Combinatorial Auction Method for Decentralized Task Assignment of Multiple-Loading Capacity AGV based on Intelligent Agent Architecture

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Abstract—**Distributed manufacturing system has steadily becoming more significant for topics for researchers within manufacturing industry. It is due to the reason that it could provide higher flexibility for an organization to cope with a demanding and fluctuating market. This paper proposes distributed task assignment mechanism for multi-load Automated Guided Vehicle (AGV) operation in manufacturing industry. The architecture is based on multi- agent system (MAS) while the task assignment is based on combinatorial auction method. Additionally, necessary improvement had been made to the standard combinatorial auction method to support dynamic attributes of AGV task assignment mechanism.**

Keywords- autonomous AGV; multi-load capacity; combinatorial auction; intelligent agent

I. INTRODUCTION

Recently, distributed system concept has been implemented in numerous industrial and research applications. One of the research applications that have attracted worldwide attention is the distributed manufacturing system. There are many factors that need to be considered in establishing a distributed manufacturing system. Among others are the system architecture, entities specification and conflict resolution procedure. Specific functions and decision making capability has to be equipped into each of the system components. In realizing AGV system for material transportation purpose, appropriate task assignment method need to be devised in order to enhance vehicle utilization to increase system performance. One of the increasingly prominent key research topics in distributed manufacturing system domain is regarding task assignment/ sharing problem [1], [2], [3].

Although significant improvement has been achieved as a result of numerous researches conducted on distributed AGV task assignment problem, it is obvious that the problem is still far from convincing in order to completely replace centralized AGV system in controlling industrial system, particularly from performance point of view. Therefore, there is an important need to address this issue.

Most of the researches on auction-based multi-load AGV assignment still employed conventional approach of assigning single-task per auction. In addition, [4] and [5] established task-pickup, delivery-dispatching and load selection rules to utilize multi-load vehicles. Meanwhile, [6] utilized fuzzy dispatching rules to decide between retrieve/ delivery action execution. Moreover, [7] also utilized conventional method in distributing tasks for multi-load AGV system.

This paper aims to i) establish a decentralized task assignment procedure for multi capacity AGV, ii) concurrently conduct multi-tasks assignment per single auction to increase system performance and efficiency and iii) investigate system performance when different vehicle's loading capacity is varied. We employed combinatorial auction method to solve task assignment problem for multi-load AGV. Several recent studies justify that combinatorial auction could provide good outcomes particularly to solve task assignment problem [8], [9].

II. PROBLEM BACKGROUND

A. Multi Agent System

Multi-agent system (MAS) is required as the base to conduct the task auctions. In employing MAS, an appropriate auctioneer - bidders' relation could be established. In this research, two agents are utilized in realizing the auction procedure:

- Machine Agent (MA) takes the task as the auctioneer. It main role is to initiate task auction procedure, evaluate bids and assign the transportation tasks to the most appropriate vehicle.
- AGV Agent (AGVA) acts as the participant/ bidder. Upon receiving Call for Proposal of an auction, the agent will calculate its ability to deliver the task. It will bid for it if the vehicle could satisfy the set of task constraints.

B. Combinatorial Auctions

In general, combinatorial auctions refer to the auction formats that permit bidders to place a single bid on

978-0-7695-4606-3/11 $26.00 © 2011 IEEE
DOI 10.1109/IBICA.2011.56

combinations of discrete items, rather than just individual items or continuous quantities [7]. It is typically employed when auctioneer has more than one item to be offered simultaneously. By doing so, the risks of only obtaining a subset of items that are not worth as much as the complete set could be minimized.

Conventional combinatorial auctions have been used for years in real-estate auctions. Recently, the method has been picked by Distributed Artificial Intelligence (DAI) researchers to solve engineering problem such as industrial procurement, bus routes determination and in the allocation of radio spectrum for wireless communications. One of the advantages of the approach is that bidders are able to fully state their bidding preferences where the importance is highlighted particularly when items are substitutable or complementary. In order to establish efficient combinatorial auction system, there are several elements that need to be planned:

- Bid generation
- Winner determination
- Auction specification

In this paper, the main research interests focus on designing a combinatorial auction system for AGV transportation assignment problem. The method could yield better efficiency of assigning tasks particularly for multi-unit auctions condition.

