TOWARDS A FLEXIBLE TRANSPORTATION IN DISTRIBUTION CENTERS
Low-level Motion Control Approach

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Abstract: In recent years autonomous mobile robots (AMR) have emerged as a means of transportation in distribution centers. The complexity of transportation tasks requires efficient high-level control planning and task scheduling, as well as low-level motion control of the robots such that a more flexible, and robust transport system can be achieved. In this work we present a methodology to achieve coordination of a group of mobile robots so that the objectives are met, focusing on low-level control approach. We use a reactive-to-dynamic-change control concept. We consider an automated distribution center in a simulation case study. The transportation is evaluated in terms of completion time and robustness to fault. In addition, the control strategies are validated in a mock-up version of the automated distribution center.

1 INTRODUCTION

The transportation in a distribution center is typically organized using conveyors systems. These systems provide a good transport capacity and high availability, but are sometimes very sensitive to conveyor failures. In the event of a conveyor breakdown, the transport system of the distribution centers will likely come to complete standstill. This is due to the fact that the their relative high-cost in the warehousing industry restrict having too much redundancy in the transportation system. Another weakness is their fixed maximum capacity. If the business owner of the distribution center changes, a larger capacity and layout changes may be needed. Besides having a high performance, an ideal distribution center transportation should be robust to system failures and flexible to system changes. An autonomous mobile robot (AMR) transport concept has these desired characteristics (Wurman et al., 2007).

In such a concept, a large collection of AMR is responsible for transportation of goods in the distribution center. As the system has a large transport redundancy, the breakdown of a single robot may lower the system's performance, but will not lead to a complete system standstill. Flexibility can easily be achieved by varying the number of robots in the system so that the AMR is capable of handling variations in transport demands. However, to meet the requirements there are needs for advanced control of individual robots as well as inter-robots coordination.

In transportation system, planning, scheduling, and control of tasks of the conveyors or robots are done by a high-level control system. In a centralized way, e.g. see (Gu et al., 2010) or decentralized way, e.g see (Weyns et al., 2005), the high-level control system allocates the tasks to the robots based on customer orders and resource availability.

Recent developments in formation and coordination control of mobile robots by low-level motion controllers show promising results to realize the transportation. In some techniques, e.g. leader-follower and virtual structure, the motion controller achieves tracking of individual robot trajectories and maintains the desired spatial formation between the robots. See for instances (Arai et al., 2002), (Chen and Wang, 2005), (Liu et al., 2010), and (Kostić et al., 2010) for reviews and recent developments around the low-level motion coordination.

Some researches are devoted to performance analysis of different high-level strategies, see e.g. (Vis, 2004), (Le-Anh and Koster, 2006), (Gu et al., 2010), and references therein. These articles discuss the trends in high-level control of distribution centers and propose different options to find the optimal throughput. It is to be pointed out that high-level control assumes known operating conditions in the distribution centers. If the system dynamics change rapidly, high-

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level control may fail in handling the system behavior. This opens possibilities for more reactive and less predictive control strategies.

As for the low-level motion controller, coordination controllers of mobile robots have been successfully simulated and validated in experiments. The applications are widely spread from cooperative cleaning (Jager and Nebel, 2002) to exploration (Burgard et al., 2005). The ability to quickly react to dynamic changes increases the robustness of the system as well as speed of conducting the required tasks. However, as indicated in (Arai et al., 2002) or (Buccieri et al., 2009), there are needs to scale-up the demonstration, and to demonstrate the advantages of cooperative mobile robots in more complex tasks. Moreover, there is a little information on how the coordination control of AMR is applied in a distribution center.

In (Adinandra et al., 2010), it is investigated how a group of AMR can execute one typical task in a distribution center, i.e. transporting items from start to end positions in a certain formation while avoiding collision. The performance of a high- and low-level coordination control are analyzed. It is concluded that the high-level has better throughput but is less robust compared to the low-level control. However, further generalization to more realistic transport tasks with a larger number of AMR is needed.

