**Simulation-Based Robust Model Predictive Control for n-Dimensional Linear Multi-Agent Systems with Uncertain and Heterogeneous Dynamics in Modular Plants**

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Abstract

The process industry has effectively used model predictive control (MPC), a potent advanced process control approach. Multi-agent systems (MASs), on the other hand, are built with various subsystems that cooperate to accomplish a particular goal. Similarly, modular plants are connections of several modules, each intended to carry out a particular task in the larger system. In this paper, first, we discuss modular plants and MASs to see if they are comparable. Then, we propose a simulation-based robust MPC strategy for n-dimensional linear MASs with uncertain and heterogeneous dynamics. The proposed control strategy consists of state space MPC and robust control. As a result, our work indicates the potential of distributed MPC for n-dimensional linear MASs with uncertain and heterogeneous dynamics in modular plants, which could help enhance the accuracy, effectiveness, and robustness of the control strategy in the process industry. The proposed control strategy can be extended to other applications in the process industry, and ongoing research is focused on using existing MAS control techniques further to improve the performance of the controller in modular plants.

**Keywords**: modular plants, multi-agent systems, model predictive control, robustness

* 1. Introduction

This paper focuses on comparing modular plants and MASs, exploring the application of MAS principles for controlling and optimizing modular plants, and examining the potential of distributed MPC for MASs in modular plants. The hypothesis is based on the idea that MAS principles can be utilized to simplify the controller design of modular plants and as a result, enhance their effectiveness and robustness in the process industry. Modular plants are instrumental in process engineering, notably within sectors such as chemicals, pharmaceuticals, and fine chemicals. They excel at rapidly deploying plants for industrial production and efficiently integrating package units and logistics systems into existing or new facilities. At the heart of these modular plants are Process Equipment Assemblies (PEAs). PEAs are self-sufficient, automated units with one or more functional equipment assemblies. These assemblies, known as Functional Equipment Assemblies (FEAs), are composed of adaptable components working together to perform specific process steps. On the other hand, components (COMP) are the smallest unit which is no longer separable in modularization. The COMPs are determined by function, performance, and type (VDI 2776-1, 2020). Modularization significantly expedites the construction of tiny to large-sized production plants. By utilizing industry-specific PEAs as self-contained functional units, this approach reduces engineering efforts, minimizes early-stage errors, and yields substantial cost and time savings (Baldea et al., 2017). Mädler et al. (2022) propose the fundamental idea of using so-called smart PEAs (= models combined with PEAs) to enable online optimization in modular plants. Multi-agent systems (MASs) are composed of multiple subsystems that collaborate towards a common objective, offering numerous advantages when compared to traditional and single-agent systems. Notably, the presence of multiple agents ensures system functionality even in the event of agent failures, showcasing the fault tolerance of such systems. Furthermore, new agents can be added to the system without significant redesign, and control is distributed among agents, leading to more efficient decision-making and less dependency on a central control point (Bloch et al., 2018). The similarity between MASs and modular plants is that each MAS agent can be considered a module in the modular plant. Therefore, the idea of MASs and consensus control can be extended to the modular plant level. Hence, we can apply controller designs specifically designed for MASs to simplify the controller design of modular plants. However, only a few papers have explored modular plants as MASs, leaving a gap in research. Hence, this study aims to fill this gap by comparing these two concepts and examining an example of achieving consensus in linear time-invariant (LTI) heterogeneous Multi-Agent Systems (MASs) in the process industry. Zamfirescu et al. (2003) present an engineering approach to address the increasing demand for managing highly modular plants. It discusses the implementation of an agent-based manufacturing controller, inspired by the social behavior of ants. The objective is to tackle challenges like variations in production resources and planning processes while maintaining optimal plant performance. Moreover, MASs have been highlighted as a useful tool in the process industry by Denkena et al. (2003) and Mönch et al. (2003) in two separate studies. In Komesker et al. (2022), the flexibility of production lines has been increased considering the modular production concept, which is like having building blocks to quickly adapt to changing production needs. However, this approach needs new ways to plan and control production. To achieve this, taking advantage of MASs has been proposed.

