Chapter 6
Architecture of an Open-Source Real-Time Distributed Cyber Physical System

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ABSTRACT

Cyber physical systems are based on a number of nodes connected through a communication network, which can interact with the environment. In this chapter, a completely open-source architecture of a cyber physical system based on off-the-shelf components will be presented. Its main characteristics are high real-time capabilities and the use of both wired and IEEE 802.11 wireless technologies for communication. The Linux operating system installed on common personal computers and communication technologies derived from the IT world make the proposed architecture highly customizable, inexpensive, and performing. Moreover, the presence of a time synchronization service allows the sharing of time between nodes. Specific software and techniques, some based on synchronized nodes, are used to increase determinism and reliability in both wired and wireless extensions.

INTRODUCTION

Cyber physical systems (CPSs) (Guan et al., 2016) are based on a number of nodes connected through a communication network, which can interact with the environment. Application contexts that foresee the use of CPSs are Industry 4.0, building automation and smart grids (Yu & Xue, 2016). In such systems, nodes are connected through a wired or a wireless network, but commonly a typical configuration relies on the combination of both. In many applications, such as those regarding manufacturing systems, determinism on data exchanges between nodes of the system is the most important requirement.

On the other hand, in recent years, open-source software and applications are approaching CPS market. Open-source provides a low cost and effective method to implement inexpensive, performing and bug free applications. The need of open-source components for many application contexts derives from their capability to be highly customizable. This characteristic impacts directly on performance

to preform actuations or sensing physical quantities, in terms of determinism and latency. The use of open-source software for real embedded systems has been described in the book (Cibrario Bertolotti, & Hu, 2015). Other examples of use of open-source software will be provided in the next sections. In the PC world, the Linux operating system is an example of widely adopted open-source platform, which offered long-term support and development. These last features are really important for systems such as CPS, which are updated and replaced infrequently. The Linux operating system is often chosen by researchers, users and developers. Moreover, the code of the operating system, and of its software suite, is well documented, allowing to expert users a really high degree of control of any behavioral aspect. From the network point of view, Ethernet is the "de facto" standard for wired networks. Regarding wireless, a number of technologies exist, but the most common, fast and easily interoperable with Ethernet is IEEE 802.11, also known as Wi-Fi. For cost reasons and ease of configuration and installation, these technologies are the best candidates for a CPS based on open-source components. It is worth pointing out that, while the majority of protocols for industrial automation rely on Ethernet, possible candidates in industrial CPS for wireless extensions are IEEE 802.11, Bluetooth or wireless sensor networks based on the IEEE 802.15.4 standard (Lu et al., 2016).

In this chapter, a possible implementation of a CPS based on the Linux operating system is presented. The proposed architecture exploits the RTAI or XENOMAI hard real-time schedulers to guarantee the required degree of determinism of nodes. It makes use of synchronization protocols, in both the wired and the wireless extensions, to provide all the nodes a common view of time. Transmission latency can be reduced in the wired network by using hard real-time protocol stacks (such as, e.g., RTnet) and channel access methods as the time division multiple access (TDMA). Regarding Wi-Fi, redundancy techniques based on the transmission of the very same data packet on two non-overlapping networks allow to reduce both the number of packets lost and latency. Finally, we will show how the proposed architecture simplifies the integration of popular industrial protocols (e.g., EtherCAT or Modbus TCP) within the communication system.

BACKGROUND

CPSs usually interact with the surrounding environment through a wired or a wireless network. Sensing applications used to measure physical values are characterized by few timing requirements. Usually, a network wide notion of the time is maintained through specific synchronization protocols. Common time allows network nodes to associate a time to measured values. It is the case of wireless sensor networks (WSN) (Zaman, Ragab, & Abdullah, 2012) or monitoring systems. A large class of CPS applications is control systems (CSs). In CSs, remote actuators have to be continuously managed by a control unit. In its control-loop, the CS cyclically makes use of data acquired by remote sensors to properly command actuators. The main requirements of CSs are the determinism of the communication network and its reliability. In practice, a network packet has to reach the receiving node within a predefined deadline. In hard real-time (HRT) systems deadlines cannot be exceed, while in soft real-time (SRT) systems they can be exceed with low probability, i.e., the deadline miss ration has to be bounded. For wired networks, a number of protocols, technologies and node architectures, typically originated from the industrial world, are able to ensure HRT constraints. Nowadays, only SRT is possible for wireless networks. This is mainly due to the non-exclusive use of the communication medium (i.e., the ether) by nodes involved in the communication. Nevertheless, a number of countermeasures appeared in scientific literature to

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