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# A Preference-based Task Allocation Framework for Multi-Robot Coordination

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***Abstract*— A market-based task allocation mechanism has been widely used in multi-robot coordination. However, most of approaches consider a bid as either quality or cost, or a combination of the two. This paper proposes a preference-based task allocation framework for coordination of multiple robots. To provide preference in task allocation, four bid elements are defined: task quality, task cost, task distance and task time. Tasks can be allocated considering the relative importance of the bid elements based on the preference. The utility of a robot is calculated using the bid elements and their weighted preference. The effectiveness of the proposed framework was demonstrated through the computer simulation of a cleaning mission.**

## I. INTRODUCTION

A market-based task allocation approach has been developed with considerable popularity in multi-robot coordination. In the market-based approach, each individual in the group tries to maximize its profit and leads the redistribution of the resources and the efficient production of the output in the system [1]-[4]. This approach provides the flexible task allocation with low computational load and communication overhead compared with the centralized approaches [5], [6], and generates more near-optimal solution than the distributed approaches [7]-[9]. Dias proposed *Traderbots*, consisting of *OpTrader* which represents a human operator and *RoboTrader* which buys and sells a task with a peer-to-peer manner [10]. It demonstrated the robustness of the total/partial failures of the robots in dynamic environment. Gerkey et al. implemented an auction-based task allocation system, MURDOCH, for global optimum of resource usage [11]. Although there have been various approaches, most of them consider the bid as either the quality or the cost of a robot. A quality represents the available capability or the performance quality for the capability of a robot. A robot's cost for a task can be considered as the estimated travel distance and the estimated task completion time of the robot to perform the task. Moreover, most of the previous approaches do not take into account of the explicit representations of robot capabilities and task requirements.

To address these issues, this paper proposes a preference-based task allocation framework. In this framework, the robot capability and the task requirement matrix are provided. To consider various characteristics of a robot in task allocation, four bid elements are defined: task quality, task cost, task distance and task time. The utility of a robot on the auctioned task is calculated using the bid elements and their weighted preference. The pairwise comparison matrix, which is widely used in determining the relative importance of the criteria, is applied to generate the preference weights [12].

The rest of this paper is organized as follows. Section II defines the tasks which the proposed framework deals with. The formal descriptions of the robot capabilities and task requirements are provided in Section III, and four types of bid elements are defined in Section IV. Section V describes the utility of a robot. In Section VI, the effectiveness of this framework was demonstrated through the computer simulation of a cleaning mission. Finally, the concluding remarks follow in Section VII.

## II. COMPOUND TASKS

In this paper, two levels of tasks, i.e., the atomic task and the compound task, are defined. The atomic task is the minimum unit of a task which can not be divided into smaller subtasks. The compound task consists of atomic tasks, and three types of compound tasks, i.e., sequential, parallel and unconstrained compound tasks are defined.

### A. Definition of Compound Tasks

The type of a compound task is decided by the relation between atomic tasks. The sequential compound task consists of atomic tasks which need to be executed in order. The parallel compound task is defined as the combination of atomic tasks which are required to be performed in parallel. The unconstrained compound task contains atomic tasks which can be performed either sequentially or in parallel.

*1) Sequential Compound Task:* In the sequential compound task, one atomic task should be performed at a time and the next atomic task should be performed after the precedent atomic task is completed. The sequential compound task can be categorized as ST-SR-IA: single-task robots, single-robot tasks and instantaneous assignment [13]. The sequential compound task, $Task^S$, is defined as

$$\begin{aligned} &Task^S = \{task_1^S, task_2^S, ..., task_s^S\} \\ &task_k^S \in Task^A \quad (k \in \{1, 2, ..., s\}) \qquad (1) \\ &task_i^S \succ task_j^S \quad (i < j) \end{aligned}$$

where $s$ is the number of atomic tasks in $Task^S$, $Task^A$ represents a set of atomic tasks, and $task_i^S \succ task_j^S$ represents that $task_i^S$ should be completed before $task_j^S$.

