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Management of autonomous straddle carrier fleet

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Abstract

The continuous development of maritime trade over the last decades has led to a significant growth of needs in every section of maritime transport and port operations. During the next 5 years the annual volume at global container terminals will rise significantly, making terminal utilization rates higher than the ones where the systems operate optimally. There is a need for finding more efficient, quick and economic ways of transporting, handling and storing goods as well as seeking more productive strategies for yard management and terminal operation. Inspired by markets' growing demands and the possibilities of transforming conventional vehicles into automatic ones, an algorithm for smart job allocation and routing of automated vehicles (Straddle Carriers) in terminals is presented in this paper. A management strategy for handling a fleet of autonomous straddle carriers in port yard areas aiming at minimizing the energy consumption while maintaining the performance of the port operations is developed. The strategy is based on a three-layer approach, with job assignment and individual routing at the first two levels and conflict resolution at the last layer, aiming at providing collision-free trajectories and speed profiles. The algorithm is integrated into the terminal operating system of the port and constitutes a complete solution for small-medium sized ports.

Keywords: Autonomous vehicles, straddle carrier, yard management.

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1. Introduction

Container trade constitutes a key indicator for global maritime commerce. The efficient management of container terminals leads to economic growth and prosperity at national level. The high rates of maritime trades' growth will push terminals' utilization rates to 75% in 2018 from the 68% of 2013, reaching 840 million TEUS in 2018 (Drewry 2014). Industry intelligence shows that yard occupancy ratio of around 70% will allow terminals to work at maximum efficiency, while working above this threshold might reduce efficiency Binghuang et al. 2011. Therefore, the development of automated operations in the direction of improving terminals' efficiency and utilization are of major importance.

Over the last decades, important technological advantages have contributed to the automation and semi-automation of terminals around the world, signaling the start of a new era in container handling and management. Conventional approaches based on man-handled jobs have been replaced by new and automated ones which minimize the number of errors and improve productivity. Many ports have already adopted automated or semi-automated operations for their major container terminals. ECT and Euromax terminals in Rotterdam as well as CTA in Hamburg are some examples of fully automated terminals, whereas Wai Hai in Tokyo and PNC in Busan are paradigms of semi-automated terminals. The common benefit of the aforementioned operations comes by the high efficiency rates which are indicated by the growing numbers of successfully handled jobs. The automation or semi-automation of the container handling vehicles is expensive and requires the renewal of the fleet, which cannot be afforded by small and medium ports in most cases. In order to be able to increase the efficiency, without investing large amounts of money the alternative is to transform existing vehicles into autonomous ones. In both cases, there is a need for integrating these new vehicles into the port environment, which means to update the existing terminal operating system (TOS) with capabilities for managing these vehicles in real-time.

The aim of the paper is to present a fleet management algorithm for assigning jobs and defining collision-free routes for autonomous SCs in port areas. The algorithm is integrated into the TOS of the port of Thessaloniki. The paper is structured as follows: A literature review is presented in chapter two, reviewing the main contributions to the fleet management in port yards. The algorithms developed and their integration in the existing operating systems of the port are described in chapter three. Finally, conclusions and future research guidelines are presented in the last chapter.

2. Literature review

Many fleet management algorithms and strategies have been developed and applied during the last decades to all transport sectors. Freight transport (Cordeau et al. 2007, Golden et al. 2008, Zeimpekis et al. 2007) is maybe the most representative one, where the vehicle routing and scheduling problem have been largely analysed. In addition, similar algorithms have been applied to city logistics (Benjelloun and Crainic 2008, Taniguchi and Thompson 2002), urban public transport (Guihaire and Hao 2008, Zhao and Zeng 2008), dial-a-ride transport (Cordeau and Laporte 2007, Gomes and de Sousa 2009), air transport (Yu and Thengvall 2009, Papadakos 2009), maritime transport (Christiansen et al. 2007, Fagerholt et al. 2010), rail and intermodal transport (Macharis and Bontekoning 2004, Crainic and Kim 2007). More details about these contributions can be found in Bielli et al. 2011.

