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A Time Synchronization Protocol for Large-Scale Distributed Embedded Systems with Low-Precision Clocks and Neighbor-to-Neighbor Communications

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Abstract

In this paper, we propose the Modular Robot Time Protocol (MRTP), a network-wide time synchronization protocol for modular robots (a class of distributed embedded systems) with neighbor-to-neighbor communications and potentially low-precision clocks. Our protocol achieves its performance by combining several mechanisms: central time master election, fast and recursive propagation of synchronization waves along the edges of a breadth-first spanning-tree, low-level timestamping and per-hop compensation for communication delays using the most-appropriate method, and clock skew compensation using linear regression. We evaluate our protocol on the Blinky Blocks system both on hardware and through simulations. Experimental results show that MRTP can potentially manage real systems composed of up to 27,775 Blinky Blocks. We observe that the synchronization precision depends on the hop distance to the time master, the synchronization periods and the number of synchronization points used for the linear regressions. Furthermore, we show that our protocol is able to keep a Blinky Blocks system synchronized to a few milliseconds, using few network resources at runtime, even-though the Blinky Blocks hardware clocks exhibit very poor accuracy and resolution. We compare MRTP to existing synchronization protocols ported to fit our system model. Simulation results show that MRTP can achieve better synchronization precision than the most precise compared protocols while sending more than half less messages in compact systems.

Keywords: Time synchronization, Distributed embedded systems, Modular robotics

1. Introduction

Technological advances, especially in the miniaturization of robotic devices, foreshadow the emergence of large-scale ensembles of small-size and resource-constrained robots that will self-organize and distributively cooperate to achieve complex tasks (e.g., modular robotic systems (Yim et al., 2009), swarm robotic systems (Şahin, 2004), distributed micro-electro-mechanical systems (Bourgeois and Goldstein, 2012), robotic materials (McEvoy and Correll, 2015), programmable matter (Goldstein and Mowry, 2004; Bourgeois et al., 2016), etc.). These ensembles are formed from independent, intelligent and communicating robots which act as a whole. In addition, these robots are able to re-arrange their connectivity in order to adapt the global structure of their ensemble to specific applications, providing robustness and versatility.

We believe that lots of innovative and complex applications based on large-scale ensembles of robots are to appear and will be fully integrated in our daily-life environment. In (Goldstein and Mowry, 2004; Bourgeois et al., 2016), it is, for example, envisioned to use thousands to millions of micro modules to build programmable matter, i.e., matter that can change its physical properties in response to external and programmed events.

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