There are two drivers for our research: (*i*) the high-level control opens possibility for less predictive and more reactive-to-dynamic-changes solutions, and (*i*) the lack of information on how low-level control manage a group of AMR in a distribution center. We conduct research on how flexible and robust transportation in a distribution center can be achieved using a group of AMR, focusing on low-level motion control approach. Compared to the work in (Adinandra et al., 2010), we investigate the transportation in a more realistic simulation case study and using more robots. We consider replacing part of the conveyor system of an automated distribution center with AMR. We analyze the performance of the transport system using relevant indicators, i.e. time to complete tasks and robustness. To validate the control strategies, we conduct experiments on a smaller scale of the automated distribution center

The main contributions of this paper are: (*i*) presentation of a methodology to organize a group of AMR in a distribution center, (*ii*) exploitation of low-level motion controller for a group of AMR to achieve flexible, and robust transportation, (*iii*) simulation and experimental validation of the control strategies in an automated distribution center.

The paper is organized as follows. In Section 2 we describe our control architecture, the kinematic model of the mobile robot and its trajectory controller, as well as the performance indicators used in this work. Section 3 explains in details the low-level control strategies. Section 4 highlights the automated distribution center used in the case study. Section 5 reports the simulation and experimental results and highlights the main finding of this work. Conclusions and outlook work are given in Section 6.

2 PRELIMINARIES

2.1 Control Architecture

As stated in references, control design and task planning in a distribution center are complex and difficult tasks, see e.g. (Gu et al., 2010). Narrowing the problem to the transportation only does not reduce the complexity. In some research, e.g. (Lacomme et al., 2010), one tries to combine the problem of task scheduling and robots dispatching in one optimization problem. On the other hand, we can also keep the problem of task scheduling and dispatching solved as separate design problems.

In this work we choose to use the separation approach. We decompose the complexity of the task into different control layers as shown in Figure 1. The control layers give us convenience of having the control design isolated from the rest of the system and the possibility to test different control algorithms. These layers also allow shifting responsibilities in a given transportation task. The main differences with respect to typical control architectures for transport using conveyors are the addition of trajectory generators and controllers.

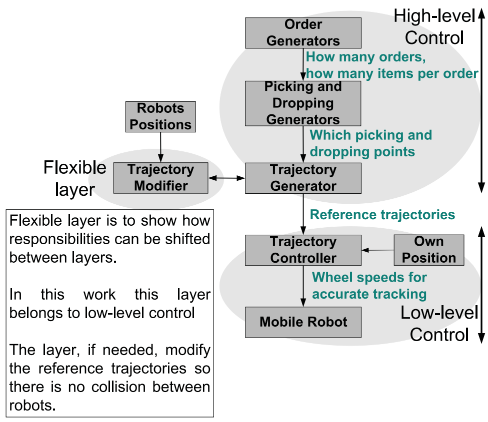

Figure 1: The proposed control architecture.

2.2 Unicycle Mobile Robots

There are various types of AMR. Some of them belong to class of AMR with non-holonomic constraints. In practice, this constraint implies that no sideways movement is allowed. Throughout this work, we consider a group of m-AMR that are described by the non-holonomic kinematic model of a unicycle mobile robot (see e.g. (Kanayama et al., 1990) and references therein):

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\theta}_i \end{bmatrix} = \begin{bmatrix} v_i \cos\theta_i \\ v_i \sin\theta_i \\ \omega_i \end{bmatrix}. \tag{1}$$

Here, v_i and ω_i are the forward and steering velocities respectively to control the AMR, x_i and y_i are the Cartesian coordinates of the robot midpoint in the world coordinate frame, θ_i is the heading angle relative to the x-axis of the world frame, and $i \in \{1,2,3,\ldots,m\}$.

2.3 Trajectory Tracking

In the most existing AMR-like systems the robots follow fixed lines, thus only controlling v_i. The problem is to find paths that result in the optimal throughput, see e.g. (Lacomme et al., 2010). This approach is simple, but cannot easily accommodate changes in transportation demands. Thus, we propose to use a trajectory tracking controller. The idea is as follows.

The high-level control provides the reference trajectory to each robot $\mathbf{p}_{ri} = [x_{ri}\ y_{ri}\ \theta_{ri}]^T$. Trajectories must fulfil the non-holonomic constraints, i.e. $-\dot{x}_{ri}\sin\theta_{ri} + \dot{y}_{ri}\cos\theta_{ri} = 0$. The low-level control is responsible for accurate tracking of these reference trajectories. In this work we use the following controller (Jiang and Nijmeijer, 1997):

$$v_i = v_{ri}\cos\theta_{ei} + k_{xi}x_{ei}, \tag{2a}$$

$$w_i = w_{ri} + k_{yi}v_{ri}y_{ei}\frac{\sin\theta_{ei}}{\theta_{ei}} + k_{\theta i}\theta_{ei}, \tag{2b}$$

where v_{ri} and ω_{ri} are the reference forward and steering velocities respectively, x_{ei}, y_{ei}, and θ_{ei} are the tracking errors represented in robot local coordinate frame, and $k_{xi}, k_{yi}, k_{\theta i} \in \mathbb{R}^+$ are control gains.

