Robotics and Autonomous Systems 62 (2014) 506–514

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Rescheduling policies for large-scale task allocation of autonomous straddle carriers under uncertainty at automated container terminals

Binghuang Cai *, Shoudong Huang, Dikai Liu, Gamini Dissanayake

Centre for Autonomous Systems (CAS), Faculty of Engineering and Information Technology (FEIT), University of Technology, Sydney (UTS), PO Box 123, Broadway, NSW 2007, Australia

HIGHLIGHTS

- We present RNJ & RCJ replanning policies for straddle carriers under uncertainty.
- We use exact BBCG and approximate auction algorithms for each short-term planning.
- Results demonstrate the superiority of RCJ policy as compared with RNJ policy.
- Long-term tests show the need of an improved solution algorithm for each planning.

ARTICLE INFO

Article history:
Received 3 September 2012
Received in revised form
8 December 2013
Accepted 13 December 2013
Available online 25 December 2013

Keywords:
Rescheduling policy
Uncertainty
Optimisation
Task allocation
Autonomous straddle carriers
Automated container terminals

ABSTRACT

This paper investigates replanning strategies for container-transportation task allocation of autonomous Straddle Carriers (SC) at automated container terminals. The strategies address the problem of large-scale scheduling in the context of uncertainty (especially uncertainty associated with unexpected events such as the arrival of a new task). Two rescheduling policies – Rescheduling New arrival Jobs (RNJ) policy and Rescheduling Combination of new and unexecuted Jobs (RCJ) policy – are presented and compared for long-term Autonomous SC Scheduling (ASCS) under the uncertainty of new job arrival. The long-term performance of the two rescheduling policies is evaluated using a multi-objective cost function (i.e., the sum of the costs of SC travelling, SC waiting, and delay of finishing high-priority jobs). This evaluation is conducted based on two different ASCS solving algorithms – an exact algorithm (i.e., branch-and-bound with column generation (BBCG) algorithm) and an approximate algorithm (i.e., auction algorithm) – to get the schedule of each short-term planning for the policy. Based on the map of an actual fully-automated container terminal, simulation and comparative results demonstrate the quality advantage of the RCJ policy compared with the RNJ policy for task allocation of autonomous straddle carriers under uncertainty. Long-term testing results also show that although the auction algorithm is much more efficient than the BBCG algorithm for practical applications, it is not effective enough, even when employed by the superior RCJ policy, to achieve high-quality scheduling of autonomous SCs at the container terminals.

1. Introduction

In the past several decades, the capacity and frequency of container ships arriving at container terminals has increased steadily due to both increasing containerisation and world trade. Correspondingly, container terminals need to turn around larger ships carrying more containers as fast as possible to improve productivity and reduce the terminal operation costs. As a consequence, the terminals have a number of different types of yard resources to assist in the movement of containers, including for example, yard vehicles (for transporting containers around different yard areas) and yard cranes (for transporting containers in a fixed small area at the terminal) [1–3]. It is important for modern container terminals that these yard resources are used efficiently to load, unload and transfer containers during the transhipment process. Yard vehicles play a very essential role in container transportation because they are more flexible than yard cranes in being able to move freely within the yard. The rapid development of autonomous material handling vehicles and robots has facilitated the development and deployment of automated equipment for container terminals, such as Automated Guided Vehicles (AGVs) [4–6] and Automated Lifting Vehicles (ALVs) [7] as yard vehicles. Compared with human-operated vehicles, these automated material handling robots require a high degree of coordination and efficiency. The effective operation of automated yard vehicles hence becomes an essential issue, one that has been investigated by researchers and engineers in robotics and logistics. A number of methods and approaches have been proposed including, for example, two heuristic

* Corresponding author. Tel.: + 61 2 9514 2676; fax: +61 2 9514 2655.
E-mail addresses: bhcai8@gmail.com, bhcai@ieee.org (B. Cai).

0921-8890/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.robot.2013.12.007