*2) Parallel Compound Task:* The parallel compound task consists of atomic tasks which should be performed in parallel. Therefore, the auctioneer auctions all of the atomic tasks in the compound task at the same time. The parallel compound task can be categorized as ST-MR-IA: single-task robots, multi-robot tasks and instantaneous assignment [13].

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Unlike the sequential compound task, one atomic task in the parallel compound task should be assigned to one robot and one robot can get at most one atomic task. As a result, each atomic task should be allocated to different robot. The parallel compound task, $Task^P$, is defined as

$$Task^P = \{task_1^P, task_2^P, ..., task_p^P\}$$
$$task_k^P \in Task^A \quad (k \in \{1, 2, ..., p\}) \tag{2}$$
$$task_i^P \succeq task_j^P \quad (i < j)$$

where $p$ is the number of atomic tasks in $Task^P$, and $task_i^P \succeq task_j^P$ represents that the priority of $task_i^P$ is the same as or higher than $task_j^P$. Since the parallel compound task requires tightly coupled coordination among the robots, they sometimes require master-slaver relationship such that the robot with has higher priority atomic task becomes a master and the robot with lower priority atomic task becomes a slave.

*3) Unconstrained Compound Task:* The unconstrained compound task consists of atomic tasks which have neither sequential nor parallel constraints. The unconstrained compound task can be categorized as either ST-SR-TA or ST-MR-TA: single-task robots, single-robot tasks and time-extended assignment or single-task robots, multi-robot tasks and time-extended assignment [13]. The unconstrained compound task, $Task^U$, is defined as

$$Task^U = \{task_1^U, task_2^U, ..., task_u^U\}$$
$$task_k^U \in Task^A \quad (k \in \{1, 2, ..., u\}) \tag{3}$$
$$task_i^U \succeq task_j^U \quad (i < j)$$

where $u$ is the number atomic tasks in $Task^U$, and $task_i^U \succeq task_j^U$ represents that the priority of $task_i^U$ is the same as or higher than $task_j^U$. Similar to the case of the parallel compound task, the priority of the atomic task represents the master-slave relationship of robots.

### *B. Trade of Compound Tasks*

In this framework, two types of auctions, i.e., the sequential single-item auctions and the multi-item auctions, are adopted to deal with different types of compound tasks [13], [14]. The sequential single-item auction method auctions one item at a time after allocating the precedent item, and the bidder bids on the task considering the previously received tasks. In this case, the bidder can get one or more atomic tasks from the auctioneer. The multi-item auction method auctions multiple atomic tasks simultaneously regarding them as independent to each other.

For the sequential compound task, the modified sequential single-item auction is used. To consider the constraint of the sequential compound task where each atomic task should be performed after the precedent atomic task is completed, the auctioneer auctions the next atomic task only after the previously allocated atomic task is completed. For the parallel compound task, the multi-item auctions are used. However, unlike the conventional multi-item auctions where one bidder can get one or more items, the bidder is allowed to get only one atomic task in the parallel compound task. For the unconstrained compound task, the conventional sequential single-item auction algorithm is used such that the bidder can get more than one atomic task. In this case, the bidder calculates the bid of the auctioned atomic task considering the previously received atomic tasks.

## III. FORMAL DESCRIPTIONS OF ROBOT CAPABILITIES AND TASK REQUIREMENTS

In market-based task allocation, the explicit representations of robot capabilities and the requirements of a task are prerequisite for effective task allocation. For the formal descriptions of robot capabilities and task requirements, the robot capability matrix and the task requirement matrix are defined.