With regards to the use of autonomous vehicles in construction site, warehouses (Guizzo 2008, Wurman et al 2008) or mines the two main problems that are solved are job assignment and routing of vehicles, which compound the Automated Straddle Carrier Scheduling (ASCS) problem in the case of port areas, an np-hard and challenging problem due to the large numbers of jobs and vehicles, as well as complicated seaport environment. The essence of the problem comes to the way of finding a feasible and efficient schedule for a number of vehicles to finish a list of jobs. This problem is modeled in Binghuang et al. 2011 and Binghuang et al. 2013 as a Pickup and Delivery Problem with Time Windows (PDPTW), which can be formulated as Binary Integer Programming (BIP) with the total travel distance of straddle carriers as the objective function. One of the most popular algorithms for solving it, is the Branch-and-Bound with column generation (BBCG) algorithm. Specifically, according to the basic theory of Dantzig-Wolfe decomposition, BBCG algorithm divides the ASCS problem to a "Master problem" and a "subproblem". The appropriateness of BBCG algorithm for providing feasible and optimal solution for the ASCS problem is demonstrated at Binghuang et al. 2011, Binghuang et al. 2013 and Binghuang et al. 2013. It is certain that Binghuang et al. 2013 and Binghuang et al. 2013 are developments of Binghuang et al. 2011, however none of these 3 papers is able to provide a sustainable solution because of lack of fundamental factors, like collisions and new task allocations. On the contrary at Binghuang et al. 2014, Yuan et al. 2009, Gawrilow et al. 2007 routing and collisions are the main objects for research, especially at Binghuang et al. 2014, Gawrilow et al. 2007, where special constraints are developed to describe the trajectory of the vehicles and the orientation of the containers. Moreover, it should be mentioned that the proposed algorithm at Binghuang et al. 2014 is based on a single vehicle time window algorithm whereas, at Yuan et al. 2009 special reference is given to path planning. In general, approaches Binghuang et al. 2011, Yuan et al. 2009 and Binghuang et al. 2013 are dealing with a significant proportion of the problem, but not every aspect of it. We can assert that Yuan 2013 is the most comprehensive study of all, not only because its proposed methods are solving every aspect of the problem but also because it introduces a new and interesting way of job assignment to Autonomous Straddle Carriers (ASC). Furthermore, a complete approach of the ASCS problem can be developed by combining the proposed algorithm of Binghuang et al. 2013 along with path-planning and collision-free methods, which are represented at papers Binghuang et al. 2014, Yuan et al. 2009 and Gawrilow et al. 2007. A different approach of the routing and assignment problem is given in Tierney 2014 as well as useful information of the approaches-solutions in Rotterdam and Hamburg automated terminals. Table 1 summarizes the commonalities and differences for the 3 main sections of the problem of every paper that has been studied.

Table 1. Autonomous vehicle fleet management researches comparison

	Assignment	Routing	Collisions
Binghuang Cai, Shoudong Huang, Dikai Liu, Shuai Yuan, Gamini Dissanayake, Haye Lau and Daniel Pagac, 2011	Pick-up and delivery problem with time windows (PDPTW)	Minimization of the total distance of all vehicles, minimize the reduced cost of an admissible route.	Not applicable
S. Yuan, B.T. Skinner, S. Huang, D.K. Liu, G.Dissanayake, H. Lau, D. Pagac, T. Pratley, 2010	Sets initial points for SC, builds SCs' job list, plan paths.	Path planning with nodes and container orientation.	Collision free via waiting at a node or shunting aside.
S. Yuan, H. Lau, D.K. Liu, S.D. Huang, G.Dissanayake, D. Pagac, T. Pratley, 2009	In each vehicle two tasks have been assigned at its initial stage. Dynamic task allocation.	Path planning with nodes.	Collision free via waiting at a node or shunting aside.
Binghuang Cai, Shoudong Huang, Dikai Liu, Shuai Yuan, G.Dissanayake, Haye Lau, Daniel Pagac, 2013	Pick-up and delivery problem with time windows (PDPTW)	Minimizes the weighting sum of SC traveling time (SCTT), SC waiting time (SCWT) and High priority jobs finishing time (HJFT),	Not applicable
Binghuang Cai, Shoudong Huang, Dikai Liu, G.Dissanayake, 2014	Rescheduling New Jobs (RNJ) policy, Re- scheduling combination of new and unexecuted jobs (RCJ) policy	Not applicable	Not applicable
Shuai Yuan, 2013 Mathematical Modelling for Automated Container Transfers (i)	Comprehensive model , Job scheduling model	Node path planning, container stacking and sequencing, container orientations, acceleration and deceleration times	Collision free
Shuai Yuan, 2013 Job Grouping Approach for Planning Container Transfers (ii)	Grouping jobs using a guiding function	Multi-vehicle path planning algorithm	Collision free by considering the motion of all other active ASCs and, as a result, will go around or give way to ASCs with already planned paths.
Shuai Yuan, 2013 Modified Genetic	The two-part chromosome technique	Not applicable	Not applicable

