Neighbourhood Monitoring for Decentralised Coordination in Multi-Agent Systems: A Case-Study

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***Abstract*—Decentralized coordination of multi-agents requires that every agent *reliably* and efficiently disseminates its state to neighbours through a wireless network. If dissemination is unreliable, safety issues may ensue. Unfortunately, the broadcast service of wireless network is efficient but unreliable (e.g., IEEE 802.11). The *Neighbourhood Monitoring Protocol* (NMP) [1] is an efficient and scalable protocol that assures a reliable state dissemination between mobile agents, under some conditions of channel utilization. NMP runs on top of IEEE 802.11. In this paper we evaluate NMP with a specific decentralized collision avoidance algorithm based on the GRP policy [2]. The algorithm is particularly challenging because it accommodates an arbitrary number non-holonomic agents. We show that NMP allows the system to scale well and provides a very high state delivery ratio even if it operates on the unreliable broadcast service like 802.11. Doing so, NMP assures the correct state information to the collision avoidance algorithm.**

***Keywords*-AGVs, coordination, reliable broadcast**

I. INTRODUCTION

Multi-agent systems offer potential advantages with respect to single-agent ones. However, deployment of a multi-agent system raises management and coordination problems such as collision and deadlock avoidance.

In a real multi-agent system, state dissemination takes place through a wireless communication network. Unfortunately, wireless networks often do not provide any reliable multicast service. Accordingly, neighbouring agents may achieve an inconsistent view of the system leading to the failure of the coordination task itself with possible safety implications.

Recently we have proposed the *Neighbourhood Monitoring Protocol* (NMP), a reliable and scalable protocol that allows an agent to accurately and timely disseminate its state to neighbours over an IEEE 802.11 wireless network [1]. In the literature, several solutions strive to provide reliability of IEEE 802.11 broadcast communication at the Medium Access Control (MAC) layer [3]–[4]. However, they result inefficient in terms of increased number of frames, increased number of collisions, and increased data transmission delay. In contrast, NMP approaches the problem at the application layer because it is specifically aimed at increasing the reliability of agent state dissemination and not other forms of broadcast traffic.

In this paper we present a case-study related to the application of NMP to a decentralized collision avoidance algorithm based on the Generalized Roundabout Policy (GRP) proposed in [2]. The proposed case-study propose an interesting challenge since it takes into account non trivial agents such as vehicles that move with constant non null velocity (non-holonomic). The impossibility of stopping the vehicle in case of a conflict makes the communication infrastructure playing a fundamental role to ensure the safety of the system.

The case-study has been evaluated from several points of view by simulation. We show that NMP maintains a high level of delivery ratio, restoring sporadic packets collisions and packets loss that could lead the collision avoidance algorithm to dangerous state as violations of safety conditions. Finally, we have investigated the NMP behaviour even in exceptionally adverse communication conditions and we have compared its performance with a simple periodic dissemination protocol without reliability features.

The paper is organised as follows. Section II describes the Neighbourhood Protocol whereas Section III describes the Collision Avoidance Algorithm. In Section IV we evaluate performance through a simulative approach. Finally, in Section V we draw our final conclusions.

II. THE NEIGHBOURHOOD MONITORING PROTOCOL

We consider set of agents that share a common environment to fulfill their tasks either in group or in isolation. We assume that each agent is able to localize itself [5], [6]. Furthermore, we assume that clocks of mobile devices are synchronised [7]. Agents cooperate at least to coordinate their own motion. As agents share a common environment, collision avoidance prevents agents from colliding into one another. In order to cooperate for coordination, agents periodically disseminate their state (e.g., position and speed) to neighbours through a wireless ad-hoc network. We focus on IEEE 802.11 but the following arguments can be applied to other wireless technologies too.

The notion of neighbourhood is application-specific and defined on geometric basis. We call *neighbours* any two agents whose distance is smaller than, or equal to, the *neighbourhood radius* D_n. Let D_c be the *communication radius*, i.e., the maximum distance allowing communication between two agents. Of course, it must be $D_n < D_c$ or, otherwise, no communication among neighbours would be possible.

