Fleets Management of Cooperative Connected Automated Vehicles in Manufacturing Processes

Marco Di Vaio, Guido Guizzi, Alberto Petrillo, Stefania Santini

***Abstract*—Industry 4.0 is a promising solution for the management of manufacturing processes, due to its potential to increase both energy saving and optimized production. Within this context, in this paper we propose the use of automated connected vehicles fleets for the autonomous handling of products among workstations in manufacturing processes. Numerical results confirm its effectiveness w.r.t a typical production process.**

Keywords*—*Industry 4.0, automated guided vehicle, vehicles fleet, industrial wireless networks.

I. INTRODUCTION

In the last decades, Industry 4.0 has raised an emerging interest from researchers, device developers and industries, since it allows to increase energy saving, contributes to cost reductions and increases an optimized production. The industry and society have gradually developed the idea of Industry 4.0 [1], smart factories [2], networking manufacturing [3] and to this aim several architectures have been recently proposed [4]–[6]. In the meantime, new information and communication technologies (ICTs), as the industrial cloud [7], [8], industrial internet of things [9] and high performance embedded system [10] have been recently proposed as key tools for manufacturing industry with the aim of combining the higher productivity demands, energy savings and flexibility market. In particular, industrial wireless networks (IWNs) are the most promising technologies for rapid achievement of Industry 4.0 advantages. In this regard, IWNs have been rapidly entering in manufacturing concept and are becoming a fundamental issue for the achievement of smart factories and the architecture of Industry 4.0 [11].

In order to achieve a smart and flexible production, it is necessary to increase the deployment of autonomous products handling, during the different production steps, within the factory. For this aim, several approaches for trajectories optimization to track within the manufacturing area and the use of autonomous driving of vehicles fleets have been proposed [12]. Both the vehicles fleet size and the scheduling/dispatching have influence on the system throughput and, hence, they have been examined in the recent technical literature (e.g., see [13], [14] and references therein). However, research activities usually do not focus on the design of cooperative control strategies for the deployment of autonomous fleets of connected vehicles in the manufacturing area, while classical attempts usually focus on fleet assignment in order to obtain the fleet operation cost minimization [15], [16], or on planning upkeep tasks in order to minimize the maintenance cost [17]. Therefore, scheduling and re-scheduling fleet assignment and maintenance planning are implemented in task-dedicated decision support systems [18].

In this context, the conjunction of the new tools for automated mobility developed in Smart City Initiatives with the concept of Industry 4.0 can increase the flexibility in the manufacturing processes by exploiting autonomous vehicles fleets that share information through IWNs [19], [20]. Following this paradigm, the paper proposes a cooperative control strategy for the management of a fleet of automated connected vehicles handling products among workstations in manufacturing processes.

The paper is organized as follows. In Section II the problem statement is provided and the novel distributed control approach is presented. In Section III stability analysis of the multi-vehicle control strategy is provided. While, in Section IV is presented the simulation results, confirming the efficiency of the proposed control approach. Finally, conclusion and future work are drawn in Section V.

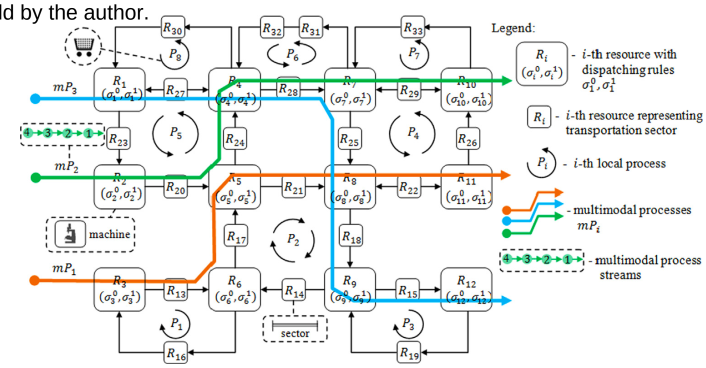

Fig. 1. Example of resources dispatching path in manufacturing process [21]

II. AUTOMATED VEHICLES IN INDUSTRY 4.0

Automated vehicles can be used for material handling within a flexible manufacturing system, and for proving asynchronous movement of product pallets through a network of guide paths between the workstations. Each work station is connected to the guide path network by a pick-up/delivery station where pallets are transferred to/from the automated vehicles [21].

