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Warehouse automation by logistic robotic networks: a cyber-physical control approach

Key words: Discrete-event systems; Cyber-physical systems; Robotic networks; Warehouse automation; Logistics

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Background of warehouse automation using robotic networks

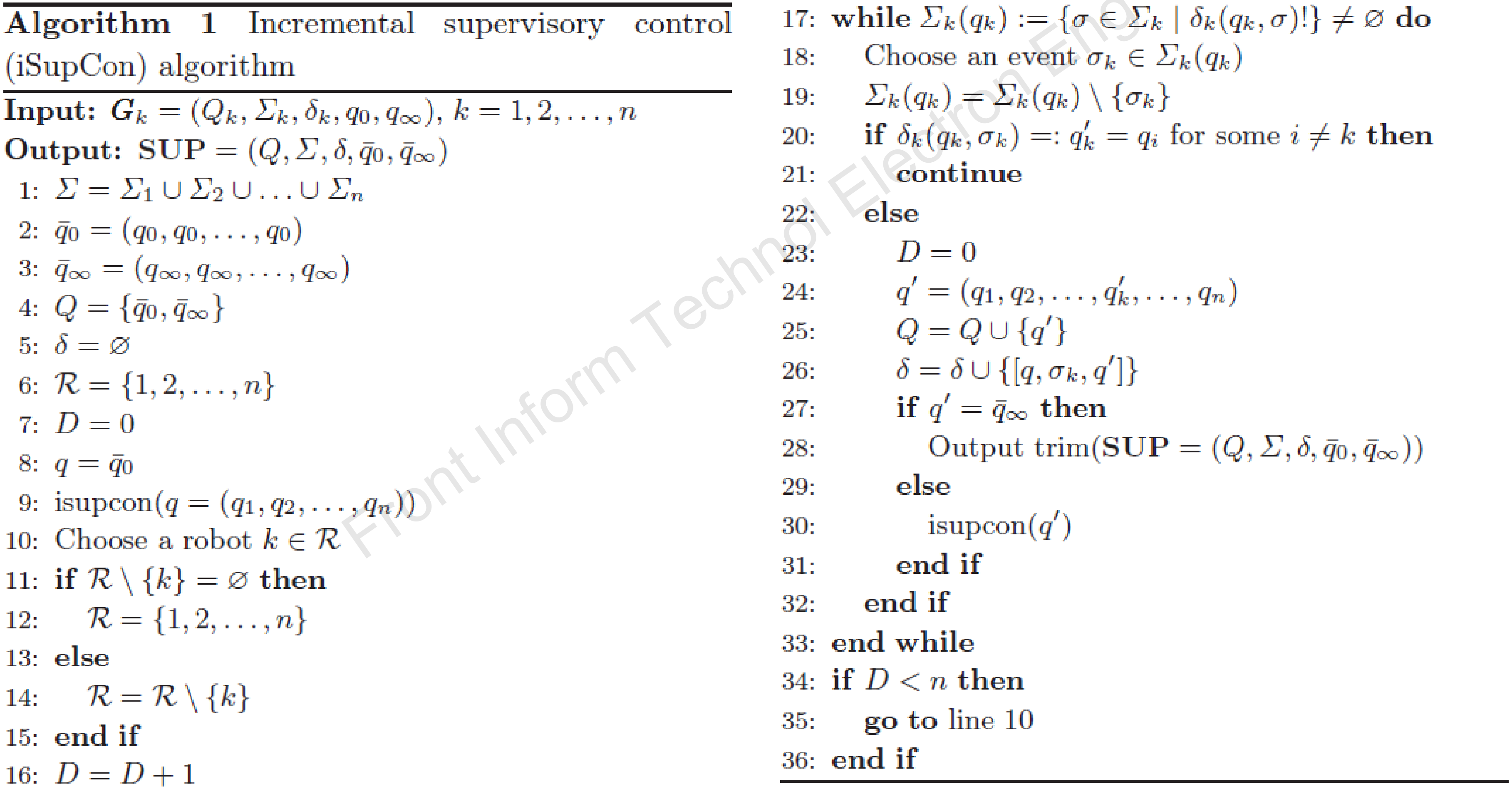
- Among many recent warehouse automation technologies, the goods-to-man approach has received significant interest from the logistics industry. This technology has game-changed several key operations in warehouses, replacing traditional manual picking and transporting items from storage locations by automatic operations using self-driving robots.
- With more mobile robots being operated in warehouses, a systematic control framework is indispensable to ensure that their operations are not only efficient and adaptive, but also safe and fault-tolerant.