### *A. Robot Capability Matrix*

Robots have various types of capabilities and each capability has different characteristics depending on a hardware resource. To represent the quality and cost of the capability, the capability vector of the $i$th robot, $Robot_i$, $i = 1, 2, ..., n$, $cap_{ik}$, $k = 1, 2, ..., m$, is defined as

$$cap_{ik} = \begin{bmatrix} q_{ik} & c_{ik} \end{bmatrix}^T \tag{4}$$

where $n$ and $m$ represent the number of robots and the number of capabilities, respectively, and $q_{ik}$ $(0.0 \le q_{ik} \le 1.0)$ and $c_{ik}$ $(0.0 \le c_{ik} \le 1.0)$ represent the capability quality and the capability cost of the $k$th capability, respectively. In case of a sensor-related capability, the capability quality represents the accuracy and precision of sensor measurement. In case of an actuator capability, it represents the maneuverability and degrees of freedom of the actuator. The capability cost represents the energy consumption rate of a capability. A robot continuously monitors its capabilities such that if the $k$th capability malfunctions, $q_{ik}$ is set to 0.0. It enables a robot to recognize its available capabilities. This also leads more reliable and robust task allocation since a robot would not bid on the task if the required capability is not available. To represent all of the capabilities of the robot, the robot capability matrix of $Robot_i$, $R_i^{cap}$, is defined as

$$R_i^{cap} = \begin{bmatrix} cap_{i1} & cap_{i2} & \cdots & cap_{im} \end{bmatrix} \tag{5}$$

where each column vector represents the characteristics of each capability.

### *B. Task Requirement Matrix*

The task requirement matrix of the atomic task represents robot capabilities that the atomic task requires for task execution. To represent the required capability of the $j$th atomic task, $task_j^A$ $(task_j^A \in Task^A)$, $j = 1, 2, ..., a$, the $k$th requirement vector, $req_{jk}$, is defined as

$$req_{jk} = \begin{bmatrix} h_{jk} & w_{jk}^c \end{bmatrix}^T \tag{6}$$

where $a$ is the number of atomic tasks, and $h_{jk}$ $(h_{jk} \in \{0, 1\})$ represents the requirement of the $k$th capability. $h_{jk}$

is set to one if the atomic task requires the capability and zero if not. $w^c_{jk}$ ($0.0 \leq w^c_{jk} \leq 1.0$) is the capability weight which represents the quality of the capability. If the atomic task requires high quality for the $k$th capability, $w^c_{jk}$ is set close to 1.0. To represent all of the required capabilities of the atomic task, the task requirement matrix of $task^A_j$, $T^{req}_j$, is defined as

$$T^{req}_j = \begin{bmatrix} req_{j1} & req_{j2} & \cdots & req_{jm} \end{bmatrix} \quad (7)$$

where each column vector represents the requirement of each capability. Note that the task requirement matrices are provided to the robots in advance of the start of the mission.

## IV. BID ELEMENTS

The proposed framework considers the relative importances of four types of bid elements, i.e., task quality, task cost, task distance and task time, in task allocation. When an auctioneer auctions the atomic task, bidders bid on the task by sending the bid elements to the auctioneer. Then the auctioneer selects a winner based on the bid elements of each bidder and the preference of them in task allocation.

### A. Task Quality

The task quality represents the overall performance quality of a robot for the auctioned atomic task. The task quality of $Robot_i$ for $task^A_j$, $Qual_{ij}$, is defined as

$$Qual_{ij} = \textstyle\sum_{k=1}^{m} h_{jk} \cdot w^c_{jk} \cdot q_{ik} \quad (8)$$

where $h_{jk}$ and $w^c_{jk}$ represent the requirement and the capability weight of the $k$th capability, respectively from (6), and $q_{ik}$ is the capability quality of the $k$th capability from (4).

### B. Task Cost

The task cost represents the computational expense of a robot to perform the auctioned atomic task. It depends on type of the robot's hardware resource for the capability. The task cost of $Robot_i$ for $task^A_j$, $Cost_{ij}$, is defined as

$$Cost_{ij} = Pow_i \cdot (\textstyle\sum_{k=1}^{m} h_{jk} \cdot (1 - w^c_{jk}) \cdot c_{ik}) \quad (9)$$

where $Pow_i$ ($0.0 \leq Pow_i \leq 1.0$) is the computation power of $Robot_i$, $h_{jk}$ and $w^c_{jk}$ are from (6), and $c_{ik}$ is the capability cost the capability, which is defined in (4).