In this paper it is considered a manufacturing system (see for example Figure 1) consisting in M workstations and r kind of resources to be dispatched following p different paths

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(chosen according to specific optimization algorithm [12]). For resources dispatching we exploit for each p-th path a fleet of N vehicles travelling together with a constant speed and maintaining a prefixed spacing policy. Each vehicle within the fleet supplies the M-th station present in the path with a specific resource r. Moreover, each vehicle has to stop at the workstations along the specific p-th path, for the necessary time of resource manufacturing, i.e. T_w. Note that, in this preliminary work we assume the manufacturing time equal for each of the M workstations along the p-th path, while the distance among vehicles i and j within the fleet has to be equal to the distance between two different workstation, i.e. k and l at which the vehicles are parked. To realize the vehicles fleet, vehicles are organized as a string, with vehicles following one another along the p-th path and sharing their state information (e.g., the absolute position, the velocity, and the acceleration) with all other agents communicating through a V2V communication paradigm, as described in [22], [23]. Vehicles are equipped with on-board units that are configured as receiving and transmitting hosts. The reference motion is provided by the first vehicle of the fleet that acts as a leader. Within our framework, the behavior of the generic i-th vehicle ($i = 1, \ldots, N$) in the fleet is mathematically described by a simple linear model that was possibly obtained by applying inputoutput feedback linearization to simplify the complexity of the model describing the longitudinal vehicle dynamics, and without considering parasitic time delays and lags as follows:

$$\dot{r}_i(t) = v_i(t)$$
$$\dot{v}_i(t) = \frac{1}{m_i} u_i(t), \tag{1}$$

where r_i (in meters) and v_i (in meters per second) are the i-th vehicle position and velocity, respectively, measured with respect to a given reference framework; m_i (in kilograms) is the mass of the i-th vehicle assumed to be constant, and u_i denotes the control input to be appropriately chosen. Due to the presence of limited communication, the control input to the i-th vehicle (1) has to be determined by choosing an appropriate decentralized coupling protocol that takes into account the V2V communication time-delay. Our aim is to ensure all vehicles along the p-th path maintain a prefixed spacing policy and travel with a common speed as imposed by the virtual leader, i.e. $v^\star(t)$.

To achieve the control objective each vehicle exploit their own state information and the information sent by other vehicles in its communication range. On the basis of these information, each vehicle computes the desired acceleration that guarantees the fleet formation. Since vehicles share information through a wireless communication channel (V2V communication paradigm), it happens that information can be received by each vehicle with a different time-varying delay, whose current value depends on the actual network conditions [24]. This implies that the control strategy has to be based on these the delayed information traveling on the vehicular network.

Hence, the control strategy, that embeds the V2V communication delays, is chosen as:

$$\begin{aligned} &u_i(t) = -b\left[v_i(t) - v^\star(t)\right] + \\ &-\tfrac{1}{\Delta_i}\textstyle\sum_{j=1}^{N} k_{ij}\alpha_{ij}[r_i(t) - r_j(t-\tau_{ij}(t)) - \tau_{ij}(t)v_0 - d^\star_{ij}], \end{aligned} \tag{2}$$

where $k_{ij} > 0$ and $b > 0$ are the stiffness and damping coefficients to be appropriately tuned to regulate the mutual behavior among neighboring vehicles (i.e., the decentralized controller parameters); α_{ij} mimic the presence/absence of a communication link between vehicles i and j; Δ_i is the degree of the vehicle i and represents the number of vehicles communicating with vehicle i; $d^\star_{ij}$ is the desired distance among vehicle i and vehicle j that is equal to distance between the workstation at which the vehicles has to stop; $\tau_{ij}(t)$ is the aggregate delay computed by vehicle i using the time stamps sent by its neighboring vehicles. Indeed, focusing on the p-th path segment close to the receiver vehicle, delay time $\tau_{ij}(t)$ can be assumed bounded between a maximum constant value and a minimal constant value, e.g., $\tau_{min} \leq \tau_{ij}(t) \leq \tau_{max}$ [25].