Related work

Goods-to-man warehouse automation based on robotic networks is broadly a multi-robot path planning and motion scheduling problem. Such a problem has been extensively studied in the literature. The listed references are by no means complete, but organized in the following three categories:
(1) symbolic motion planning and formal methods;
(2) dynamic vehicle routing;
(3) path planning and motion scheduling.

Cyber-physical control approach

- ☐ Learning-based incremental supervisory control design



Algorithm 1 Incremental supervisory control (iSupCon) algorithm

Input: $G_k = (Q_k, \Sigma_k, \delta_k, q_0, q_\infty)$, $k = 1, 2, \ldots, n$

Output: $\mathbf{SUP} = (Q, \Sigma, \delta, \bar{q}_0, \bar{q}_\infty)$

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 1: $\Sigma = \Sigma_1 \cup \Sigma_2 \cup \ldots \cup \Sigma_n$
 2: $\bar{q}_0 = (q_0, q_0, \ldots, q_0)$
 3: $\bar{q}_\infty = (q_\infty, q_\infty, \ldots, q_\infty)$
 4: $Q = \{\bar{q}_0, \bar{q}_\infty\}$
 5: $\delta = \varnothing$
 6: $\mathcal{R} = \{1, 2, \ldots, n\}$
 7: $D = 0$
 8: $q = \bar{q}_0$
 9: isupcon($q = (q_1, q_2, \ldots, q_n)$)
10: Choose a robot $k \in \mathcal{R}$
11: if $\mathcal{R} \setminus \{k\} = \varnothing$ then
12:     $\mathcal{R} = \{1, 2, \ldots, n\}$
13: else
14:     $\mathcal{R} = \mathcal{R} \setminus \{k\}$
15: end if
16: $D = D + 1$
17: while $\Sigma_k(q_k) := \{\sigma \in \Sigma_k \mid \delta_k(q_k, \sigma)!\} \neq \varnothing$ do
18:     Choose an event $\sigma_k \in \Sigma_k(q_k)$
19:     $\Sigma_k(q_k) = \Sigma_k(q_k) \setminus \{\sigma_k\}$
20:     if $\delta_k(q_k, \sigma_k) =: q'_k = q_i$ for some $i \neq k$ then
21:         continue
22:     else
23:         $D = 0$
24:         $q' = (q_1, q_2, \ldots, q'_k, \ldots, q_n)$
25:         $Q = Q \cup \{q'\}$
26:         $\delta = \delta \cup \{[q, \sigma_k, q']\}$
27:         if $q' = \bar{q}_\infty$ then
28:             Output trim($\mathbf{SUP} = (Q, \Sigma, \delta, \bar{q}_0, \bar{q}_\infty)$)