Algorithm for Scheduling Optimization (iii)			
Ewgenij Gawrilow, Ekkehard Kohler, Rolf H. M¨ohring, Bjorn Stenzel, 2007	Shortest path for each job request	Time dependent approach of Dijkstra algorithm (using arcs and polygons)	Collision free with distance-dependent and a time-dependent policies
Kevin Tierney, Stefan Voí, Robert Stahlbock, 2014	Time-space graph modeled with time periods, terminal nodes, intersection nodes and long term nodes for load/unload	Multi-vehicle path planning using arcs with maximum number of vehicles that travel in a single time period, time space nodes	Not applicable

Finally, the main competitors offering similar product are Kalmar, Hyundai and Konecranes. Table 2 below summarizes their main characteristics.

Table 2. Characteristics of the main competitors

Provider	Kalmar - Autostrad	Hyundai - HiTops	Konecranes
Tools available	5 different "tools" for optimised automation (SmartLift, SmartStack, SmartPath, SmartRail, SmartFleet).	One single "tool" for: Planning algorithm, optimised resource utilization and yard management functions.	3 major sectors-tools for terminal management.
Autonomous components	Autonomous functionality of each tool.	Converts a manual terminal to an automated one without TOS affect.	Autonomous functionality of each tool.
Handling of unexpected situations	Real time control functionality for unexpected situations.	Real time control functionality for unexpected situations.	Alternative algorithm solution for unexpected/priority jobs.
Vehicles	Suitable software for any kind of vehicle (RTGs, straddle carriers, shuttle carriers, reachstackers, empty container handlers and front-end loaders).	Suitable software for any kind of vehicle (RTGs, straddle carriers, shuttle carriers, reachstackers, empty container handlers and front-end loaders).	Suitable for Straddle Carriers
Navigation system	Magnet ruler calibrates the calculation of the vehicle position relative to magnets embedded in the pavement (Innovative solution).	Radar-GPS navigation.	Radar-GPS navigation.
Type of port	Applies to medium/large ports	Applies to large ports	Ideal for small/medium sized ports

3. Methodology

The proposed 3-level approach combines elements of all the aforementioned studies. The designed algorithm (AVMPA) has been developed in the direction of improving automated operations. In more details, by collecting data from the operations management system of the terminal (TOS), the algorithm firstly calculates the shortest path between every SC location (as also collected through the TOS) and every job location (origin and destination of container movement within the terminal), secondly it solves a minimization algorithm in order to assign available SCs to jobs minimizing the total distance while guaranteeing adherence to routing rules (e.g. certain paths allowed for entry/exit of SC in yard areas etc.). It is important to note that the algorithm is not based in the perspective of "closest vehicle" for the assignment part of the problem, but to a more aggregated view of the position of every vehicle in the yard. Third, it re-calculates the shortest paths and includes the temporal dimension by defining detailed speed profiles along the paths.