III. Stability Analysis of Multi-Vehicle Control Strategy

To derive the fleet dynamics under the action of the collaborative strategy in (2), and then prove its convergence, we first define the position and speed errors with respect to the reference signal $r_0(t)$, v_0 ($i = 1, \ldots, N$) as

$$\begin{aligned} \bar{r}_i(t) &= r_i(t) - r_0(t) - d^\star_{i0} \\ \bar{v}_i(t) &= v_i(t) - v_0. \end{aligned} \tag{3}$$

Re-writing the control action $u_i(t)$ (see (2)) in terms of the state error (see (3)), expressing the desired spacing policy $d^\star_{ij}$ with respect to the leading vehicle, i.e. $d^\star_{ij} = d^\star_{i0} - d^\star_{j0}$, the closed-loop dynamics can be rewritten $\forall i = 1, \ldots, N$ as

$$\left\{ \begin{array}{lcl} \dot{\bar{r}}_i(t) & = & \bar{v}_i(t) \\ m_i\dot{\bar{v}}_i(t) & = & -b\bar{v}_i(t) - \frac{1}{\Delta_i}(k_{i0}\alpha_{i0} + \sum_{j=1}^{N} k_{ij}\alpha_{ij})\bar{r}_i(t) \\ & & +\frac{1}{\Delta_i}\sum_{j=1}^{N} k_{ij}\alpha_{ij}\bar{r}_j(t-\tau_{ij}(t)). \end{array} \right. \tag{4}$$

To describe the fleet dynamics in the presence of time-varying delays, associated to the different links, in a more compact form, we define the position and the speed errors vectors as $\bar{r}\,(t) = \left[\ \bar{r}_1^\top(t) \cdots \bar{r}_i^\top(t) \ \cdots \ \bar{r}_N^\top(t)\ \right]^\top \in R^N$, $\bar{v}\,(t) = \left[\ \bar{v}_1^\top(t) \cdots \bar{v}_i^\top(t) \ \cdots \ \bar{v}_N^\top(t)\ \right]^\top \in R^N$, and the error state vector as $\bar{x}\,(t) = \left[\ \bar{r}^\top(t) \ \ \bar{v}^\top(t)\ \right]^\top \in R^{2N}$. Furthermore, delays $\tau_{ij}(t)$ can be represented as elements of the following delay set: $\tau_\rho(t) \in \{\tau_{ij}(t) : i, j = 1, 2, ..., N, i \neq j\}$ for $\rho = 1, 2, ..., q$ with $q \leq N(N-1)$. According to the above definition, the closed-loop fleet dynamics can be represented as the following set of functional differential equations:

$$\dot{\bar{x}}(t) = A_0\bar{x}(t) + \textstyle\sum_{\rho=1}^{q} A_\rho\left(\bar{x}(t-\tau_\rho(t))\right), \tag{5}$$

where

$$A_0 = \left[\begin{array}{cc} 0_{N\times N} & I_{N\times N} \\ -\mathcal{M}\widetilde{K} & -\mathcal{M}\widetilde{B} \end{array}\right] \in R^{2N\times 2N}, \tag{6}$$

$$A_\rho = \left[\begin{array}{cc} 0_{N\times N} & 0_{N\times N} \\ \mathcal{M}\widetilde{K}_\rho & 0_{N\times N} \end{array}\right] \in R^{2N\times 2N}, \tag{7}$$

being

$$\mathcal{M} = diag\Big\{\frac{1}{m_1}, \cdots, \frac{1}{m_N}\Big\} \in R^{N\times N}; \tag{8}$$

$$\widetilde{B} = diag\Big\{b, \cdots, b\Big\} \in R^{N\times N}; \tag{9}$$

$$\widetilde{K} = diag\Big\{\widetilde{k}_{11}, \cdots, \widetilde{k}_{NN}\Big\} \in R^{N\times N}, \tag{10}$$

with

$$\widetilde{k}_{ii} = \frac{1}{\Delta_i}\sum_{j=0}^{N} k_{ij}\alpha_{ij}; \tag{11}$$

and $\widetilde{K}_\rho = [\widetilde{k}_{\rho ij}]$ is the matrix defined as:

$$\widetilde{k}_{\rho ij} = \begin{cases} \frac{\alpha_{ij}k_{ij}}{\Delta_i}, & j \neq i,\ \tau_\rho(\cdot) = \tau_{ij}(\cdot)\ , \\ 0, & j \neq i\ , \tau_\rho(\cdot) \neq \tau_{ij}(\cdot)\ , \\ 0, & j = i\ . \end{cases} \tag{12}$$

