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RoboNetSim: An integrated framework for multi-robot and network simulation

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ABSTRACT

In networked multi-robot systems, communication plays a major role defining system's dynamics and performance. Unfortunately, existing multi-robot simulators do not provide advanced communication models. Therefore, given the intrinsic unreliability of wireless communications, significant differences might be observed between simulation and real-world results.

Addressing these issues, we present *RoboNetSim*, an integrated simulation framework for communication-realistic simulation of networked multi-robot systems. RoboNetSim integrates multi-robot simulators with network simulators. We present two model implementations based on ARGoS at the robotic side, and NS-2 and NS-3 as network simulators. We evaluate the framework in terms of accuracy and computational performance, showing that it can efficiently simulate systems consisting of hundreds of robots.

Using the Stage simulator as an example, we also show the integration of a robotic simulator with RoboNetSim by only adapting robot controllers, without the need to adapt the general code of the simulator.

Finally, we demonstrate the effects of communication on mobile multi-robot systems. We consider two different case studies: a distributed coordination and task assignment scenario, and a coordinated mobility scenario. We compare realistic network simulation with simplified communication models and algorithms, and we study the resulting behavior and performance of the multi-robot system and the impact of different parameters.

1. Introduction

There are three main motivations behind the use of multi-robot systems compared to single-robot approaches. The first one is robustness, which is particularly important in autonomous robotics: if one of the robots fails, other robots can potentially take over its tasks. The second motivation is efficiency: some tasks can be naturally solved more efficiently by exploiting the intrinsic parallelism and distributedness of multi-robot systems. The third one is efficacy: tasks that may be unreachable for individual robots could be effectively solved by a robot team through an explicit synergy of behaviors. These motivations lie at the roots of swarm robotics [1], and other approaches to distributed robotics.

Although the robots of a multi-robot system can be designed to act as autonomous and independent agents, in most cases the key to best exploit the capabilities of a multi-robot system lies in the use of *information sharing*. Coordination, cooperation and behavioral synergies, they all require the robots to exchange information. This applies to autonomous robotic systems, where robots exchange information within a team, as well as to externally controlled systems, where robots may be required to aggregate gathered information and send it to the control center to close the loop. In any case, effective communication tools and techniques are desired in order to unleash the full power of a multi-robot system.

Robot communication can be realized in many different ways using different physical interfaces. In the literature one can find approaches based on *indirect communication* via sensing or via interaction with the environment (see [2,3] for a review), or based on *simple direct communication* between robots, e.g. utilizing visual communications based on LEDs [4]. If robots are not mobile, fixed telecommunication lines can be reliably employed for high-bandwidth data exchange. However, in the context of mobile multi-robot systems, which is the case we focus on in this paper, it is rather obvious that *wireless radio communication* is the most powerful technique in terms of fast and effective information sharing (e.g. [5]). However, when using wireless communications, one basic problem arises. On the one hand, we expect the communication tools to be effective and trustworthy in order to enable the correct implementation of desired cooperation and coordination strategies. On the other hand, in the real world communications are not fully reliable. This is particularly true for *wireless mobile ad hoc networks* (MANETs [6]), which are the natural choice for fully autonomous multi-robot systems. The

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presence of unreliable communication can seriously affect the actual performance of a multi-robot system. Therefore, this issue needs to be taken into account while designing and simulating such systems.

In multi-robot (or multi-agent) systems, one typical approach for dealing with the problem of unreliable communication consists in trying to avoid or limit communication as much as possible, emphasizing the pure locality of interactions. This approach is popular in swarm robotics, where, for instance, the above mentioned indirect communication is commonly used. This way of proceeding, although it may increase the robustness of the system as a whole, does not allow to fully benefit from effective information dissemination and long-range interactions that would be available from advanced wireless telecommunication techniques. In simulation-based works, another typical approach is to make idealized assumptions about communication. For instance, in [7] the authors assume that messages sent by robots via broadcasting are immediately available to all other robots. This approach allows one to focus on other scientific issues, yet makes the study less realistic. In fact, we claim that, in order to reflect what happens in the real-world and properly validate high-level team strategies, a communication model for networked robotic systems, especially for large-scale ones, needs to consider the operations of different network protocols, radio interferences, and MAC layer collisions. Thus, a reliable and detailed (packet-level) communication model is required. As a matter of fact, only a few works deal with the problem of realistic simulation of communication among networked robots (see Section 2.3).