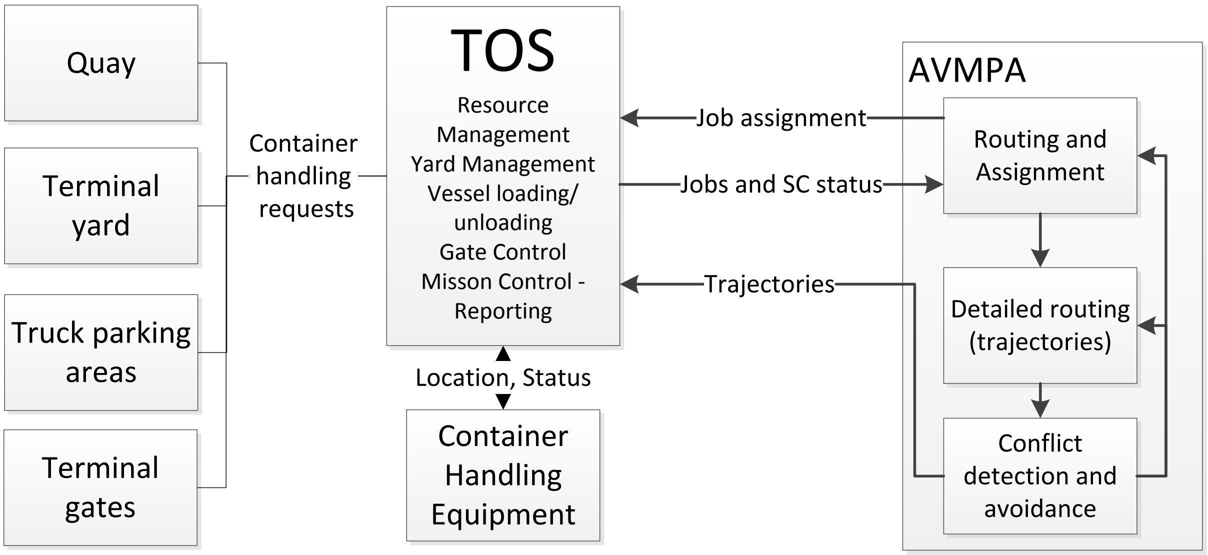

Fig. 1. Logic of the fleet management algorithm

Finally, it checks potential collisions and modifies the speed profiles, the routes or even the assignments aiming at avoiding them. Firstly the algorithm try to avoid the collisions by slightly modifying the speed profiles of the two SCs in a way that one will accelerate and the other will decelerate a few meters before the potential collision, modifying again their velocity (oppositely) in order to respect the timestamps as defined in the original routing. If this is not feasible, the algorithm will go to level 2 and change the routing of one of the two SCs, which means that new collisions may appear. Finally, if the no routes are feasible the algorithm will go to level 1 and modify the job assignment. At the end the system delivers the job assignment together with the routes to be followed by each vehicle, composed by location (GPS coordinates) and timestamp (at what time should the vehicle be at each location). This is then forwarded via TOS to the automated SC (via a specific TOS – OnBoardUnit interface) and assignment execution is constantly monitored in order to identify any deviation which will again feed a reactive action (re-routing).

Concerning the assignment problem, the fundamental idea is to reduce the total travel distance of the fleet while guaranteeing adherence to routing rules (e.g. certain paths allowed for entry/exit of SC in yard areas etc.). For that purpose, greedy heuristic based on nearest-vehicle-first algorithms were tested but the results were not satisfying, thus the problem was solved exactly by minimizing the objective function of the fleets' travelled distance and calculating the distance from all the ASCs to all the jobs using the Dijkstra algorithm. For this, firstly the physical terminal environment, of pier 6 in Port of Thessaloniki was transformed into a map with links and nodes. Moreover, way points with timestamp are provided in order to examine the progress and the consistency of the carrying procedure using vehicles dynamics for estimating the trajectory to follow and the speed profile. Special reference has been also given to the definition of container orientation since there is a specific way for storage the container to the yard as well as loading it to the trucks (Binghuang et al. 2015). Since the orientation of containers is fixed in a single direction for both ships and trucks, path planning must consider the orientation at the initial and destination nodes. The acceptable orientation has been modeled during the container transportation procedure from the initial to the destination node Binghuang et al. 2015.