### C. Task Distance and Task Time

The task distance represents the estimated travel distance of a robot to complete the auctioned atomic task. The task distance of $Robot_i$ for $task^A_j$, $Dist_{ij}$, represents the estimated travel distance of $Robot_i$ to complete $task^A_j$. The estimated travel distance is the total distance of the robot until it completes the task from the task starting point.

The task time represents the estimated time of the bidder to complete the auctioned atomic task. The task time of $Robot_i$ for $task^A_j$, $Time_{ij}$, is defined as

$$Time_{ij} = Time^{Tran}_{ij} + Time^{Perf}_{ij} \quad (10)$$

where $Time^{Tran}_{ij}$ is the estimated task transition time for the robot to move from the current position to the starting position of $task^A_j$, and $Time^{Perf}_{ij}$ is the estimated task performance time to complete $task^A_j$ from the starting position of $task^A_j$. The main difference between the task distance and task time is that the task distance only considers the auctioned atomic task, while the task time contains the information of the estimated task transition time as well as the estimated task performance time of the auctioned task.

## V. PREFERENCE IN TASK ALLOCATION

### A. Preference Degree

The preference of task allocation in this framework is determined by the mission planner such that if the planner prefers the high task quality robots for the auctioned task, the robot which bids on the task with the highest task quality would get the highest utility on the task. The preference of the planner is obtained from the relative importance between each pair of the bid elements.

The pairwise comparison matrix, which is widely used in determining the relative importance of the criteria, is employed to obtain the preference weights of the bid elements. [12]. It is defined as

$$M = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1g} \\ p_{21} & p_{22} & \cdots & p_{2g} \\ \vdots & \vdots & \ddots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{gg} \end{bmatrix} \quad (11)$$

where $p_{ij}$ represents the preference degree between the $i$th criterion and the $j$th criterion, $g$ is the number of criteria, $p_{ii}$ is 1.0, and $p_{ji} = 1/p_{ij}$. For example, if $p_{12}$ is set to 5.0, it represents that the $i$th criterion is five times more preferable to the $j$th one. Based on the pairwise comparison matrix, the preference weight of the $i$th criterion, $w_i$, is defined as

$$w_i = \frac{\sum_{j=1}^{g} p_{ij}}{\sum_{i=1}^{g}\sum_{j=1}^{g} p_{ij}}. \quad (12)$$

In this framework, six preference degrees, which are described in Table. I, should be assigned to represent the preference of the mission planner for the four bid elements.

TABLE I
PREFERENCE DEGREES

| Preference degree | Bid elements |
|---|---|
| $p_{12}$ | Task quality over task cost |
| $p_{13}$ | Task quality over task distance |
| $p_{14}$ | Task quality over task time |
| $p_{23}$ | Task cost over task distance |
| $p_{24}$ | Task cost over task time |
| $p_{34}$ | Task distance over task time |

### B. Utility

When a robot desires to auction a compound task, it acts as an auctioneer, and auctions the atomic tasks of the compound task. The robot which is interested in the task act as a bidder, and sends its bid elements to the auctioneer. After receiving the bid elements from the bidders, the auctioneer calculates the utility of each bidder using the bid elements and the preference weights. The utility of $Robot_i$ for $task_j$ ($task_j \in Task^A$), $U_{ij}$, is defined as

$$U_{ij} = \sum_{k=1}^{4} w_k \cdot bid_{ij}^k \tag{13}$$

with

$$bid_{ij}^1 = \frac{Qual_{ij}}{\sum_{i=1}^{b} Qual_{ij}}, \quad bid_{ij}^2 = 1 - \frac{Cost_{ij}}{\sum_{i=1}^{b} Cost_{ij}},$$

$$bid_{ij}^3 = 1 - \frac{Dist_{ij}}{\sum_{i=1}^{b} Dist_{ij}}, \quad bid_{ij}^4 = 1 - \frac{Time_{ij}}{\sum_{i=1}^{b} Time_{ij}}$$

where $bid_{ij}^k$ is the $k$th bid value. As shown in the equation, the utility increases as the task quality of the robot is high, and as the rest of the bid elements are low. Using the preference wights and the normalized bid elements, the preference of the mission planner is considered in the bidder's utility.