By exploiting Leibniz-Newton formula [26], the time-delayed model (5) can be recast as

$$\dot{\bar{x}}(t) = F\bar{x}(t) - \textstyle\sum_{\rho=1}^{q} C_\rho \int_{-\tau_\rho(t)}^{0} \bar{x}(t+s)ds, \tag{13}$$

where

$$C_\rho = \begin{bmatrix} 0_{N\times N} & 0_{N\times N} \\ 0_{N\times N} & \mathcal{M}\widetilde{K}_\rho \end{bmatrix}, \tag{14}$$

and

$$F = A_0 + \sum_{\rho=1}^{q} A_\rho = \begin{bmatrix} 0_{N\times N} & I_{N\times N} \\ -\mathcal{M}\widehat{K} & -\mathcal{M}\widetilde{B} \end{bmatrix}, \tag{15}$$

with

$$\widehat{K} = -\sum_{\rho=1}^{q} \widetilde{K}_\rho + \widetilde{K}. \tag{16}$$

Furthermore the following lemmas hold:

Lemma 1: [23] Supposing $k_i = \frac{k_{i0}\alpha_{i0}}{\Delta_i} \geq 0$ ($i = 1,\ \ldots,\ N$), the matrix $\widehat{K}$ in (16) is positive stable.

According to lemma 1 the following matrix

$$\widehat{K}_M = \mathcal{M}\widehat{K} \tag{17}$$

is also positive stable since $\mathcal{M} > 0$ (eq. (8)).

Lemma 2: [23] Let F be the matrix defined in (15). F is Hurwitz stable if and only if $\widehat{K}_M$ (17) in lemma 1 is positive stable and

$$b > \max_i \Big\{\frac{|Im(\mu_i)|}{\sqrt{Re(\mu_i)}}\mathcal{M}_i\Big\} \tag{18}$$

being μ_i the i-th eigenvalue of $\widehat{K}_M$ ($i = 1,\ \ldots,\ N$).

Stability in the presence of the heterogeneous time-varying delays can be now guaranteed under the classical constraints on bounded delay functions [27], i.e $\tau_\rho(t) \in [0;\ \tau_\rho^\star]$, $\dot{\tau}_\rho(t) \in [0, d_\rho]$ $\forall t$, $\forall \rho$ and $d_\rho \leq 1$, according to the following LMI-based criterion that can be easily verified by using, for example, the interior-point method [28].

Theorem 1: [29] Consider the vehicular network in (5) under the assumptions of lemma 1 and lemma 2. Also assume all delays $\tau_\rho(t)$ ($\rho = 1, \ldots, q$) to be bounded. If there exist constant, symmetric and positive definite matrices $P \in \mathcal{R}^{2N\times 2N}$ and $S_\rho \in \mathcal{R}^{2N\times 2N}$ ($\rho = 1, \ldots, q$) such that it holds

$$\begin{cases} \frac{\tau_1^\star}{2}P - S_1(1-d_1) < 0\ , \\ \qquad \vdots \\ \frac{\tau_q^\star}{2}P - S_q(1-d_q) < 0\ , \end{cases} \tag{19}$$

then the closed loop system (5) is asymptotically stable, i.e.

$$\lim_{t\to\infty} \bar{x}(t) = 0 \tag{20}$$

for

$$\tau^\star = \max_\rho\{\tau_\rho^\star\} < \frac{\|Q - \sum_{\rho=1}^{q} S_\rho\|}{\|\sum_{\rho=1}^{q} PC_\rho P^{-1}C_\rho^\top P^\top + \frac{P}{2}\|}. \tag{21}$$

Sketch of the proof: The above statement can be proved by using the Lyapunov-Krasovskii theory [26].