29:         else
30:             isupcon($q'$)
31:         end if
32:     end if
33: end while
34: if $D < n$ then
35:     go to line 10
36: end if
```

Cyber-physical control approach (Cont'd)

- ☐ Physical level

Once a supervisor **SUP** on the cyber level is computed by the iSupCon algorithm, it will send supervisory control signals to the physical level, in terms of which events to be executed by which robots.

When robot *k* finishes the commanded maneuver, it sends a report signal back to the supervisor **SUP** to indicate its status of completion. Once **SUP** receives the report signal from robot *k*, it updates its state by executing the event σ_k. Then the cycle of command and report repeats (until all robots reach their goal states q_∞).

Cyber-physical control approach (Cont’d)

☐ Online reconfiguration-recomputation

Specifically, when a change is detected, we reconfigure the automaton models of the robots that are affected by the change.

Once the automaton models of the relevant robots are reconfigured, we apply the iSupCon algorithm to recompute a new supervisor. In this way, the new supervisor adapts to the new scenario, thus achieving adaptive behavior.

Case study

We consider 30 robots serving the warehouse, and 30 tasks assigned in three batches (10 tasks per batch). The following sequence of scenarios is considered:

1. Initially 10 robots are dispatched to serve the first batch of 10 tasks.
2. Next 10 more robots are dispatched to serve the second batch of 10 tasks.
3. Subsequently 10 more robots are dispatched to serve the third batch of 10 tasks.
4. A while later, a fallen box occupies the cell numbered “54,” thus blocking the corresponding aisle.

Case study (Cont’d)

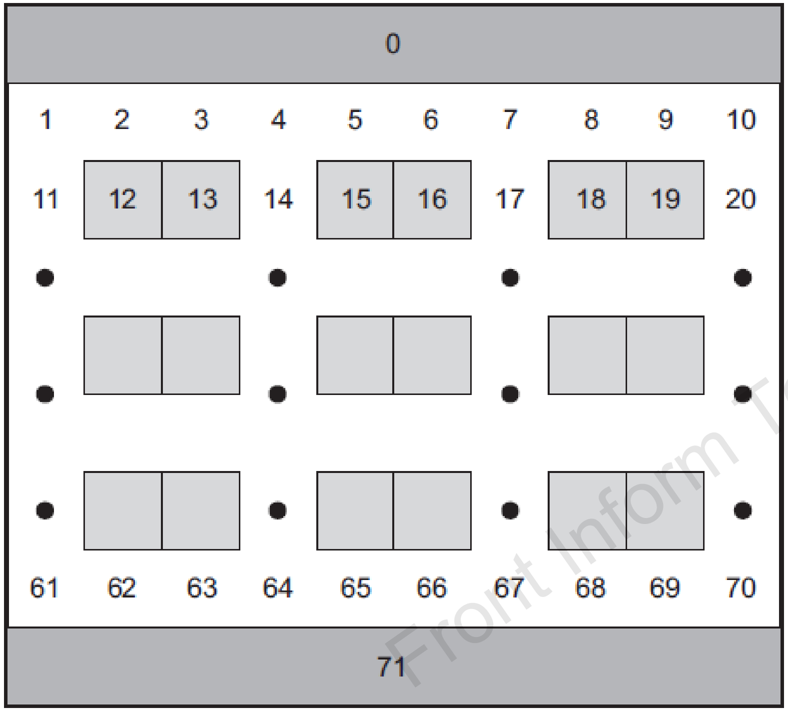


Fig. 3 Case study: warehouse layout. Reprinted from Tatsumoto et al. (2018a), Copyright 2018, with permission from Elsevier