* 1. Comparing MASs and Modular Plants

As modular plants and MASs live on different levels of abstraction, comparing them would be challenging. In other words, MASs are rather an automation architecture while modular plants in their entirety, are a technology. This technology comprises a default automation architecture with Module Type Package (MTP), services, Process Orchestration Layer (POL), and recipes. To compare MASs and modular plants, a common ground for assessment should be created. This common ground can be created by mapping modular automation components into automation architecture categories where MAS also fits. Imagine we have three modules with individual MTPs, each providing different services. Here, the POL defines how these modules collaborate in a process and recipes guide the actions of these modules. To clarify this, imagine we have a toolbox and a set of rules to construct different things. The tools we are using, are our MTP. The rules telling how to use these tools are our recipes and how we organize our tools following the rules is like POL. Besides, the different tasks, our tools can do, are our services. On the other hand, if we compare this concept with a MAS, each agent has its own set of tools or MTPs and can follow the rules or recipes to fulfill its tasks or services. The MAS automation architecture defines how they coordinate and work together and who decides what to do. Now, considering factors like decision-making processes, communication patterns, fault tolerance, and adaptability, this common frame could assess how well MAS principles align with the modular plant’s structure. Several aspects of MASs are comparable with modular plants, and this can lead to using the MAS principles to ease the control and optimization of the modular plants. For instance, collaboration is essential in MASs to achieve common goals and efficient operation. The cooperative approach also applies to modular plants, where PEAs, services, and the POL work together to enhance efficiency. One of the most critical aspects of both MASs and modular plants is decision-making based on local information, with modules relying on internal states, inputs, and predefined rules encoded in recipes and control algorithms for decision-making. Also, coordination between these autonomous units becomes vital in certain situations. Considering resiliency aspects, in MASs, adaptation to failures, and integrating new agents are paramount. On the other hand, as in MASs, when one module fails, the other ones reconfigure the system to maintain the overall performance and efficiency and in the case of module removal or addition, modular plants can perform the plug-and-play integration of modules more easily. However, it is noteworthy that modules have very different capabilities which means that the redistribution of workload is heavily constrained. Furthermore, in both MASs and the case, modular plants are associated based on the choreography method, decisions are made in a distributed way and agents or modules are interconnected, exchanging data to reach an agreement or to optimize the performance of the plant, (Stutz et al., 2020). However, it is important to note that the specific control methods and organizational forms used in MASs require adaptation and tailoring to be appropriate for the objectives, constraints, and characteristics of modular plants for different industrial applications. In the context of applying the MAS concept to modular plants, the leader-follower form would be more applicable. In a modular plant, we can consider a ‘leader’ module that leads the actions of the other ‘follower’ modules. The leader module would be responsible for managing and orchestrating the actions of the whole plant, by taking decisions and defining control objectives. On the other side, similar to the MASs, the follower modules would execute the control commands of the leader. The choice of the leader module would be important due to the capabilities of different PEAs, both in terms of physical attributes and software functionalities. Also, the consensus form of the MASs and modular plants are comparable and it can be an interesting approach to consider for the control of the modular plants. For instance, both consensus-based MAS and modular plants need communication among different components. In modular plants, PEAs require coordination to achieve specific goals and similarly, in consensus systems, agents agree on a common state or value. The consensus and leader-follower forms are just examples, and another organizational form of MASs may suit better depending on the system's complexity. The dynamics, interactions, and goals of the plants should be carefully analyzed to determine the most suitable MAS approach. In conclusion, the synergy of modules in the plants and MASs can result in higher flexibility and resiliency in the industry. There are several reasons for this claim. For example, in a modular plant, similar to MASs, as mentioned before, each module can act as an autonomous agent that can make local decisions based on the requirements. This form of decentralized decision-making allows modules to adapt to condition changes. Besides, communication and coordination between different modules, similar to MASs, enables adaptiveness against disturbances. For instance, if one module faces changes in production requirements, it can communicate with the neighbor modules to adjust resource allocation.