In what follows we provide, for the sake of brevity, a sketch of the proof that is based on the following steps [29]:

i) Consider the following Lyapunov-Krasovskii function for system in (13):

$$V(\bar{x}(t)) = \bar{x}^\top(t)P\bar{x}(t) + \textstyle\sum_{\rho=1}^{q} \int_{t-\tau_\rho(t)}^{t} \bar{x}^\top(s)S_\rho\bar{x}(s)ds, \tag{22}$$

where $P = P^\top > 0 \in R^{2N\times 2N}$ and $S_\rho > 0 \in R^{2N\times 2N}$ ($\rho = 1, \ldots, m$) are appropriately chosen;

ii) Differentiate the functional in (22) along the trajectories of the system (13);

iii) Select the control gains k_{ij}, b according to lemma 1, lemma 2

iv) Satisfy the following inequalities:

$$-Q + \sum_{\rho=1}^{q} S_\rho + \sum_{\rho=1}^{q} \frac{\tau^\star}{2}\left[2PC_\rho P^{-1}C_\rho^\top P^\top + P\right] < 0 \tag{23}$$

$$\begin{cases} \frac{\tau_1^\star}{2}P - S_1(1-d_1) < 0\ , \\ \qquad \vdots \\ \frac{\tau_q^\star}{2}P - S_q(1-d_q) < 0\ , \end{cases} \tag{24}$$

so that $\dot{V}(\bar{x}(t)) < 0$.

Note that the LMI problem in (23) and (24) is feasible by selecting the delay bound $\tau^\star$ as (21).

IV. Simulation Results

In this section, we show numerical results obtained via the software Matlab/Simulink, in which we consider considered a fleet of four automated vehicles plus a leader moving among six workstations. The reference behaviour is imposed by infrastructure with a trapezoidal velocity profile, with the aim of moving each vehicle among different workstations. Once each vehicle reaches the next workstation, the reference behavior ensures that it remains there for a time T_w that is required for manufacturing process. Without loss of generality, we consider the case a maximum velocity of 10 [m/s] with $T_w = 10$ [s], as depicted in fig. 2-a and fig. 3-a.

Moreover, each vehicle has mass $m_i = 1000[kg]$, while, at

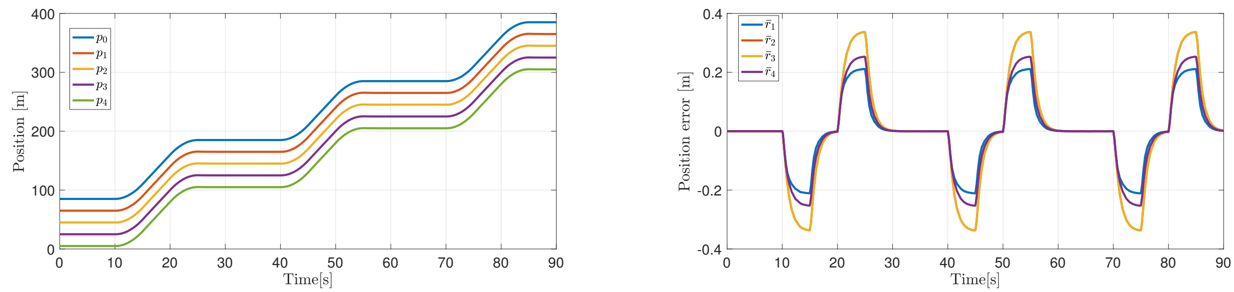

Fig. 2. Desired reference signal tracking which allows the fleet to move between 4 different work stations. Left panel: time history of position. Right panel: time history of position error.

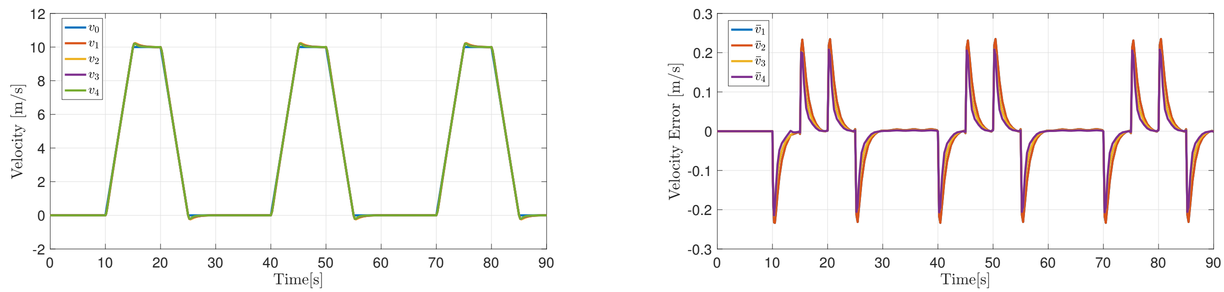

Fig. 3. Desired reference signal tracking which allows the fleet to move between 4 different work stations. Left panel: time history of velocity. Right panel: time history of velocity error.

