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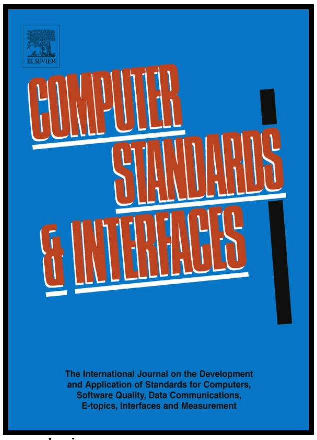

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Adjusting middleware knobs to assess scalability limits of distributed cyber-physical systems

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***Abstract*—The traditional development paradigm for time-sensitive distributed systems (and even more for real-time domains) has typically relied on unflexible low-level schemes; these have been based on (also) low-level programming of improved medium access control protocols to obtain deterministic network schedules. Such technique does not scale well in the context of cyber-physical systems (CPS), which have a complexity of several orders of magnitude higher. In this paper, we explore the actual trend of cyber-physical systems (CPS) that are progressively integrated with Internet technologies to fulfill their requirements of being highly connected systems. The integration pillar is the communication middleware; however, communication middleware technologies are prone to introducing delays at different levels, increasing the potential uncertainty of the system execution. Therefore, individual analysis of middleware technologies is needed to assess the bounds on the type and scale of CPS that they can support. We analyse the behavior of a specific a middleware technology and its cost for handling the interaction of distributed nodes in the context of cyber-physical systems. We propose the design of a reliable middleware-based communication infrastructure for distributed embedded systems integrated in a CPS environment. Our approach considers time requirements specified by the system nodes or *units*, and fine tunes a few specific parameters of the middleware that we refer to as *knobs*. We validate our solution implementation in a experimental setting and show the system scale that can be supported in a stable way.**

I. INTRODUCTION

The vision of cyber-physical systems is extremely challenging as they are highly dynamic systems immersed in ultra large scale deployments, prone to suffering interference by other subsystems [26]. Although they have inherent real-time requirements, it is often the case that in their large scale structure there are different subsystems with *different levels of temporal requirements*; these may range from hard safety-critical real-time subsystems to time-sensitive domains such as cloud computing [13] or best effort ones. Figure I shows a typical deployment of a CPS related to the remote monitoring and control of a factory floor that involves the monitoring of physical processes. Gathered information may be sent to the cloud to be analysed, resulting in the fine tunning of the factory floor processes.

One challenging point of CPS is their development cost at both hardware and software levels due to the number of techniques, paradigms, and technologies that are involved. Only software-wise, the development of CPS [26] requires mastering a number of different modeling, design, and verification paradigms as well as the associated platform technologies

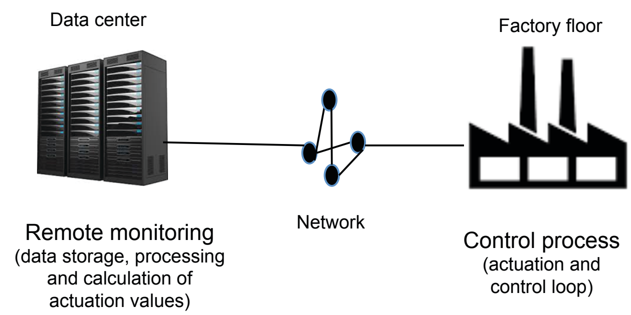

Fig. 1. A CPS for remote monitoring and control of a factory floor.

such as operating systems and kernels, network protocol run-time software, middleware technology, and the specific application level logic.All these technologies have to cooperate to ensure the functional correctness as well as the non-functional properties that are essential as *timeliness*. Therefore, easing their *programming* becomes essential, so techniques and technologies that support *platform abstraction* and *reusability* have to be integrated in their development.

Middleware solves part of this problem as it clearly favors programmability by providing *platform abstraction* allowing highly *heterogeneous* subsystems (or nodes) to effectively *interoperate*. Also, it is the layer in the software stack where enhanced functionality can be put in place to address requirements such as *adaptation* and *dynamic reconfiguration*.

Nevertheless, the CPS community (mainly, real-time systems) has been reluctant to use middleware, as it has been typically seen as a black box software layer prone to *unpredictable behavior*. To guarantee predictability, low-level network programming has been usually employed making direct use of the media access protocols in order to ensure timely delivery and the calculation of a network schedule for real-time communications. However, this has yielded to unflexible designs where the dynamic behavior could hardly be accomodated. Addition/removal of a functional piece or node would typically result in the redesign of the system and of the network transmission schedule.

In this paper, we describe an approach to support adaptivity and dynamic behavior in distributed systems in the context of cyber-physical environments by providing a middleware that performs active monitoring and ensures the service time contracted by the system nodes (called *units*). The middleware is validated on a soft real-time environment with the dynamic