C. AGV Resource Allocation based on Knapsack Problem

Allocating transportation tasks to an AGV with multi loading capacity could be categorized as resource allocation problem. In dealing with the problem, this research used multiple-unit knapsack problem (MKP) to model the load selection mechanism. MKP that is NP-hard are formulated as in Eq 1 to Eq. 3 where j is an item within a set of n items. Each item has its own cost, c_{ij} and integer weight w_{ij} attributes.

Minimize
$$\sum_{ij=1}^{n} c_{ij} y_{ij} \tag{1}$$

$$\sum_{ij=1}^{n} w_{ij} y_{ij} < c \tag{2}$$

$$y_{ij}^{x} \in \{0,1,...,Cp_x\} \tag{3}$$

AGV has the objectives to minimize its expected arrival time and the cost to transport the loads it is taking as in Eq. 4. Since AGV does not deal directly with monetary profit or cost as in the conventional MKP, there is a need for this research to consider the mapping of pj component of the objective function as in Eq. 5 and Eq. 6. Thus the complete objective function is formulated as in Eq. 7.

$$at_{ij}^{x} + \sum_{j=1}^{n} c_{ij} y_{ij} \tag{4}$$

$$c_{ij} = \sum_{ij=1}^{IJ} ct \cdot d_{ij}^{x} \cdot \beta_{ij}^{x} \tag{5}$$

$$y_j = y_{ij}^{x} \tag{6}$$

III. AUCTION MODEL

In order to determine optimal transportation sequence, the tasks assignment problem has been formulated as a mixed integer program. The bids are designed to provide transportation sequence of each AGV. Upon receiving bids, a heuristic approach is utilized to evaluate each bid.

TABLE I. MATHEMATICAL NOTATIONS

Symbol	Description
at_{ij}^{x}	Expected arrival time of vehicle-x for operation-*ij*
tr_{ij}	Time duration for AGV to retrieve the announced operation-*ij*
td_{ij}	Delivery time for operation-*ij*
tv_{ij}	Loading time for operation-*ij*
tw_{ij}	Unloading time for operation-*ij*
te_{ij}	Earliest pickup start time for operation-*ij*
tl_{ij}	Latest delivery start time without delaying the entire job sequence
tpa_{ij}	Start time of machine processing of operation-*ij*
ts_{ij}	Machine setup duration of operation-*ij*
rt_j	Released time of job-*j*
mt_j	Remaining time of the respective job
dt_j	Due time of job-*j*
tva_{ij}	Loading start time of operation-*ij*
tp_{ij}	Machine processing time of operation - *ij*
d_{ij}^{x}	Shortest distance for AGV-*x* to deliver load-*ij*
ct	Cost for AGV to travel for a unit length
y_{ij}^{x}	Number of operation-*ij* to be transported
β_{ij}^{x}	Binary value representing status of operation-*ij* assigned to AGV-*x* where $a_{x,ij} = 0$ if the operation-*ij* is not assigned $a_{x,ij} = 1$ if operation-*ij* is assigned
ξ_b^x	Binary value representing status of bid-*b* $\xi_b^x = 1$ if the active bid is accepted $\xi_b^x = 0$ if otherwise
δ_m^x	Binary variable stating if AGv-*x* selects to travel along path-*yz* $\delta_{mn}^x = 1$ if the active bid is accepted $\delta_{mn}^x = 0$ if otherwise
Cc_m^x	Number of loaded tasks on board for AGV-*x* when it arrives at machine-*m*
Cl_m^x	Number of tasks to be loaded/ unloaded when AGV-*x* arrives at machine-*m*
Cp_x	Total loading capacity for AGV-*x*
mp_{ij}	Pickup station for operation-*ij*
md_{ij}	Destination station for operation-*ij*

The model is divided into two main modules - i) bid generation and ii) winner determination. It was directly encoded within a mixed-integer programming (MIP) formulation. As this research utilizes agent architecture, bid generation function is installed into AGVA while winner determination function is owned by Machine Agent. Decision variables used in this research are non-negative values. The following notations are listed in Table 1:

A. Bid Generation Module

One of the elements need to be resolved is regarding the bid generation. It defines what buyers should bid based on specific objectives and constraints. Each AGVA is equipped with this function in order to enable distributed decision making capabilities. The function used to determine the optimal task assignment is as the following.