The objective of NMP is to allow an agent to reliably monitor its neighbourhood and, contextually, disseminate its state to such neighbours. To accomplish that, an agent periodically broadcasts its state with a given *state dissemination frequency* ϕ. We denote by τ the corresponding period, i.e., $\tau = 1/\phi$. Every agent periodically broadcasts a STATE packet that conveys the agent state and time information about the next STATE packet. When an agent receives a STATE packet, it reads the STATE information and uses the time information to establish the next STATE packet is going to arrive. If the expected STATE packet does not arrive, the agent starts a coordinated retransmission procedure based on NAC packet.

In our solution, we reduce the number of transmission when they are not necessary, namely when the closer agent is "far" enough.

More details on NMP are available in [1].

III. Collision Avoidance Strategy

We consider the following kinematic model for each agent involved in the system: $(\dot{x}, \dot{y}, \dot{\theta}) = (u\cos\theta, u\sin\theta, \omega)$, where u and ω are linear and angular velocity respectively. The linear velocity is supposed to be constant but non zero for any agent. A bound on angular velocity is obtained as $|\omega| \leq \frac{u}{R^c}$ where R^c defines the minimum curvature radius achievable. The agent has a safety disc of radius R^s centered in the agent itself that must be kept disjoint from safety discs of other agents to avoid collisions.

The GRP policy is based on the concept of *reserved region*, over which each active agent claims exclusive ownership: the circle it would describe under the action of a constant control input $\omega = -\frac{u}{R^c}$. In other words, $(x^c, y^c) = (x + R^c\sin(\theta), y - R^c\cos(\theta))$. The reserved region for the i-th agent is defined as a disc of radius $R_i^c + R_i^s$ centered at (x^c, y^c). Furthermore, we associate a heading angle to the reserved disc that coincides with the agent heading θ_i. Our policy is based on the following basic observations: the reserved region (i) can be stopped at any time, by setting $\omega = -\frac{u}{R^c}$ and (ii) once stopped, it can be moved in any direction, provided one waits long enough for the heading θ to reach the appropriate value.

A sufficient condition to ensure safety is that the interiors of reserved regions are disjoint at all times; if such a condition is met, conflicts can be avoided if agents hold their reserved regions fixed, and move within them (by setting $\omega = -\frac{u}{R^c}$). As a consequence, each point of contact between reserved regions defines a constraint on further motion for both agents involved. Hence, constraints can be determined if each agent is aware of the configuration of all agents within an *alert distance* $d_a = 2(\hat{R}^s + 2\hat{R}^c)$ where $\hat{R}^c = \max_j R_j^c$ and $\hat{R}^s = \max_j R_j^s$ are respectively the maximum value of R^c and R^s for all agents.

For space limitations we recommend to refer to [2].

IV. Performance Evaluation

We have simulated the collision avoidance algorithm and NMP by means of Omnet++ and the INET Framework.

Simulations consider a 10 m × 10 m shared area where each agent move with a constant linear speed u equal to 5 cm/s. D_n and D_ℓ are respectively fixed to 2 m and 3 m for all agents. Every agent has $R^s = 10cm$ and whereas values of R^c vary between 0 cm (holonomic) and 20 cm. So simulations encompass an heterogeneous set of both holonomic and nonholonomic agents. The communication module emulates a 802.11g NIC in ad-hoc mode with a 2 Mbps transmission rate. The state dissemination frequencies are $\phi_M = 20\ Hz$ and $\phi_m = 0.33\ Hz$.

In order to implement the collision avoidance on NMP we have solved two important implementation issues. The first of them was the *contact condition*. We must initially observe that, theoretically, the collision avoidance algorithm reasons upon the tangency of reserved regions. However, in practice it is impossible. Therefore, we practically assume that two reserved regions are in contact when they are closer than $d_t = 4 \times \tau \times u_M$. This is a conservative value for the worst case.

The second issue was the relationship between the radii. The value of the neighbourhood radius D_n depends on application features. In this case, in order to preserve the contact condition, a agent's neighbourhood must be large enough to encompass the reserved region of a neighbour. It means that $D_n > 4R^c + 3R^s$.

