

Delay's Impact in Adaptive Versatile Intelligent Portable (VIP) Communications on Consensus in a Robotic Multi-Agent System

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Abstract—In multi-agent robotic systems, communication plays a key role in achieving coordinated behavior. This paper studies a consensus-based framework for networked multi-agent system where communication topology is described by using adjacency and Laplacian matrices. The analysis investigates the importance of communication performance and how it can affect system performance and stability. We demonstrate that the introduction of discrete-time delays impairs system convergence and compromises the stability of Versatile Intelligent Portable Robot (VIPRO) interfaces. These findings are relevant for applications that require precise coordination and emphasize the importance of communication when designing multi-agent robot systems.

Keywords—multi-agent systems, communication, stability and performance of networked multi-agent, consensus, versatile, intelligent, portable robot control

I. INTRODUCTION

Multi-Agent systems have received a significant amount of attention in recent years due to its capability to perform complex missions while ensuring coordination and cooperation. This system consists of multiple robots that interact locally to achieve a common objective without the need of an external controller [2].

Consensus algorithms are used to achieve coordinated behavior in multi-agent systems, allowing them to reach agreement through local interactions without having the need to receive any command from outside. The convergence of these algorithms is dependent on the communication topology and the spectral properties of the Laplacian matrix [1].

This article, according to similar researches in the field, investigates the impact of communication delays on the coordination of a networked multi-agent systems, with a focus on adaptive Versatile Intelligent Portable Robot (VIPRO) interfaces [2]. A framework has been developed in order to analyze how discrete-time delays affects convergence and stability and its results will highlight the importance of taking into account all possible issues that communication might bring when designing a multi-agent system.

II. STATE OF THE ART

The framework developed considers that multi-agent system is modeled as a network of N agents interacting through a communication graph, where V represents the robotic agent while E defines the communication link

between them.

$$N = (V, E)$$

This graph is widely used in similar studies to describe communication and coordination mechanisms [3]. This paper will test a ring communication graph consisting of 6 robot agents.

For this paper we are going to use a discrete-time consensus model by adding 5 different discrete-time delays in the network. Each robot agent is associated with a scalar state $x_i(k)$ updated at discrete-time steps according to the consensus formula [1]:

$$x_i(k+1) = x_i(k) + \alpha \sum_{j=1}^N a_{ij}(x_j(k-d) - x_i(k))$$

where $\alpha > 0$ is the consensus gain and d represents the communication delay expressed in discrete-time steps. This formulation expresses how each robot agent updates its state based on its current value and delayed information received from its neighbors [4].

The considered consensus protocol follows the classical formulation widely used in the literature for modeling coordination in multi-agent systems [5, 6].

III. NUMERICAL SIMULATION

This paper considers a ring communication graph instead of a full-mesh network. This choice is motivated because literature shows that in full-mesh topologies, each agent has direct access to all other robot agents resulting in faster convergence. Since ring topologies restrict interactions to local neighbors, it highlights the focus of this study on the importance of communication.

In order to analyze how communication delays have an impact on the consensus process, different discrete-time delay values are going to be evaluated in this paper. The delay is expressed in discrete-time steps, with the values $d = 0, 10, 20, 50$ and 70 , allowing us to measure system performance under different conditions. In addition, a comparative analysis is carried out between two consensus gain strategies: a constant gain and an adaptive formulation, proposed by the authors, based on a normalized error term where the initial system error is used as the reference value:

$$E(k) = \frac{e(k)}{e(0)}$$

So, the adaptive consensus gain becomes:

$$\alpha(k) = \alpha_{min} + (\alpha_{max} - \alpha_{min}) \times E(k)$$

where α_{min} and α_{max} define the range within which the consensus gain varies. This allows a more aggressive correction for larger errors and a smoother correction as the system approaches consensus.

Some existing discrete-time adaptive consensus methods estimate the communication Laplacian online and determine the gain and feedback matrix through adaptive learning algorithms. Other discrete-time approaches use a predefined dependent gain that changes only with the iteration index. In contrast, the proposed method adjusts a common gain that varies within the interval $[\alpha_{min}, \alpha_{max}]$ according to the normalized network wide max–min disagreement [7, 8].