$$\text{Minimize} \quad at_{ij}^{x} + \sum_{ij=1}^{IJ} ct \cdot d_{ij}^{x} \cdot \beta_{ij}^{x} \cdot y_{ij}^{x} \tag{7}$$

$$\text{Subject to} \quad at_{ij}^{x} = tr_{ij} + ct_{x} \tag{8}$$

$$ct_{x} = \sum_{i=1}^{I} \sum_{j=1}^{J} \left[\left(tta_{ij} + (tr_{ij} + td_{ij}) + (tv_{ij} + tw_{ij}) \right) \beta_{ij}^{x} \right] \tag{9}$$

$$\beta_{ij}^{x} = 1, \forall i, j \tag{10}$$

$$tr_{ij} > ct_{x} \tag{11}$$

$$Cc_{m}^{x} < Cp_{x} \tag{12}$$

$$Cc_{m}^{x} \geq 0 \tag{13}$$

$$Cc_{m}^{x} + Cl_{m}^{x} \leq \sum_{m,n \in M}^{M} \delta_{mn}^{x} \cdot Cp_{x} \tag{14}$$

Equation (8) calculates the earliest expected arrival time for the AGV could start the pickup. Constraint (9) ensures that tasks assigned to the specific vehicle are taken into consideration to determine the arrival time. Constraint (10) verifies the start of traveling time for operation-*ij* to be later than the finish time of prior operation. Constraint (11) ensures that the number of tasks on-board is less than the full capacity the vehicle can carry. Constraint (12) defines that whenever the AGV intents to bid, the number of loaded tasks should be less than its total capacity. Constraint (13) rules that the loading only takes non-negative values. Constraint (14) ensures that unloading and loading decisions should comply with the rules for multiple loading capacity utilization.

B. Winner Determination Problem (WDP)

Winner determination is a function for an auctioneer to evaluate all of the bids received in an auction. The function should be able to single-out buyer with the best bid hence awarding the contract/ good to the buyer. In this research, MA takes the role as the auctioneer. Thus, each of the agents is equipped with the winner determination function. The function is designed to find the vehicle that could provide earliest pickup time.

$$\text{Minimize} \quad \sum_{ij \in IJ}^{IJ} y_{ij} \cdot \xi_{b}^{x} \tag{15}$$

$$\text{Subject to} \quad at_{ij}^{x} \leq tl_{ij} \tag{16}$$

$$at_{ij}^{x} \geq te_{ij} \tag{17}$$

$$tl_{ij} = rt_{j} + dt_{j} - mt_{j} \tag{18}$$

$$te_{ij} = tp_{ij} \cdot \theta_{m,ij} + tpa_{ij} \cdot \theta_{m,ij} \tag{19}$$

$$y = te_{ij} - at_{ij}^{x} \tag{20}$$

$$\xi_{b}^{x} \leq 1 \tag{21}$$

$$\sum_{ij \in IJ}^{IJ} \xi_{b}^{x}(ij) \leq 1 \tag{22}$$

$$\sum_{ij \in IJ}^{IJ} IJ_{m} \cdot \xi_{b}^{x} \leq IJ_{m} \tag{23}$$

The auctioneer's objective function is to minimize the difference between earliest pickup time and vehicle's expected arrival time as in (15). Constraints (16) and (17) ensure that expected arrival time should be within the earliest start time and the latest start time. Constraint (18) defines the latest start time for operation-*ij* and Constraint (19) suggests the definition of earliest start time while Constraint (20) calculates the difference between earliest transportation time for operation-*ij* and the expected arrival time of AGV-*x*. In addition, Constraint (21) restricts a bid to receive at most one assignment. Constraint (22) restricts each task is assigned to exactly one vehicle. Constraint (23) verifies total assignments made should not exceed the total number of tasks an auctioneer possesses.

C. Auction Specification

Using combinatorial auction method, participants can place a bid on an item or on a combination of items offered by the auctioneer. Conventionally, bid is a participant's expression of intention to acquire a specific item by indicating numerical amount that the participant is willing to pay to the auctioneer in return for the good [7]. In this research, bids are represented by the time needed to complete the transportation request. In submitting bids, there are several bidding strategies that were utilized in numerous researches [1].

XOR bidding strategy is used in this research where each participant can submit an arbitrary number of pairs (Si; pi), where (S_1, p_1) *xor* (S_2, p_2) *xor… xor*(S_k, p_k) and the bidder is willing to obtain at most one of these bids. This research adopted indivisible bid approach for the MA to evaluate bids submitted. Indivisible bid refers to a condition where should the auctioneer make an award to a specific bidder; it is for the entire package the bidder bid.