In order to evaluate NMP efficiency and accuracy, we refer to three factors: packet loss, delivery ratio and reserved regions overlapping. The *packet loss* is defined as the ratio between the number of lost packets due to packets collision and the total number of sent packets during an execution of the collision avoidance algorithm. The *delivery ratio* as function of the delay between two consecutive receptions of STATE packet from the same neighbour. It shows the probability that a packet arrives within a specific time interval. Ideally, all packets should arrive with a interval equal to τ. The *reserved regions overlapping* is a sufficient condition for avoiding collisions (see Section III) so it tests the system integrity.

Fig. 1 shows the packet loss versus the number of agents in the same communication radius. Less than 10% with 40 agents and $\phi_M = 20$ Hz and it increases rapidly with the number of agents.

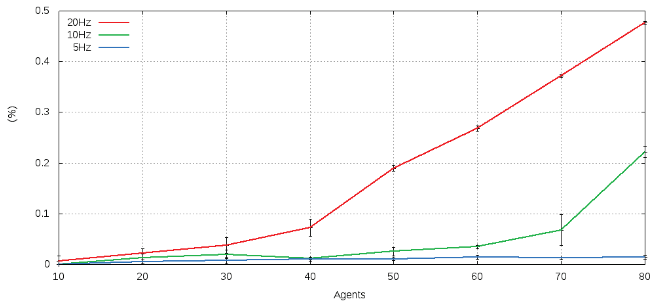

Figure 1. Packet loss vs. number of agents. ϕ_M: 20Hz, 10Hz and 5Hz.

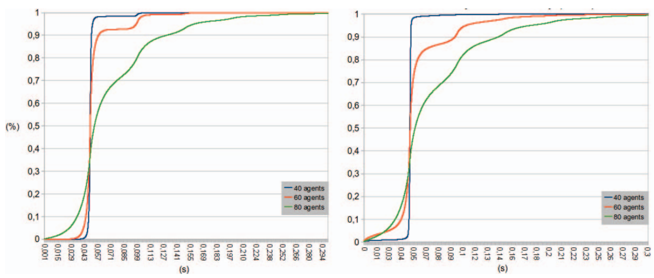

Figure 2. Delivery ratio vs. delay. Left: unreliable protocol. Right: NMP.

We have evaluated the NMP behaviour varying the number of agents and we have identify three configurations that reflect the cases of low, medium and high packet loss, respectively with 40, 60 and 80 agents. Usually, the actual collision avoidance applications operate at lower frequencies (2-5Hz). The packet loss is very small if not negligible in the most of practical cases as showen in fig. 1 and it allows a greater number of agents managed simultaneously. But, in order to test under stress the communication protocol, we have set our simulations with higher dissemination frequency (20Hz).

Fig. 2 shows the delivery ratio using an unreliable broadcast dissemination protocol and using NMP. The delivery ratio gets worse with the number of agents. We have observed that NMP has better performance than the unreliable protocol in case of low packet loss (40 agents), because NMP can easily restores the lost STATE messages if the channel is not congested. On the contrary, in a crowded scenario, NMP contributes to get worse the communication, due to the control messages (NACK packets) that increases the traffic amount. In this case, the unreliable protocol overcomes NMP performance.

Basing on these results, NMP is not recommended in a heavy congested scenario, but it can restore sporadic STATE packets loss that occur in a unreliable dissemination protocol. This small packet loss could lead the system in an inconsistent state. Analysing the reserved regions overlapping, there are no violation of the safety conditions with NMP in the case of 40 agents. Even if the STATE packet interval is slightly delayed, it is tolerated by collision avoidance algorithm. Otherwise, the unreliable dissemination protocol can experience a single state transmission that is heavy delayed, causing the reserved regions overlapping. In the other two cases with medium and high packet loss, the reserved regions overlapping occurs in both NMP and unreliable broadcast protocol.

V. Conclusions

In this paper we have discussed a case-study related to the application of NMP, reliable state dissemination protocol, to a challenging collision avoidance algorithm. Early results prove that NMP is scalable due to its distributed nature, and guarantee both reliability and timeliness under the condition of not heavy congested scenarios. In this work, we have used the unit disk model that implies complete correlation between the properties of geometric space and the topology of the network. Future efforts will aim at implementing more realistic communication model. Moreover, future work will be devoted to integrate security in NMP and to carry out a more accurate performance evaluation.

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