2.3.1 Performance Indicators

We use the following indicators to evaluate the performance of the proposed transportation system:

- Completion time, t_{complete}, which is the time needed to accomplish all transportation tasks and is expressed as:

$$t_{\text{complete}} = t_{\text{last,task}} - t_{\text{first,task}}, \tag{3}$$

  where $t_{\text{first,task}}$ and $t_{\text{last,task}}$ are the times for starting the first and completing the last task respectively.

- Robustness. We define robustness as the ability to cope with exceptional situation, i.e. if uncertainties and faults occur, and is quantified as follow:

$$\rho_{ob} = \frac{t_{\text{complete,exceptional}} - t_{\text{complete,normal}}}{t_{\text{complete,normal}}}. \tag{4}$$

3 LOW-LEVEL CONTROL

As shown in Figure 1, the low-level control is mainly responsibilities of the trajectory controller given in (2). Since in this work we put the flexible layer into low-level control, we implement collision avoidance algorithms in the low-level control.

3.1 Assumptions on High-level Control

Since low-level control needs information from the high-level control, the following assumptions are used: (*i*) the high-level control provides the complete orders, their allocations to the AMR, as well as the robots' dispatching rules; (*ii*) the high-level control does not provide collision-free reference trajectories.

3.2 Slow-down using Penalty Function

Consider a situation where two robots almost collide as shown in Figure 2(a).

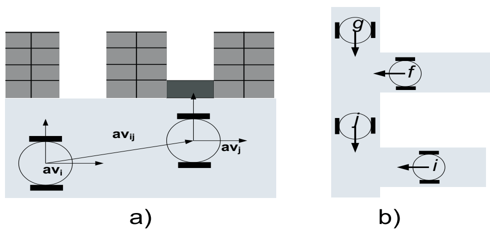

Figure 2: a) Situation in which robot j stops. Robot i has to modify its path to avoid collision; b) Situation with 4 robots at two junctions.

In this example robot j stops to pick items. Robot i has to slow down or alter its path to avoid collision. In our case study we choose to slow down using a set P_γ of continuous, monotone, and bounded penalty function concept (Kostić et al., 2009). An example of a function in P_γ is

$$\delta_\gamma(x) = \begin{cases} 0, & x < \gamma_{\min} \\ \frac{1}{\gamma}\left(x - \frac{\gamma\sin(2\pi x/\gamma)}{2\pi}\right), & \gamma_{\min} \le x \le \gamma_{\max} \\ 1, & x > \gamma_{\max} \end{cases}, \tag{5}$$

If $\mathbf{q}_i = [x_i\ y_i\ \theta_i]^T$ and $\mathbf{q}_i = [x_j\ y_j\ \theta_j]^T$ are the position and orientation of robots i and j in Cartesian space, we define a vector

$$\mathbf{av}_{ij} = \left[\begin{array}{cc} x_j - x_i & y_j - y_i \end{array}\right]^T, \quad (6)$$

with its magnitude, representing the distance between the centers of robots i and j:

$$|\mathbf{av}_{ij}| = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2}. \quad (7)$$

Define the projection of the direction of robot i $\mathbf{dir}_{ai} = [\cos\theta_i \;\; \sin\theta_i]^T$. The slowing down coefficient of robot i with respect to robot j is expressed as:

$$\sigma_{ij} = \begin{cases} 1, & \text{if } \mathbf{dir}_{ai} \bullet \mathbf{av}_{ij} \leq 0 \\ \delta_{\gamma ij}(|\mathbf{av}_{ij}|) & \text{if } \mathbf{dir}_{ai} \bullet \mathbf{av}_{ij} > 0 \end{cases}, \quad (8)$$

where the $\bullet$ sign represents the dot product of two vectors, $\delta_{\gamma ij}(|\mathbf{av}_{ij}|)$ is a penalty function. The computation is repeated for all $j \neq i$, $j \in \{1, 2, \ldots, m\}$ robots. The reference forward velocity of each robot is penalized as follows:

$$v_{ri} = v_{des,i} \prod_{j=1, j\neq i}^{m} \sigma_{ij}, \quad (9)$$

where $v_{des,i}$ is the desired forward velocity of each robot.