the initial instant, is supposed to be stopped ($v_i(0) = 0, i = 1, \dots, 4$) at different workstation, i.e. $p_0 = 85$, f$p_1(0) = 65$ [m], $p_2(0) = 45$[m], $p_3(0) = 25$[m], $p_4(0) = 5$[m].
Communication delays are modeled as stochastic variables with a uniform discrete distribution, i.e., $\tau_i(t) \leq \tau^\star; \tau_i(t) \in [\tau_{\min}, \tau_{\max}]$, with $\tau_{\min} = 0$ [s], and $\tau_{\max} \leq \tau^\star = 10.9 \cdot 10^{-2}$[s], where the theoretical upper bound is within the average end-to-end communication delay that is typical of IEEE 802.11 vehicular networks [30]. As illustrated in fig. 2-a and fig. 3-a, and as expected from the theoretical analysis in section III, the strategy presented in this manuscript guarantees the tracking of the reference behaviour, while the position and speed errors converge toward zero, as reported in fig. 2-b and fig. 3-b respectively.

V. Conclusion and Future Work

The paper presents a seminal work aimed to shows how automatic mobility concepts can increase flexibility in manufacturing industry. In particular, it illustrates the performance of a cooperative control protocol that allows the autonomous motion of fleets of conneced vehilces for products handling among different workstation. As future work we will consider the case in which the manufacturing time is different for each workstation and the desired trajectories of vehicles fleets can intersect among themselves.

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References

[1] J. Posada, C. Toro, I. Barandiaran, D. Oyarzun, D. Stricker, R. de Amicis, E. B. Pinto, P. Eisert, J. Döllner, and I. Vallarino, "Visual computing as a key enabling technology for industrie 4.0 and industrial internet," *IEEE computer graphics and applications*, vol. 35, no. 2, pp. 26–40, 2015.

[2] Q. Liu, J. Wan, and K. Zhou, "Cloud manufacturing service system for industrial-cluster-oriented application," *Journal of Internet Technology*, vol. 15, no. 3, pp. 373–380, 2014.

[3] J. Davis, T. Edgar, J. Porter, J. Bernaden, and M. Sarli, "Smart manufacturing, manufacturing intelligence and demand-dynamic performance," *Computers & Chemical Engineering*, vol. 47, pp. 145–156, 2012.

[4] F.-J. Wu, Y.-F. Kao, and Y.-C. Tseng, "From wireless sensor networks towards cyber physical systems," *Pervasive and Mobile Computing*, vol. 7, no. 4, pp. 397–413, 2011.

[5] D. Yang, Y. Xu, H. Wang, T. Zheng, H. Zhang, H. Zhang, and M. Gidlund, "Assignment of segmented slots enabling reliable real-time transmission in industrial wireless sensor networks," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 6, pp. 3966–3977, 2015.

[6] P. Yuan and P. Liu, "Data fusion prolongs the lifetime of mobile sensing networks," *Journal of Network and Computer Applications*, vol. 49, pp. 51–59, 2015.

[7] J. Wan, D. Zhang, S. Zhao, L. Yang, and J. Lloret, "Context-aware vehicular cyber-physical systems with cloud support: architecture, challenges, and solutions," *IEEE Communications Magazine*, vol. 52, no. 8, pp. 106–113, 2014.

[8] J. Wan, C. Zou, S. Ullah, C.-F. Lai, M. Zhou, and X. Wang, "Cloud-enabled wireless body area networks for pervasive healthcare," *IEEE Network*, vol. 27, no. 5, pp. 56–61, 2013.

[9] F. Chen, P. Deng, J. Wan, D. Zhang, A. V. Vasilakos, and X. Rong, "Data mining for the internet of things: literature review and challenges," *International Journal of Distributed Sensor Networks*, 2015.

[10] J.-f. Wan, D. Li, H.-h. Yan, and P. Zhang, "Fuzzy feedback scheduling algorithm based on central processing unit utilization for a software-based computer numerical control system," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 224, no. 7, pp. 1133–1143, 2010.

[11] R. Drath and A. Horch, “Industrie 4.0: Hit or hype?[industry forum],” *IEEE industrial electronics magazine*, vol. 8, no. 2, pp. 56–58, 2014.