Once the routes have been selected and defined in detail, potential collisions are identified by comparing locations and timestamps. Collision-free part constitutes a very important issue since it is the structural element for the applicability of the algorithm to real conditions. Three sections compose the "collision-free" solution.

- Safety box - As safety box is defined as the desired area occupied by each straddle carrier. More specifically, this area should be equal or larger than the vehicle's dimensions. The larger it is the safer works our system. Nevertheless, a large Safety Box will cause the system to be less optimized.
- Standard arrival time - The idea of Standard arrival Time is that regardless the speed and aiming at avoiding a collision, every vehicle's time of entering and leaving a link stays constant during the procedure. Therefore, the system needs no rerouting every time a collision is avoided. If this constraint cannot be satisfied, the routes of various vehicles may need to be recalculated.

- Collision zone - Last but not least, the Collision Zone is based on the geometrical formulations for avoiding overlap of safety boxes in the intersections and it depends on the angle between the links as well as on the dimensions of the safety boxes. Collision Zone is the part of each link before and after the intersection where the two Safety Boxes intersect, which means that vehicles inside these areas at the same time would have a collision.

4. Materials and methods

4.1. Study Area

The study area is located at the port of Thessaloniki Greece and specifically, the western part of pier no.6, where the containers are handled.

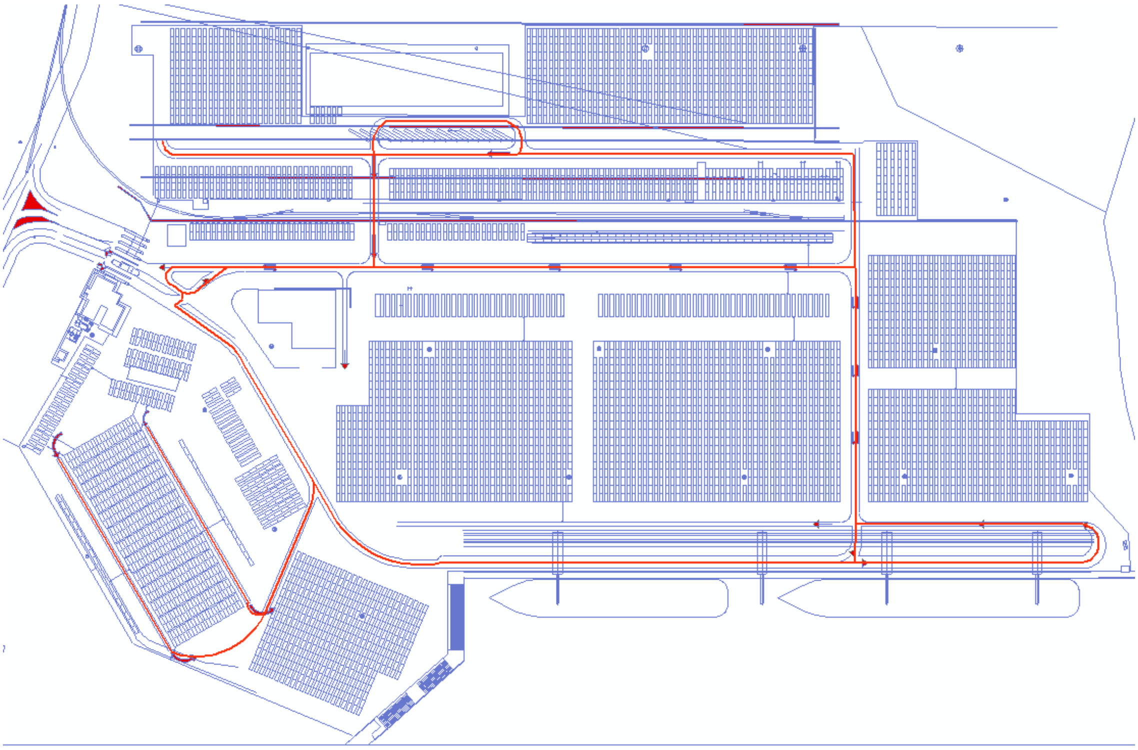

Fig 2 Thessaloniki’s port pier 6 and terminals’ designed network

The 550 m. long and 340 m. wide Container Terminal can berth ships with a draught of 12 m. Being part of the Free Zone, it covers a surface area of 254,000 m2 with an on-site storage capacity of 5,000 TEUs in ground slots. The terminal includes manned technical support facilities. Four cranes are used for container loading-unloading services (2 post panamax). Moreover, the Container Terminal is linked with a double track railway to the national railway networks. To load-unload containers from/to the railway wagons, the terminal uses 1 transtainer of 50-ton lifting capacity.