In this paper different discrete-time delay values are introduced in order to observe their effect on convergence speed. In the beginning of the simulation index “ $K - d$ ”. is negative so the robot agent assumes to use the initial state of its neighbor, ensuring that the update state is well-defined during the initial simulation steps (see Fig. 1).

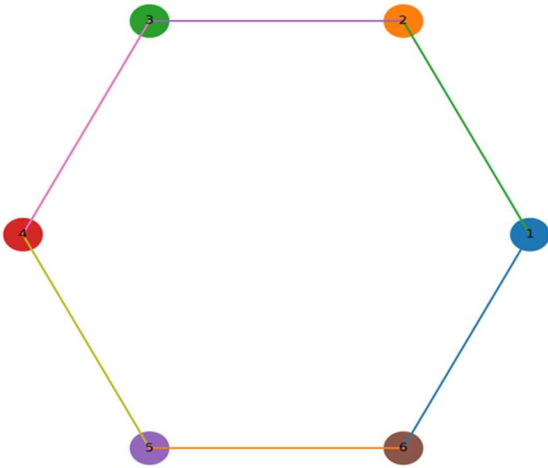


Fig. 1. Multi-Agent communication graph.

IV. RESULTS AND CONCLUSION

As explained in Section III, the considered communication topology is a ring network composed of 6 robotic agents. The consensus simulations were carried out in a custom environment. The initial agent states were randomly generated in the interval $[-5, 5]$. To ensure reproducibility, a fixed seed was used so that the same initial values were obtained in every simulation run, allowing direct comparison of the results. The tested delay values were 0, 10, 20, 50, and 70, and each simulation was executed for a maximum of 2,000 discrete-time steps. When index “ $K - d$ ”. is negative, each agent uses the initial state of its corresponding neighbor.

For the first scenario, the consensus gain is fixed at $\alpha = 0.12$. In the adaptive scenario, the gain varies between $[0.02, 0.12]$. The upper bound has been chosen based on previous simulation observations, where that value led to successful consensus achievement. The robotic agents are considered to

have reached consensus when the network wide max–min disagreement is within 0.1% of the ideal consensus value, defined as the average of the initial states of the six agents.

Starting the simulation with the benchmark case with no delay, Fig. 2, it can be observed that the system requires a small number of discrete-time steps to reach a consensus agreement between robot agents.

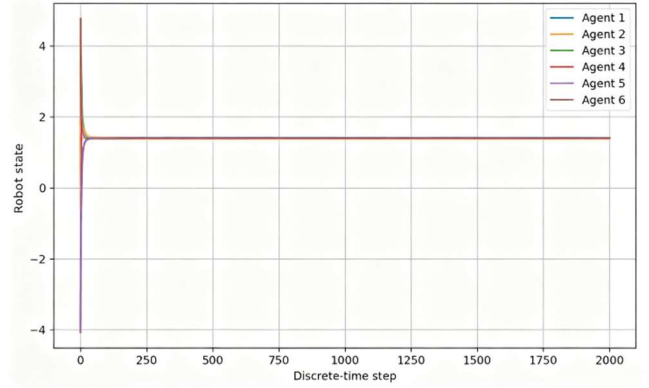


Fig. 2. Benchmark simulation.

As delay value increases, the number of discrete-time steps required for convergence also increases. This behavior is illustrated in Fig. 3 where convergence process becomes slower for larger delay values.

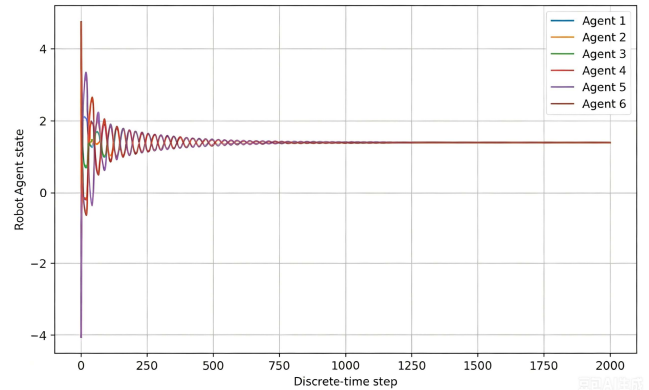


Fig. 3. Twenty discrete-time delay – Fixed gain scenario.

