1 Introduction

The progressive automation of technical systems requires new perspectives on the design of controllers. In the classical point of view, a controller is designed to achieve a desired behaviour of a plant, e.g., set-point following or attenuation of disturbances [2]. Modern concepts, on the other hand, focus on more global aims, e.g., synchronisation of multiple oscillators. For this purpose, it is not possible to focus on a single plant, which leads to the concept of multi-agent systems [1].

Figure 1 shows a multi-agent system, which consists of physically uncoupled plants \( P_i, i \in \{1, 2, \ldots, N\} \), which are controlled by local controllers \( C_i \). The combination of plant and controller is denoted by \( \Sigma_i \). These controlled subsystems are able to communicate with each other via a given communication network to exchange control variables and set-points or possibly model information in a more general framework.

\[ \Sigma_1 \\
\begin{array}{c}
P_1 \\
\end{array} \\
\begin{array}{c}
C_1 \\
y_1 \quad u_1 \\
\end{array} \]

\[ \Sigma_2 \\
\begin{array}{c}
P_2 \\
\end{array} \\
\begin{array}{c}
C_2 \\
y_2 \quad u_2 \\
\end{array} \]

\[ \ldots \]

\[ \Sigma_N \\
\begin{array}{c}
P_N \\
\end{array} \\
\begin{array}{c}
C_N \\
y_N \quad u_N \\
\end{array} \]

Fig. 1: Multi-agent system

2 Project aim

The aim of this project is to find methods for the design of the local controllers \( C_i \) and the communication structure \( K \) such that the overall system possesses a desired behaviour, which leads to the following question:

How can one translate requirements on the overall system into requirements on the controlled subsystems and the communication structure?

The developed methods should consider that there is no coordinating unit with global model knowledge. Furthermore, the communication structure should be sparse for the sake of low data traffic.

3 Vehicle platoon

A typical example for multi-agent systems is a string of vehicles driving in a straight line as depicted in Figure 2. Each vehicle is equipped with a communication system and a velocity controller. The velocity of each vehicle is denoted by \( v_i(t) \), the inter-vehicle distance by \( d_i(t) \) and the position by \( s_i(t) \). The controllers are designed such that the following requirements are met:

(R1) Asymptotic synchronisation: In a steady state all vehicles should follow a reference trajectory \( s_0(t) \)

\[ \lim_{t \to \infty} |s_i(t) - s_0(t) + \bar{s}_i| = 0, \forall i \]

with a specific safety distance \( \bar{s}_i \).

(R2) Continuous progression: There should be no situation in which a vehicle moves backwards, i.e.,

\[ v_i(t) \geq 0, \forall t, i. \]

(R3) Collision avoidance: All distances should be non-negative:

\[ d_i(t) \geq 0, \forall t, i. \]

These requirements state desired properties on the overall system. However, they have to be met using appropriate controllers on the subsystems. The first requirement is satisfied if the open loop has two vanishing eigenvalues, which enables the closed-loop subsystem to follow ramped reference trajectories according to the internal-model principle. To satisfy the other requirements the following definition is utilized:

**Definition 1.** A linear system is called **externally positive** if and only if its output is non-negative for zero initial state and any non-negative input.

**Theorem 1.** A linear system is externally positive if and only if its impulse response is non-negative.

Thus, the aim of the controller design is to generate closed-loop subsystems with externally positive dynamics.

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4 Cooperative behaviour in multi-agent systems

Consider a traffic situation with multiple lanes and vehicle platoons on them. There might be incidents, where a vehicle wants to switch the lane for example to do an overtaking manoeuvre or in the case of an upcoming road junction. In this context, cooperation describes a behaviour of the participating vehicles that ensures collision free and efficient merging by working together.

For this purpose, the vehicle that wants to switch the lane might broadcast a message to the neighbouring platoon, which thereupon makes space for the switching vehicle. In contrast to the scenario we encounter in the daily traffic, a cooperative approach helps to prevent congestion and increases traffic safety while consuming less energy.

5 Simulation study

Consider a platoon of $N$ vehicles with the dynamics of each vehicle described by

$$\dot{v}_i(t) = -c v_i(t) + \frac{1}{m} u_i(t),$$

where $c$ and $m$ denote a friction constant and the mass respectively. The inter-vehicle distance is governed by the relative velocity, i.e.

$$\dot{d}_i(t) = v_{i-1}(t) - v_i(t),$$

where $v_{i-1}(t)$ denotes the velocity of the predecessor of vehicle $i$. To satisfy the internal-model principle, a regulator state

$$\dot{x}_{ri}(t) = d_{si}(t) - d_i(t)$$

is introduced, that ensures set-point following for ramped reference trajectories. The control circuit is closed using the state feedback law given by

$$u_i(t) = -k^T \begin{pmatrix} v_i(t) \\ d_i(t) \\ x_{ri}(t) \end{pmatrix}$$

with $k$ chosen appropriately.

Figure 3 shows the velocity and inter-vehicle distance of a platoon of $N = 20$ vehicles. In the steady state, all vehicles move with the reference velocity $\bar{v} = 20 \text{ m/s}$. The inter-vehicle distances follow the time-headway policy given by

$$d_{si}(t) = \beta v_i(t)$$

with $\beta = 2 \text{ s}$. Each vehicle receives the current velocity of the predecessor vehicle via the communication network. The monotonic behaviour is a result of the externally positive dynamics of the closed-loop systems and is obtained by appropriate controllers. Since systems with externally positive dynamics are not able to overshoot, it is guaranteed that no collisions occur and hence the platoon is arbitrary scalable.

References