The coefficient computed in (8) indicates whether robot j is behind or in front of robot i relative to the direction of movement of robot i. According to expression (9), if robot i is behind j and the other robots, then robot i will slow down to avoid collisions.

Furthermore, priority rules need to be applied if situation shown in Figure 2(b) occurs, i.e. more robots wait to enter the junctions. Applying only (9) will result in deadlock, i.e. no robots move. This is because robots that enter the junction assume they are behind each other, i.e. $\sigma_{fg} = \sigma_{gf} = \sigma_{ij} = \sigma_{ji} = 0$. Suppose we implement right-hand priority, i.e. at the junction a robot that comes from the right side of other robots has higher priority, σ_{fg}, σ_{gf}, σ_{ij}, σ_{ji} is adapted as follow: $\sigma_{ji} = 1, \sigma_{ij} = 0$, and $\sigma_{fg} = 0, \sigma_{gf} = 1$. Other priorities rules like low-number or left-hand priority can also be applied.

Artificial Potential Field (APF) Concept. The collision avoidance to coordinate the robots presented above is used in a normal situation, i.e. there is no fault in the system and all robots are operational.

To add robustness against faults, i.e. some robots are subject to failures or unexpected obstacles block the paths, we add collision avoidance using APF algorithm presented in (Kostić et al., 2010). In the APF algorithm a robot generates repulsive forces based on other robots' positions. In this way a robot can alter its path and avoid collision with the failure robots.

4 AN AUTOMATED DISTRIBUTION CENTER

For the simulation case study, we investigate the performance of the transportation system of the automated distribution center shown in Figure 3 (Andriansyah et al., 2010). It consists of storage, conveyors for transportation, and order picking workstations. The overall system can be classified as product-to-picker distribution center (van den Berg, 1999).

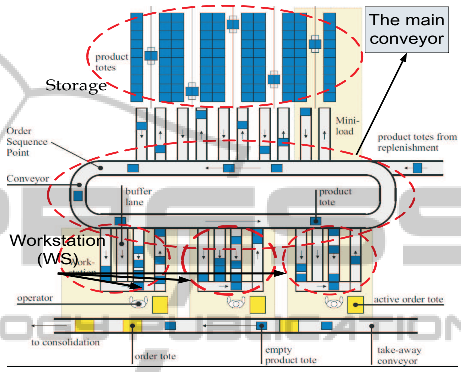

Figure 3: An automated distribution center.

4.1 Using AMR to Replace Conveyors

We deploy AMR to replace the main conveyor loop, i.e. the conveyor that transport the items from the storage to the workstation. We choose two possible paths, i.e. the single-path that resembles the conveyor geometry and multiple-paths that allows short-cuts. We assume that the robot: (*i*) has a size of 0.8 m × 0.8 m, (*ii*) has nominal speed of 1 m/s, (*iii*) in each task carries a product tote with one type of sku/item. For comparison basis we use maximum conveyor capacity, i.e. 1000 totes/hour.

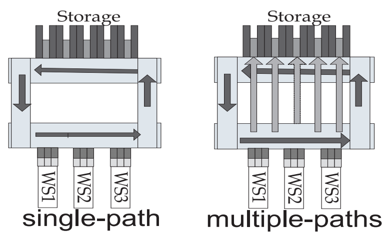

Figure 4: The geometric path options for the robots.

5 RESULTS AND DISCUSSION

Scenarios. We consider different scenarios, i.e. different number of robots (n_{robots}), priority rules, and fault status. We choose $n_{\text{robots}} \in \{2, 4, \ldots, 20\}$.

The following abbreviations are used: SP: single-path; MP-LN: multiple-paths, low number priority; MP-LH: multiple-paths, left-hand priority; MP-RH: multiple-paths, right-hand priority. The conveyor capacity is identified by CS.