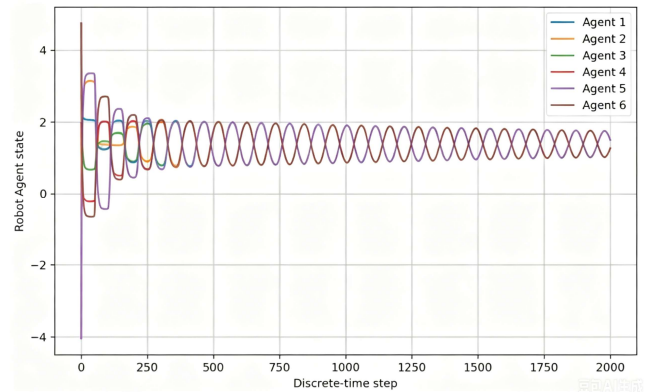


Fig. 4. Fifty discrete-time delay – Fixed gain scenario.

As shown in Fig. 4, when larger values for communication delays are introduced, the system is not able to reach consensus within 2,000 discrete-time steps when using a

constant consensus gain. Since the constant gain approach fails to achieve consensus for a delay of 50 discrete-time steps, the following results focus on the improvements obtained using an adaptive gain that is more aggressive when the consensus error is larger and gradually decreases as the agents get closer to consensus.

For small discrete-time delays, the adaptive gain does not bring significant benefits, since the constant gain used in first scenario is already more aggressive. However, favorable results are expected for larger communication delay values. Therefore, in the second scenario, the adaptive consensus gain is evaluated for discrete-time delays of 20, 50 and 70.

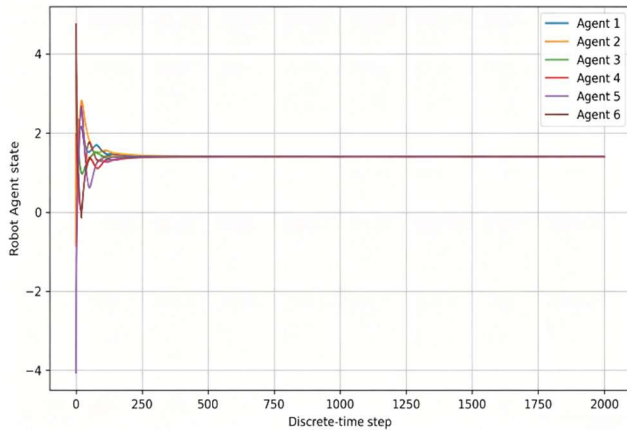


Fig. 5. Twenty discrete-time delay – Adaptive gain scenario.

By comparing Fig. 3 to Fig. 5, it can be observed that using an adaptive consensus gain reduces the oscillations of the multi-agent system during the convergence process. This indicates that the system applies a stronger correction when the error is larger and a smoother one when the system is approaching consensus.

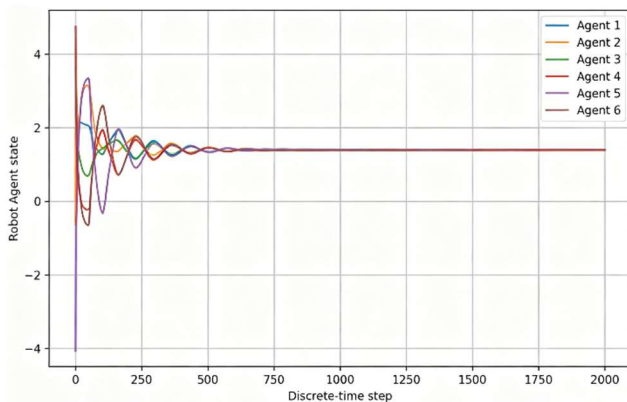


Fig. 6. Fifty discrete-time delay – Adaptive gain scenario.

As shown in Fig. 6, while the constant gain approach did not reach consensus within 2.000 discrete-time steps for the same delay, the adaptive gain enabled convergence in approximately 800 steps, considering a threshold of 0.1%.

Furthermore, Fig. 7 shows that consensus is still achieved in fewer than 1.300 steps under larger delay values. This represents an important improvement compared to the constant gain scenario. This can be explained by the adaptive formulation: as the consensus error decreases, the gain is gradually reduced from α_{max} toward α_{min} .