[12] G. Cerullo, G. Guizzi, C. Massei, and L. Sgaglione, “Efficient supply chain management: Traceability and transparency,” in *Signal-Image Technology & Internet-Based Systems (SITIS), 2016 12th International Conference on*. IEEE, 2016, pp. 750–757.

[13] L. Qiu, W.-J. Hsu, S.-Y. Huang, and H. Wang, “Scheduling and routing algorithms for agvs: a survey,” *International Journal of Production Research*, vol. 40, no. 3, pp. 745–760, 2002.

[14] H. Fazlollahtabar and M. Saidi-Mehrabad, “Methodologies to optimize automated guided vehicle scheduling and routing problems: a review study,” *Journal of Intelligent & Robotic Systems*, vol. 77, no. 3-4, p. 525, 2015.

[15] J. Abara, “Applying integer linear programming to the fleet assignment problem,” *Interfaces*, vol. 19, no. 4, pp. 20–28, 1989.

[16] C. A. Hane, C. Barnhart, E. L. Johnson, R. E. Marsten, G. L. Nemhauser, and G. Sigismondi, “The fleet assignment problem: Solving a large-scale integer program,” *Mathematical Programming*, vol. 70, no. 1, pp. 211–232, 1995.

[17] A. Chelbi and D. Ait-Kadi, “Analysis of a production/inventory system with randomly failing production unit submitted to regular preventive maintenance,” *European journal of operational research*, vol. 156, no. 3, pp. 712–718, 2004.

[18] W. El Moudani and F. Mora-Camino, “A dynamic approach for aircraft assignment and maintenance scheduling by airlines,” *Journal of Air Transport Management*, vol. 6, no. 4, pp. 233–237, 2000.

[19] M. Lom, O. Pribyl, and M. Svitek, “Industry 4.0 as a part of smart cities,” in *Smart Cities Symposium Prague (SCSP), 2016*. IEEE, 2016, pp. 1–6.

[20] E. Natale, M. Tufo, and A. Salvi, “A fleet management service for smart cities: The s 2-move project,” in *Smart Cities Conference (ISC2), 2016 IEEE International*. IEEE, 2016, pp. 1–6.

[21] G. Bocewicz, I. Nielsen, and Z. Banaszak, “Automated guided vehicles fleet match-up scheduling with production flow constraints,” *Engineering Applications of Artificial Intelligence*, vol. 30, pp. 49–62, 2014.

[22] E. Coelingh and S. Solyom, “All aboard the robotic road train,” *Ieee Spectrum*, vol. 49, no. 11, 2012.

[23] A. Salvi, S. Santini, and A. S. Valente, “Design, analysis and performance evaluation of a third order distributed protocol for platooning in the presence of time-varying delays and switching topologies,” *Transportation Research Part C: Emerging Technologies*, vol. 80, pp. 360–383, 2017.

[24] W. Ren and R. W. Beard, *Distributed consensus in multi-vehicle cooperative control*. Springer, 2008.

[25] A. Botta, A. Pescapé, and G. Ventre, “Quality of service statistics over heterogeneous networks: Analysis and applications,” *European Journal of Operational Research*, vol. 191, no. 3, pp. 1075–1088, 2008.

[26] K. Gu, V. Kharitonov, and J. Chen, *Stability of Time-Delay Systems*, ser. Control Engineering. Birkhäuser Boston, 2012.

[27] E. Fridman and Y. Orlov, “Exponential stability of linear distributed parameter systems with time-varying delays,” *Automatica*, vol. 45, no. 1, pp. 194–201, 2009.

[28] S. Boyd, L. El Ghaoui, E. Feron, and V. Balakrishnan, *Linear matrix inequalities in system and control theory*. SIAM, 1994.

[29] A. Petrillo, A. Pescapé, and S. Santini, “A collaborative control strategy for platoons of autonomous vehicles in the presence of message falsification attacks,” in *Models and Technologies for Intelligent Transportation Systems (MT-ITS), 2017 5th IEEE International Conference on*. IEEE, 2017, pp. 110–115.

[30] W. Alasmary and W. Zhuang, “Mobility impact in ieee 802.11 p infrastructureless vehicular networks,” *Ad Hoc Networks*, vol. 10, no. 2, pp. 222–230, 2012.