* 1. Develop a Consensus Achievement MAS Case for the Modular Plants

Consensus achievement in MASs refers to a collaborative process in which agents aim to reach a common state or decision through communication. Despite having different initial information and preferences, agents coordinate their decisions to agree on a shared objective (Mesbahi et al., 2010). In Badrno et al. (2023), the distributed consensus control of the linear n-order MASs using model predictive control has been investigated. Each agent has different dynamics from the others, but the number of the inputs and outputs of the systems has been considered the same. In this study, two types of model uncertainties are considered: polytopic and multi-model uncertainties. In reality, multi-model uncertainties refer to the cases in which the specific model of the system is not precisely known or when we have different operational modes or different task requirements, user commands, and environmental conditions. The ability of an industrial process to tolerate the expected variability of raw materials, operating conditions, environmental variables, parameter uncertainties, and human factors is referred to as robustness. Even when levels of input variables and noise parameters undergo severe and substantial variations, a robust process maintains its steady performance consistently at the target level and minimizes the impact of disturbances on product quality (Wei et al., 2010). In the mentioned paper, consensus is achieved using linear matrix inequalities and slack variables. The graph representing the communication among different neighbor agents is considered as a directed graph or digraph meaning the collaboration among agents is directional. Also, in this paper, the determined common point for all agents is point zero, but this condition does not restrict the application while we can control the deviations from a setpoint, or in other words, control the error signals. Besides, in safety-critical systems, converging to point zero, can be considered for certain safety-related variables in which returning to point zero in certain circumstances is crucial. Also, while doing module reconfigurations, reaching point zero can be considered as a reset or initial condition.

* 1. Case Study

To clarify the applicability of the consensus form of MASs in modular plants, consider the following simulation example implemented in MATLAB. There are five PEAs with linearized dynamics, each fulfilling a task in a modular plant. The dynamics of each PEA are different from the others, but they have the same dimensions, or in other words, same number of inputs and outputs, and all systems are stable and controllable. The purpose is to simulate the consensus-based predictive control of these PEAs. As mentioned before, all PEAs would agree on a common point of zero. Different quantities could be considered as the states of the systems. For instance, in one PEA, the state would be the deviation between the desired temperature and the real temperature, in the other PEA, it would be the deviation between the desired level and the real level, and in other PEAs, the states would be safety critical variables of the systems. These PEAs interact with each other based on a predefined communicational fixed digraph as follows.



Figure 1: System digraph

In other words, PEAs would send and get data only from the neighboring PEAs. These communications would be defined based on the purpose of the plant and the requirements of the other PEAs. The dynamics of the PEAs can be considered unknown or different operational modes can be considered for each PEA. Here it is assumed that the exact dynamics of each PEA is unknown and it may be one of the three given linear dynamics in the example in Badrno et al. (2023). Multi-model uncertainty, which is considered in this paper, is one of the prevalent uncertainties in the process industry, and addressing this issue would be an achievement in increasing system resiliency. The initial conditions, constraints, weighting matrices, the eigenvalues of the Laplacian matrix, and dynamics of the PEAs are assumed to be the same as in Badrno et al. (2023). The eigenvalues of the Laplacian matrix are representative of the communication features of our digraph. The digraph of figure 1, fulfills the necessary conditions of consensus achievement, which contains a spanning tree. The states of the system are 3 in 1 vector indicating the physical quantities in different zones. It is important to note that, to do the mathematical calculations, the value of the states should be normalized at first. All mathematical formulations used in the code are derived from the aforementioned reference Badrno et al. (2023). The consensus protocol guarantees the convergence of all defined states as follows in figure 2. The control inputs of all PEAs are depicted in figure 3.







Figure 2: State Trajectories of PEAs, (a) state value in first zone, (b) state value in second zone, (c) state value in third zone



Figure 3: Time history of the control inputs of the PEAs

* 1. Conclusion

In this study, the research brings together three fields MASs, MPC, and modular plants. Recognizing the common principles in these domains, which are adaptability and modularity, the study proposes a robust model predictive control of n-order LTI MASs interpreting agents of MASs as modules of a modular plant. Therefore, we can apply controller designs specifically designed for MASs to the modular plants. Besides, the application of distributed consensus control in MASs, specifically addressing multi-model uncertainty, is explored in this research, with the help of simulations. However, it is important to note that the specific control methods and organizational forms used in MASs require tailoring to be appropriate for the objectives and characteristics of modular plants and this can be the future work.

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