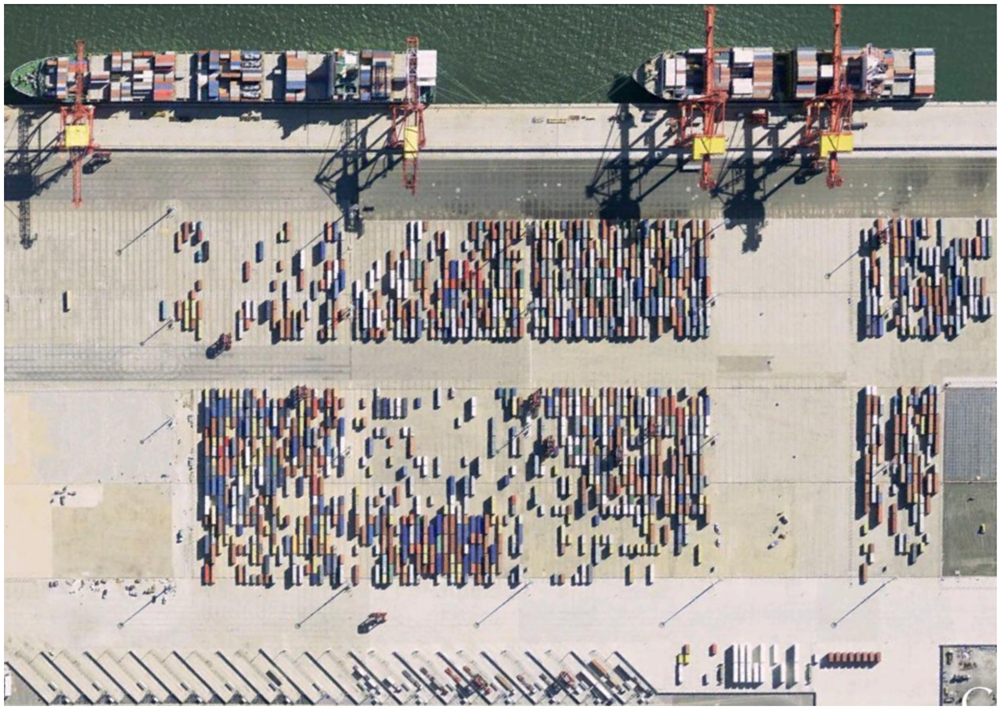

Fig. 1. Patrick AutoStrad container terminal (Google Earth, 16 June, 2009).

methods—one based on a flexible priority rule for AGV dispatching at highly automated container terminals in [4] and another based on a mixed-integer programming model for dispatching a small fleet of ALV [7]. Different approaches, such as simulated annealing, ant colony, auction algorithm, job grouping and column generation have been investigated for multiple autonomous vehicle operation at an automated container terminal by the authors [8–13].

The Patrick AutoStrad container terminal (a fully-automated container terminal shown in Fig. 1) uses a type of ALV known as an autonomous Straddle Carrier (SC) [14–16]. The operation of the autonomous SCs plays a key role in enabling container transportation to increase the transhipment productivity of the terminal. A fundamental problem for the SC operation is SC task allocation. This is known as Autonomous Straddle Carrier Scheduling (ASCS): finding a feasible and efficient schedule for the straddle carriers to finish a list of container transportation jobs. The found schedule should satisfy the relations and constraints of yard vehicles, transhipment jobs, and seaport environments, as well as meet performance requirements of the terminal operation. The ASCS problem is very difficult to solve due to (1) large number of jobs, (2) large number of SCs and (3) complicated terminal environments. Scheduling algorithms have been developed and employed to solve such a problem and some of these algorithms (e.g., genetic algorithms and job grouping developed by the authors) have been or are being implemented in the real operation system of the Patrick AutoStrad container terminal [11]. These methods are based on approximate methodology, which could get a feasible solution but may not be optimal. Note that optimal scheduling can greatly reduce the cost of the operation of the container terminal [14–16]. An exact algorithm based on column generation has been presented for the ASCS problem to obtain the optimal schedule [12,13]. However, this column generation based algorithm is more time-consuming for large-scale problem than approximate methods. Thus, to improve algorithm efficiency and solution quality, there remains a need to investigate approaches for solving large-scale ASCS problem.

An important aspect of the task allocation problem of autonomous SCs is that the operation of autonomous SCs is subject to uncertainties that occur due to interaction with the real-world (autonomous vehicles can stop, delay or face problems like a new job arrival) and hence job and vehicle schedules need to be replanned [17]. Replanning of autonomous SC in dynamic container handling environments is essential for maintaining high productivity in the face of unexpected events. Thus, the ASCS problem should be solved in a way that it can react to such uncertainties. One of the most common and effective ways to do this is to formulate and solve small-scale ASCS problem from time to time using updated information based on the change of jobs and the state of the SCs. To some extent, this is similar to job-shop rescheduling in manufacturing systems [18,19]. Different strategies and policies, such as new job rerouting, complete rerouting, periodic rescheduling and event-driven rescheduling, have been investigated for job-shop rescheduling [18,19]. Dynamic replanning methods have been investigated and developed by robotic and logistic researchers in relation to the replanning of yard cranes and yard vehicles at container terminals [17,20,21]. However, their efficiency and effectiveness still require improvement for long-term operation performance, especially for application in autonomous SC task allocation under uncertainties.

This paper focuses on investigating replanning strategies for large-scale ASCS problems under the uncertainty of new job arrival and on providing related guidelines for the operation of automated container terminals. Two event-driven rescheduling policies are developed and compared for the long-term task allocation of autonomous straddle carriers to handle an unexpected event of new job arrival: (1) Rescheduling New Jobs (RNJ) policy (solving the ASCS problem with new arrival jobs only in each planning) and (2) Rescheduling Combination of new and unexecuted Jobs (RCJ) policy (solving the ASCS problem with all the new jobs and unexecuted jobs in the previous planned schedule). To evaluate the performance of the two policies, a multi-objective cost function is used in the form of combining the costs of SC travelling, SC waiting and delay of finishing high-priority jobs via weighting factors. For each rescheduling policy, a Branch-and-Bound with Column Generation (BBCG) algorithm [12,13] and a simple auction