Data structure of the tasks announcement made by MA could be described as $<IJ, mp_{ij}, md_{ij}, te_i, tl_{ij}>$. After computing its ability to transport the auctioned tasks, AGVA will send set of bids attempting to acquire the tasks. Bidding data submitted are $B_x = \{ (b_1) \text{ xor } (b_2) \text{ xor } (b_t) \}$ where $b_1 =$

(<IJ, at_{ij}^{x}>). Auctioneer will find the best offer and award the task to the winner. The award data structure is <IJ, AGV_x>.

IV. Experimental Setup

Simulation of the combinatorial auctions has been developed based on Recursive Porous Agent Simulation Toolkit (Repast) platform [10]. Repast is an open-source agent-based simulation package. Repast enables systematic study of complex system behaviors through controlled and replicable computational experiments. Meanwhile, the MIP program was solved using ILOG CPLEX solver that is integrated into Java IDE by OptimJ [11].

Problem specification from [12] has been adopted in this research. The configuration representing a Flexible Manufacturing System (FMS) is illustrated in Fig. 8. System resource consists of six non-identical machines and two identical AGVs for material delivery purpose. Vehicles' speeds are constant at 40 m/min. Loading and unloading times are fixed at 0.5 min each. There are 6 job sets with each possessing six different operation sequences, dedicated machine (M) and processing time (PT) as in Table II while the distances (in meter unit) are shown in Table III.

Several vehicle loading capacity are used to investigate the sensitivity of the proposed approach. Machines and AGVs are assumed to operate at full efficiency. Machines processing times are normally distributed with standard deviation, σ = 0.5 minutes and jobs arrival rate with mean, E = 20 minutes follow an exponential distribution.

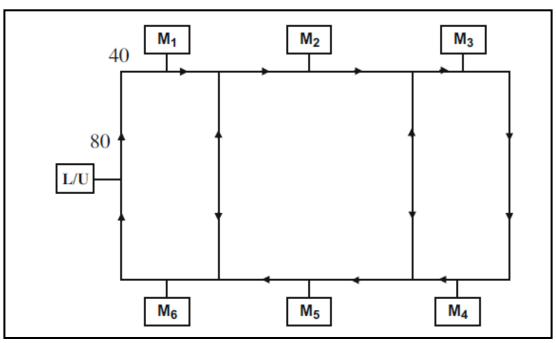

Figure 1. FMS Layout.

TABLE II. Job Set Specification

Job Set	DT	M (PT)	M (PT)	M (PT)	M (PT)	M (PT)	M (PT)
1	35	2 (1)	6 (3)	1 (6)	3 (7)	5 (3)	4 (6)
2	70	1 (8)	2 (5)	4 (10)	5 (10)	6 (10)	3 (4)
3	105	2 (5)	3 (4)	5 (8)	6 (9)	1 (1)	4 (7)
4	140	1 (5)	6 (5)	2 (5)	3 (3)	4 (8)	5 (9)
5	175	2 (9)	1 (3)	4 (5)	5 (4)	6 (3)	3 (1)
6	210	1 (3)	3 (3)	5 (9)	6 (10)	4 (4)	2 (1)

M= Machine PT= Processing time

V. Simulation Analysis

Analysis had been carried out to determine the performance of auction-based AGV task assignment system. This section discusses an example of the combinatorial auction in order to explain the working principle. Tasks assignment condition for 2 vehicles capable to carry 3 loads simultaneously is taken. Table IV shows an example of six independent tasks that need to be transported.

Each participant calculates the best transport combination it could offer and submits the bid to the auctioneer. In this case each AGV would attempt to minimize its traveling distance subject to a set of constraints. Shortest path for AGV-x, $d_{x,mn}$ from pickup node, m to destination node, n is derived from the distance matrix.

Participant will then submit arbitrary number of bids as XOR bidding rule is employed. To ease the auction process, participant is programmed to submit a limited number of combinations based on its loading capacity. Table V shows the computed expected arrival times submitted for the announced tasks as in Table III.

Upon receiving bids, auctioneer executes WDP module to assign tasks to the vehicle with the best offer. Indivisible award rule is employed where award is made to the complete package within a bid. This eliminates the need for participant to re-route if each task is evaluated and assigned independently. Assignment is made based on the vehicle that could provide the best pickup time compared to the earliest pickup start time.