The above observations led us to the conclusion that there is a strong need for investigating the actual influence of communication on the operation of multi-robot systems. Such studies can be performed either on real robots or using advanced simulation tools. Unfortunately, real testbeds are costly, difficult to realize and often limited in the number (and/or size) of experiments that can be done. At the same time, no single tool exists that offers advanced and realistic simulation of both robotic and communication issues.

The aim of this paper is precisely to propose a simulation tool which is communication-realistic and helps understanding the relation between the quality of communication and the operation of a large multi-robot system (a partial version of this work was published in [8]). We propose *RoboNetSim*: a general framework that is capable of combining physics-based multi-robotic simulators with state-of-the-art network simulation tools. We apply the proposed architecture and implement two integrated simulation environments, both based on open source tools, namely the *NS-2* [9] and *NS-3* [10] network simulators and the *ARGoS* simulator, designed for swarm robotics [11,12]. The first environment combines ARGoS with NS-2, and the second one combines ARGoS with NS-3. We perform an extensive experimental study to evaluate the general framework architecture and the instantiated simulation tools in terms of computational performance, correctness, and generated overhead. We show that the integrated framework is able to efficiently and realistically simulate systems consisting of hundreds of mobile robots.

The two integrated environments above are based on the full integration of a robotic simulator with a network simulator: they provide additional modules of the robotic simulator (e.g., sensors, actuators, etc.) that make the integration with a network simulator transparent to the user who develops robot controllers. Since this integration process requires some structural changes in the simulators at hand, we also demonstrate a simpler way of integrating with RoboNetSim. Namely, we show a minimum number of steps that must be taken in order to 'plug in' a robotic simulator into the proposed architecture by only acting at the level of robot controllers. As a practical example, we consider the plug-in of the *Stage* [13,14] robotic simulator.

In order to show in practice the importance of realistic network simulation and the impact of different communication models, we employ RoboNetSim in the context of simple, yet paradigmatic tasks for multi-robot cooperation and coordination. We design a distributed task-assignment problem and a coordinated mobility problem, and we show that simulating networking issues with different degrees of accuracy results in different behaviors and performance. In turn, these would have a clear impact on the final claims associated to a scientific work in multi-robot/robot-swarm domains.

The rest of the paper is organized as follows. In Section 2 we discuss related work. We focus on the relation between network simulations and reality (Section 2.1), on the scalability of network simulators (Section 2.2), and on the simulation of networked multi-robot systems (Section 2.3). In Section 3 we present RoboNetSim as a general framework for integrating robotic simulators with discrete-event network simulators. Section 4 demonstrates the application of the RoboNetSim architecture in two integrated simulation environments. In Section 4.5 we provide a step-by-step guide on how to simply plug-in a robotic simulator in our framework only acting on robot controllers. In Section 5 we analyze the proposed tools in terms of computational performance, correctness, and generated overhead. Sections 6 and 7 present two case studies showing how different simulated communication models affect the operation of multi-robot teams. Finally, in Section 8 we draw conclusions and outline future work.

2. Related work

2.1. Reliability of network simulations

We start discussing related literature focusing on the relations between network simulations and reality. The key question that needs to be answered first is: can existing network simulation tools describe the communication behavior of a networked multi-robot system with the desired/necessary accuracy?

In the context of ad hoc wireless communication, it is well known that real-world results might significantly differ from the results obtained through simulation. In [15] an extensive survey of real-world implementations of mobile ad hoc networks is presented, showing the discrepancy between simulation and the real world. Various simplifications that are commonly made in simulations and their impact on predicted outcomes are discussed in the context of key findings from real experiments. A similar discussion, supported by routing experiments in large outdoor areas, can be found in [16].

However, while these works seem to indicate, in general, a gap between simulation and the real world, it is also know that simulation can provide important insights into the asymptotic behavior of large networks when the appropriate models with the correct parameters are chosen [17]. A discussion on the level of detail that should be selected in wireless simulations can be found in [18]. In [19], the authors combine a real testbed consisting of driving cars and a proposed emulation technique. They show that NS-2 can accurately simulate network traffic in an ad hoc network consisting of 16 moving vehicles. An indoor static wireless network simulated in NS-2 is analyzed in [20] showing that packet delivery ratios and the connectivity graphs can be modeled with high accuracy, provided the shadowing radio propagation model is used and properly calibrated. In [21] NS-2 simulations related to QoS issues in ad hoc networks are compared with real data, showing that experimental results are consistent with simulations in terms of overall trends, although simulation results tend to be more optimistic in terms of both delay and throughput measurements.

The accuracy of NS-3 to simulate Wi-Fi networks has been assessed in a number of works. The real-world experiments