k)$	Output-variable in discrete time.
$\Theta(z)$	Time-series matrix of state-variables to process zth event in E_i.
$\Gamma(z)$	Time-series matrix of outputs to process zth event in E_i.

Analysis:

$r_\tau(z)$	State-variable in discrete time.
$r_\Theta(z)$	Output-variable in discrete time.