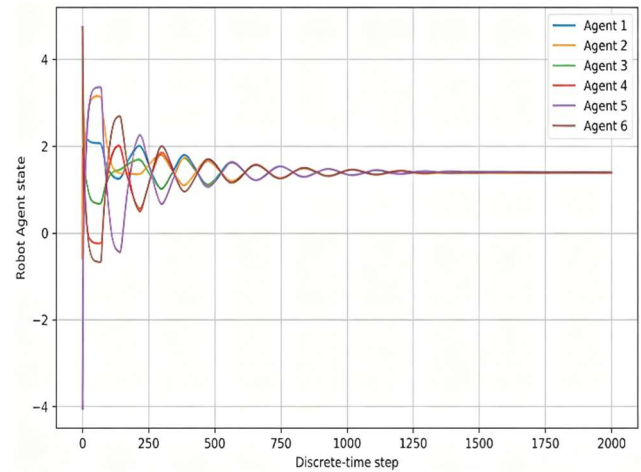


Fig. 7. Seventy discrete-time delay – Adaptive gain scenario.

For the considered ring topology, each agent has only two neighbors, so the consensus formula can be written as:

$$x_i(k+1) = (1 - 2 \times \alpha(k)) \times x_i(k) + \alpha(k) \times x_{i-1}(k-d) + \alpha(k) \times x_{i+1}(k-d)$$

The coefficients of the relation are always non-negative and their sum is always equal to 1. Therefore, each state update during consensus process, remains bounded by the current agent state and the delayed neighbor state. In addition, since the adaptive gain decreases together with the normalized error term, the delayed corrections become smoother near consensus, which explains the reduced oscillations observed in the simulations.

Unlike the constant-gain approach, which applies the same correction throughout the entire process, the adaptive formulation leads to a more aggressive convergence in the initial stage, when the system disagreement is larger, and progressively reduces the correction as the consensus error becomes smaller, resulting in a smoother behavior near consensus.

To conclude, although the adaptive formulation used in second scenario does not bring major improvements for small delay values, its effect becomes more visible when discrete-time delay increases. In this paper, it has been demonstrated how communication delays have an impact on the convergence behavior of the multi-agent system. The results obtained confirm the proposed approach and encourages authors for further research efforts in this area.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Luige Vladareanu conducted the research; Nicolae Mola and Alexandru Gheorghita developed the framework; Stefan Ghibanu and Ionel Puscasu analyzed the results and proposed further actions; Nicolae Mola wrote the paper; all authors contributed to the conception of the article; all authors had approved the final version.

REFERENCES

- [1] R. O. Saber, J. A. Fax, and R. M. Murray, "Consensus and cooperation in networked multi-agent systems," in *Proc. IEEE*, 2007, vol. 95, no. 1, pp. 215–233.
- [2] V. Vladareanu *et al.*, "Versatile intelligent portable robot control platform based on cyber physical systems principles," *Studies in Informatics and Control*, 2015, vol. 24, no. 4, pp. 409–418.
- [3] A. Shetty, T. Hussain, and G. Gao, "Decentralized connectivity maintenance for multi-robot systems under motion and sensing uncertainties," *Navigation: Journal of the Institute of Navigation*, vol. 70, no. 1, 2023.
- [4] R. O. Saber, "Flocking for multi-agent dynamic systems: Algorithms and theory," *IEEE Transactions on Automatic Control*, vol. 51, no. 3, pp. 401–420, 2006.
- [5] Y. Gong, "Consensus control of multi-agent systems with delays," *Electronic Research Archive*, vol. 32, no. 8, 2024.
- [6] X. F. Ling *et al.*, "Distributed consensus control for discrete-time T-S fuzzy multiple-agent systems based on an unknown input observer," *Sensors*, vol. 24, no. 24, 8149, 2024.
- [7] Y. Jiang, L. Liu, and G. Feng, "Fully distributed adaptive control for output consensus of uncertain discrete-time linear multi-agent systems," *Automatica*, vol. 162, 111531, 2024.
- [8] J. Wang, J. M. Ke, and J. F. Zhang, "Differentially private bipartite consensus over signed networks with time-varying noises," *IEEE Transactions on Automatic Control*, vol. 69, no. 9, pp. 5788–5803, 2024.

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