In term of the AGV movement, a reasonably good vehicle routing could be obtained based on the transportation assignment made. Fig. 3 depicts the route for both vehicles and their respective total traveling distances.

TABLE III. Machine to Machine Distance Chart

Machine	L/U	M1	M2	M3	M4	M5	M6
L/U	0	160	240	320	560	480	400
M1	400	0	120	200	440	360	280
M2	480	600	0	120	360	280	360
M3	560	680	600	0	280	360	440
M4	320	440	360	280	0	120	200
M5	240	360	280	360	600	0	120
M6	160	280	360	440	680	600	0

TABLE IV. Example of Tasks On Auction

Operation ID	Pickup-Delivery Node	Delivery Time	Earliest/ Latest Start Time
6.3	M3 - M5	9	10.35/ 10.45
5.3	M1 - M4	11	10.32/ 10.40
1.1	M0 - M2	6	10.28/ 10.36
2.4	M4 - M5	3	10.45/ 10.54
5.2	M2 - M1	15	10.30/ 11.40
6.2	M1 - M3	5	10.35/ 11.45

VI. Result and Discussion

Based on the simulation conducted, comparison between single-load and multi-load capacity AGV has been obtained. Throughput and percentage of loaded travels over empty vehicle had been selected as the performance measures as both could act as good indicators for the system performance. Fig. 4 shows the comparison of total system throughput (per 24-hour operation) produced. It is clear that there are steady improvements in the number of throughput produced when the loading capacity is increased. The throughput reach saturation point after vehicles with 7-load capacity are deployed. Meanwhile, Fig. 5 illustrates the comparison of mean distance traveled per job when the loading capacity variable is varied. We detected a significant distance drop particularly when multi-load capacity vehicle is introduced where the distance is reduced by 23%.

VII. Conclusion

The research has successfully achieved its aims in establishing a decentralized task assignment method for multi-capacity AGV. The impact of the method on different loading capacity was also investigated. It is found that the proposed method is able to provide better throughput compared to the conventional approach.

TABLE V. Computed Expected Arrival Times

Vehicle	Operation Sequence	Pickup Time Sequence
AGV_1	1.1, 5.3, 6.2	10.28, 10.32, 10.35
AGV_2	5.2, 6.3, 2.4	10.30, 10.35, 10.45

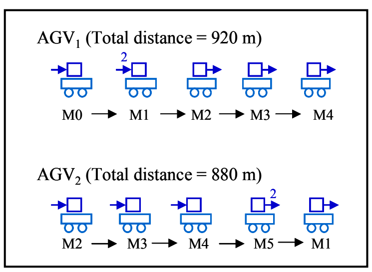

Figure 2. Vehicle routing based on the awarded tasks.

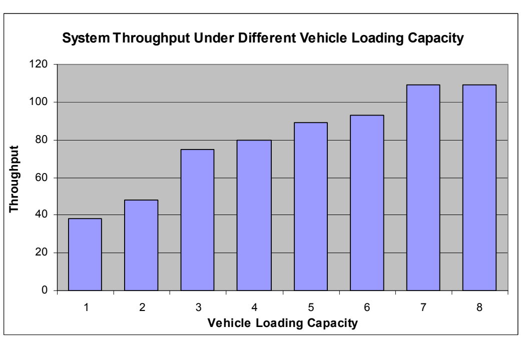

Figure 3. System throughput.

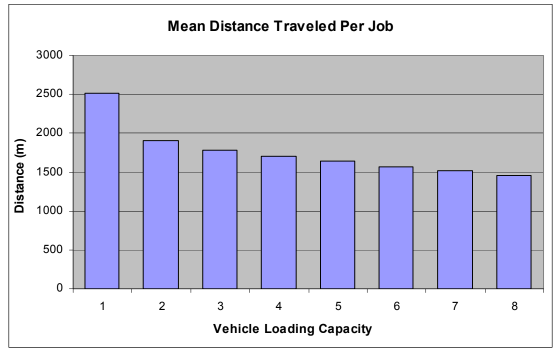

Figure 4. Mean distance traveled per job.

Acknowledgment

This work was partially supported by the Public Services Department of Malaysia (JPA) and Universiti Teknikal Malaysia Melaka (UTeM).

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