4.2. Assignment

The initial problem was to match every SC to one and only job at a time in the direction of minimizing the total traveled distance of the fleet while ensuring that all jobs are assigned.
The idea is to reduce the total travel distance of the fleet while satisfying all the requested jobs, thus the solution is on the minimization of a simple optimization problem. Let SC be the set of Straddle Carriers, J be a set of jobs, D_{ij} is the distance between SC_i and job j within the network (not Euclidian). Also, let x_{ij} be a decision variable that becomes 1 when job j has been assigned to SC_i and 0 otherways. The objective function to minimize is presented in Equation (1). Concerning the constraints, each job had to be assigned to one and only one straddle carrier, and , one straddle carrier cannot perform two jobs at the same time (at this point the assumption that the number of straddle carriers is equal or greater than the number of jobs is needed)

$$Min \sum_{i=1}^{SC} \sum_{j=1}^{J} (D_{ij} \cdot x_{ij}) \tag{1}$$

s.t.

$$\sum_{i}^{SC} x_{ij} = 1 \; \forall \, j \in J \tag{2}$$

$$\sum_{j}^{j} x_{ij} \leq 1 \; \forall \, i \in SC \tag{3}$$

$$x_{ij} \geq 0 \tag{4}$$

$$x_{ij} \in \mathbb{N}, x_{ij} \in \{0,1\} \tag{5}$$

4.3. Routing - scheduling

The routing is initially done using the predefined network and by applying the Dijkstra algorithm (Dijkstra 1959) and secondly adapting it to feasible curvatures based on the vehicle dynamics. In addition to the trajectory of the vehicles, a timestamp is provided based on real acceleration/deceleration profiles of the vehicles.

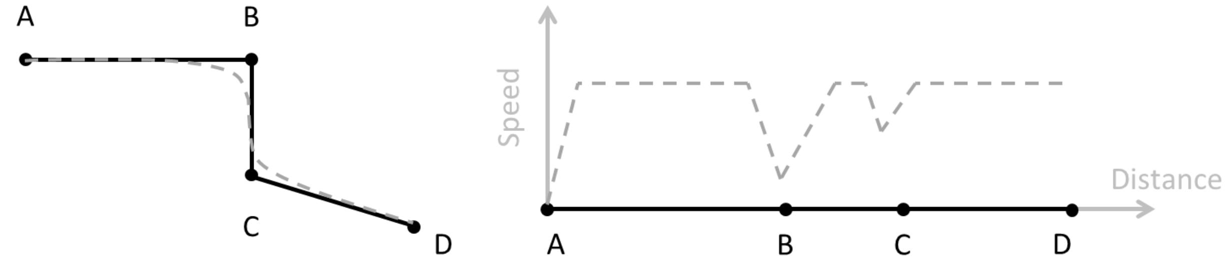

Fig 3 Routing plan with nodes A, B, C, D (left) and speed-distance diagram (right)

In order to do this, the sequence of concatenate links is analyzed as a total for each SC and a speed profile is defined following the radius of curvatures and the vehicle dynamics while taking into account if the vehicle is loaded.

4.4. Collision avoidance

Once all the trajectories and speed profiles have been defined they are analyzed towards potential collisions by comparing their locations and timestamps along the trajectory. The design of the network (e.g. spacing between links) has been done aiming at minimizing the areas where collisions can occur, but this is inevitable at the intersections.