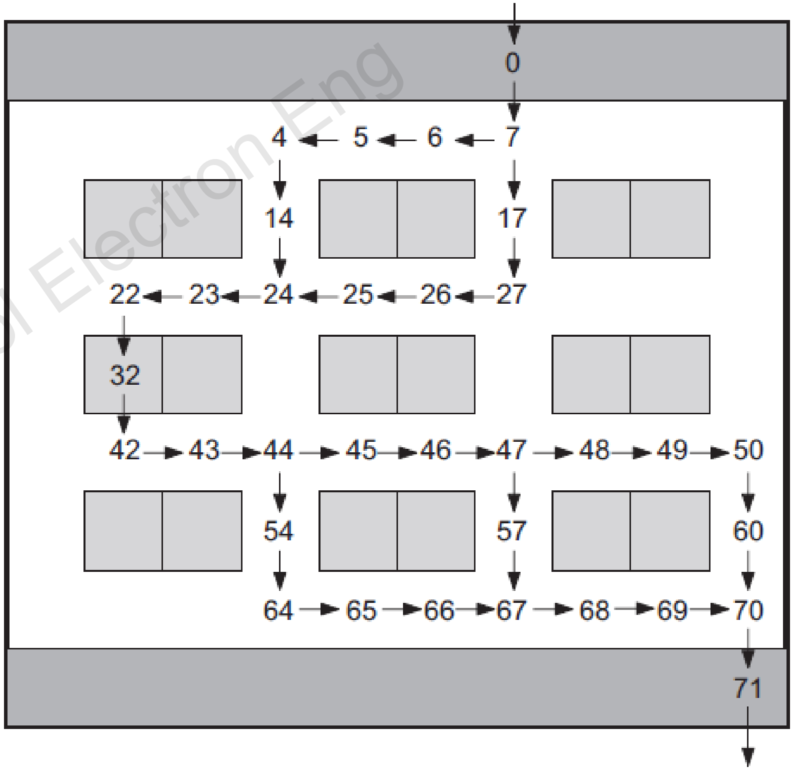
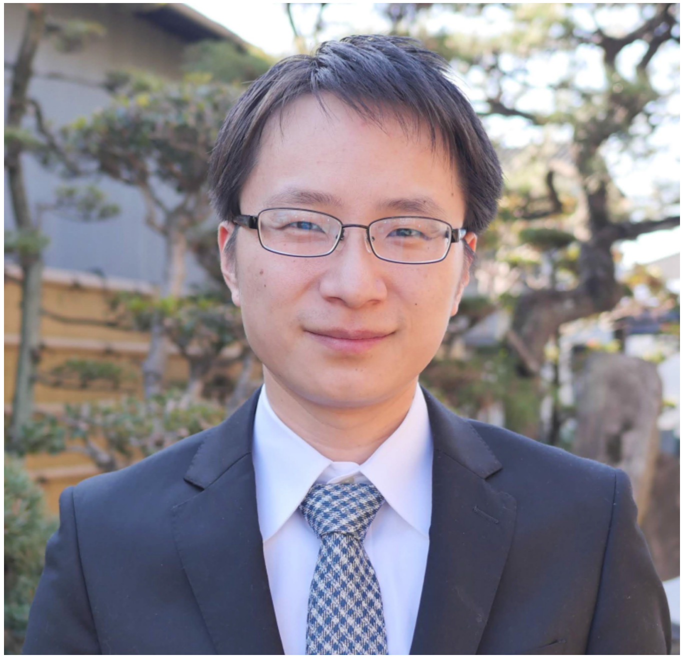


Fig. 5 Case study: automaton model of the robot in Fig. 4. Reprinted from Tatsumoto et al. (2018a), Copyright 2018, with permission from Elsevier

Conclusions

- The proposed cyber-physical control method successfully achieves safe, deadlock-free, efficient, and adaptive behavior for multiple robots serving goods-to-man logistics.
- In each of the four computations by the iSupCon algorithm, the computation time is less than 1 s. In contrast, for the size of 30 robots, neither the standard supervisory control theory used in Tatsumoto et al. (2018b), nor the online method in Tatsumoto et al. (2018a) can feasibly compute a supervisor due to the exponential complexity of synchronous product computation.



Kai CAI received the B.Eng. degree in Electrical Engineering from Zhejiang University, Hangzhou, China, in 2006, the M.A.Sc. degree in Electrical and Computer Engineering from the University of Toronto, Toronto, ON, Canada, in 2008, and the Ph.D. degree in Systems Science from the Tokyo Institute of Technology, Tokyo, Japan, in 2011. He is currently an Associate Professor at Osaka City University. Previously, he was an Assistant Professor at the University of Tokyo (2013–2014), and a Postdoctoral Fellow at the University of Toronto (2011–2013).

Dr. Cai's research interests include distributed control of discrete-event systems and cooperative control of networked multi-agent systems. He is the co-author (with W.M. Wonham) of "Supervisory Control of Discrete-Event Systems" (Springer 2019) and "Supervisor Localization" (Springer 2016). He is serving as the Chair for the IEEE CSS Technical Committee on Discrete Event Systems and an Associate Editor for *IEEE Trans Autom Contr*. He was the recipient of the Best Paper Award of SICE in 2013, the Best Student Paper Award of the IEEE Multi-conference on Systems and Control, and Young Author's Award of SICE in 2010.