5.1 Results and Analysis

Figure 5 shows how the low-level control performs in different scenarios. We can observe that the AMR concept, under the assumptions, can have similar, even better performance as the conveyor systems. By simulation, we can choose which combination of n_{robots} and priority rule that give us the desired performance. The low-level control works with any number of AMR, i.e. we can easily add/remove robot to increase/decrease the throughput. In this particular case, the scenario SP with 16 robots give us the optimal throughput. Although adding more robots can increase the capacity, if the space is kept constant, this also means less space for movement. This results in worse throughput or a deadlock if robots occupies all spaces.

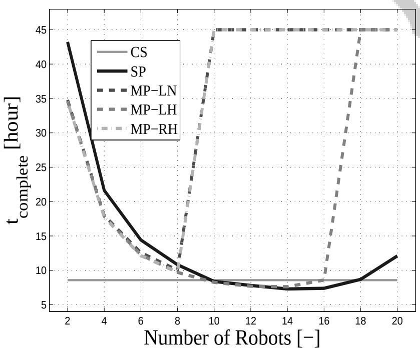

Figure 5: t_{complete} in different scenarios.

Furthermore, Figure 6 show how robustness against failures can be achieved using the APF concept. In this example scenarios SP and MP-LH are investigated. The ability of APF to generate alternative paths for the non-malfunctioned robot makes the overall transport system still operate under failures, although with lower throughput. This means that robustness against failure is achieved. This phenomenon can be observed by the shifting of the original solid-curves to the dashed-curves in Figure 6. In each scenario the mean value of ρ_{ob} is 0.1066 and 0.1068 respectively.

Experimental Results. We conduct experiments using similar set-up to the one in (Adinandra et al., 2010). We use similar distribution center layout as in simulation but on a smaller scale.

In overall the low-level control works well in practical situation. It can handle noise in measurement and small time delays in sending the control signal. Furthermore, Figure 7 shows a real-time situation where 4 robots are in a threat of collision. In this example robot 7 stops to collect an item. Thus, robot 8, 9, 10 has to slow down to avoid collision. This can be seen in Figure 8 where the control signals of the robots are zero. Once robot 7 starts to move again, robot 8 will start moving. By, e.g. the left-hand priority, robot 10 gets higher priority than 9, so robot 10 will move forward followed by robot 9.

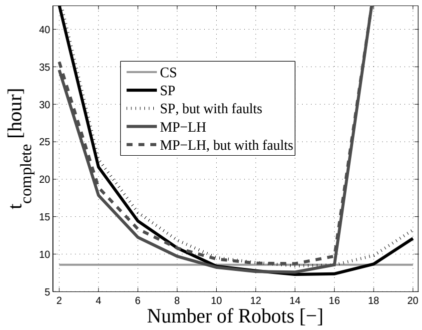

Figure 6: t_{complete} of two scenarios in normal and fault modes. In fault case two robots stops working and block some paths (in different time) for 30 minutes.

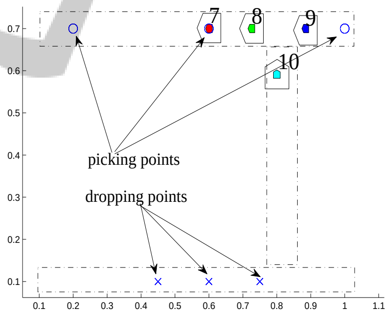

Figure 7: Threat of collisions at a junction.

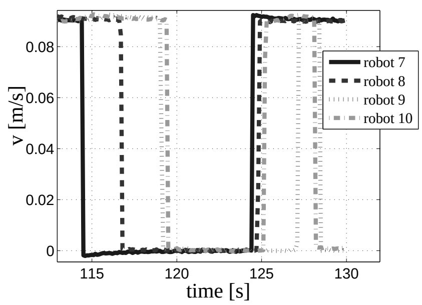

Figure 8: Control signals of robots 7, 8, 9, 10.

6 CONCLUSIONS

In this work we have presented a methodology to extend flexibility and robustness of transportation in distribution centers using a group of AMR. We show how the low-level motion controller can achieve flexibility and robustness at the same time. This allows us, by simulation, to find the best solution according to the requirements. Our experimental results show that the control strategies work well in a real-time situation.

To reduce the dependency from simulation results, it is important to find an analytical estimation or lower bound of the system throughput. In addition, investigation on optimal-low-level control algorithms need to be done so better throughput can be gained.

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