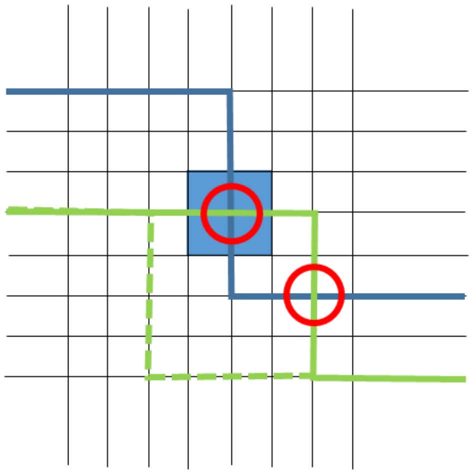

Fig 4 Identification of collision area and proposal of a detour for avoiding it

In order to tackle collisions, a collision zone is defined at each intersection based on a virtual safety box, which is considered the desired obstacle free area around each straddle carrier. More specifically, this area should be equal or larger than the vehicle's dimensions. The larger it is the safer works our system. Nevertheless, a large Safety Box will reduce the systems performance and efficiency. The Collision Zone takes into account the geometric limitations. Collision Zone is the part of the link before and after the intersection where two Safety Boxes are having collision if applied to each link, which means that as long as there is a SC inside the grey part of one of the links, any other SC cannot enter the grey area of the other link of the intersection.

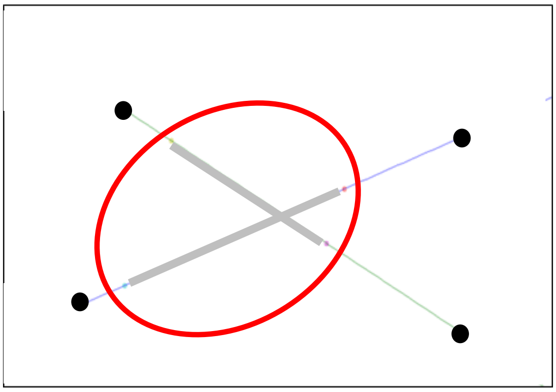

Fig 5 Collision Zone at an intersection

In order to avoid the collision, one of the vehicles will accelerate and the other will decelerate. The values of the acceleration and deceleration are obtained by minimizing the differences between the expected speeds and the real ones (one larger and one lower in order to avoid collision) and having as constraints that the time of entrance of one of the vehicles in the grey part of the link should be equal to the time the other vehicle leaves the grey part of its link. In addition, and in order to minimize the impact to the overall trajectories, the vehicles accelerate and decelerate (depending on what they did before) when leaving the grey zone in order to arrive at the end of the link when it was expected if there was no collision issues. When there is no feasible solution by just reducing/increasing speeds, the whole trajectory should be redefined and potential collisions of the whole fleet checked again, as shown in figure 5. An ultimate solution, is new routes are not feasible if to re-define the job assignment.

Once all collisions have been avoided the new speed profile may presents speed drops in areas where there are no turns. The final trajectory and timestamps are then fixed and send to TOS as waypoints for each vehicle.

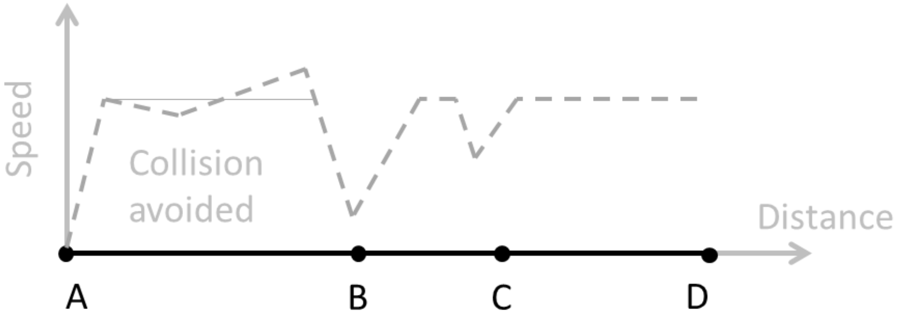

Fig 6 Speed-distance diagram (avoiding a collision)

In order to facilitate the execution of the routes by the ASC, the waypoints have safety intervals both in the spatial and temporal dimensions, composed of 1-2 meters for the spatial dimensions and 3-5 seconds for the temporal one. Larger safety intervals will make more complicate to find a solution which at the same time may be less optimum.

4.5. Integration into TOS

Being the core of the efficient planning and management of the container terminal operations, the TOS is in direct bidirectional communication with the algorithm as well as with the autonomous SC. TOS is responsible for sending the list of jobs (container movements that need to be executed) and the locations of all the SCs to the algorithm and receives back the job assignments and the waypoints of the trajectories of each SC. At the same time TOS is constantly communicating with the autonomous SC via a specified interface and wireless network connectivity in order to assign paths/jobs and monitor SC and job assignment status. The communication between the algorithm and TOS is dynamic in the sense that every 5 seconds the algorithms runs again with the new dataset, taking into account the locations of all SCs (loaded or not) and analyzing all trajectories for finding potential collisions. In the case a SC is delayed and did not respect the waypoints, the algorithm will re-calculate the optimum route and update it when analyzing potential collisions.

4.6. Testing scenarios

The solution will be tested within the LOGIMATIC project in a controlled environment in the 6th pier of Port of Thessaloniki Container Terminal. The tests will focus on the verification of the complete solution and more specifically:

- connectivity of the solution to the existing TOS from which certain container movement orders will be communicated (including origin and destination of movement as well as container details)
- connectivity of the TOS to autonomous straddle carrier to receive status (availability) and position
- the above two will be fed to the algorithm in order to decide the best assignment and routing
- continuous monitoring and re-routing will also be tested

The scenarios planned include:

- available autonomous straddle carrier move to origin of container handling request to pick up a container stacked on a ground slot in a yard block: the movement and testing scenario involves (1) the movement of the straddle carrier and correct position in front of respective yard block row; (2) the movement of the straddle carrier on top of the row above other containers until the correct slot is reached; (3) final handling of container (pick-up) by controlling the spreader. This last step will be performed via manual (remote) operating the straddle carrier to avoid possible mishandling and eliminate safety risks
- the above scenario will also be executed for picking up a container that is stacked on second tier
- loaded autonomous straddle carrier moving to final destination in yard to unload the container on specific yard slot. Again – as above – the steps (1) and (2) will enable positioning the straddle carrier on the correct slot while the last part (unloading) will be performed via remote control.

The above two basic scenarios will be tested with both a 20-feet and a 40-feet container while one specific straddle carrier has been chosen and modified to enable autonomous movements. For the testing scenarios empty containers will be used and a specific yard area (with less traffic) in Thessaloniki port container terminal has been chosen.

Finally for large scale testing a simulation is foreseen to validate the functionality across the entire container terminal area. For that purpose historical container movements will be extracted from existing TOS and the resulted (simulated) operations will be compared to actual performed ones.

5. Conclusions

This paper has presented the development of an exact algorithm for efficient job allocation of container movement orders to Straddle Carriers as well as SC routing in port terminals applying a case study at the 6th pier of Port of Thessaloniki, Greece. The continuous growth of container-terminal activity globally reveals the need for moving from manual to automated operations. The proposed algorithm results to the enhancement of productivity and efficiency of the terminal by reducing travel distance and at the same time it provides increased safety and performance even to the most demanding operations. At the same time the use of such an algorithm in combination with autonomous vehicle operations may result in significant improvements in operational processes (e.g. 24/7 operations in all terminal areas, reduced operational expenses).

The major next step is to assess the performance of the algorithm, for which a simulation environment with multiple vehicles and jobs will be created. This will allow for understanding its limitations with respect to the number of vehicles, number of jobs, area size where the vehicles operate and other constraints. In addition, real tests will be executed with one vehicle in the port of Thessaloniki, which will give important clues about the accuracy in which the movements are performed, both in spatial and temporal terms, thus providing feedback about the safety margins that the algorithm should take into account as well as expected deviations between planned and executed routes.

Future research directions should cover the topics of micro-routing details which concern all the movements that a SC has to do as it approaches the container stack, as well as the actions that it has to do in order to complete a job. A sub-algorithm needs to be developed in order to define the aforementioned procedures.

Aknowledgements

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