## VI. CLEANING MISSION

In the cleaning mission, six heterogeneous robots work together to collect randomly dispersed blocks, sort them, and carry them to the designated place. The mission consists of five compound tasks where each of them requires different types of robot capabilities.

### A. Robot Descriptions

In the simulation, each robot consists of different kinds of capabilities with different hardware resources. There are five capabilities, i.e., localization (LOC), color recognition (COL), mobility (MOB), gripping (GRP) and carring (CAR) blocks, and each of them has different characteristics depending on hardware resources as in Table II. The localization is implemented either by laser range-finders (LRF) or ultrasonic sensors (USS), and color recognition is implemented either by a high quality camera (HQC) or a low quality camera (LQC). For the mobile capability, either omni-directional drive (OD) or differential drive (DD) is used. The block gripping and carrying capabilities are realized by a robot hand (RH) and a pusher (PUSH), respectively. The hardware resources of the robots are defined in Table III.

TABLE II
CAPABILITY VECTORS WITH DIFFERENT HARDWARE RESOURCES

| | Hardware resource | Capability quality | Capability cost |
|---|---|---|---|
| LOC | *LRF* | 0.9 | 0.6 |
| | *USS* | 0.5 | 0.3 |
| COL | *HQC* | 0.9 | 0.6 |
| | *LQC* | 0.6 | 0.3 |
| MOB | *OD* | 0.9 | 0.6 |
| | *DD* | 0.5 | 0.3 |
| GRP | *RH* | 0.6 | 0.3 |
| CAR | *PUSH* | 0.9 | 0.1 |

TABLE III
CAPABILITIES OF ROBOTS

| Robot | LOC | COL | MOB | GRP | CAR |
|---|---|---|---|---|---|
| $Robot_1$ | LRF | HQC | OD | RH | n/a |
| $Robot_2$ | LRF | LQC | DD | RH | n/a |
| $Robot_3$ | USS | LQC | DD | RH | n/a |
| $Robot_4$ | LRF | HQC | OD | n/a | PUSH |
| $Robot_5$ | LRF | LQC | DD | n/a | PUSH |
| $Robot_6$ | USS | LQC | DD | n/a | PUSH |

### B. Task Descriptions

The mission consists of five compound tasks and each of them has two atomic tasks. The descriptions of the compound tasks are shown in Table IV. In the first compound task, $Task_1^U$, all of the blocks in the rooms should be collected on $Tray_1$ as shown in Fig. 1(a). In $Task_1^U$, $task_1^A$ and $task_2^A$ are provided to collect the blocks in $Room_1$ and $Room_2$, respectively. The second compound task, $Task_2^P$ requires two robots to carry $Tray_1$ to $Hall$ as shown in Fig. 1(b). Since the front and rear sides of $Tray_1$ should be carried in parallel, $task_3^A$ and $task_4^A$ are provided for each side of the tray. In the third compound task, $Task_3^U$, $task_5^A$ and $task_6^A$ are provided to collect the black blocks on $Tray_2$ and the white blocks on $Tray_3$, respectively as shown in Fig. 1(c). The fourth compound task, $Task_4^S$, requires the robots to open the gate. To open the gate, $task_7^A$ and $task_8^A$ are provided as pulling out the locker and pushing the gate as shown in Fig. 1(d) and 1(e), respectively. In the fifth compound task, $Task_5^U$, $task_9^A$ and $task_{10}^A$ are provided to carry $Tray_2$ and $Tray_3$ to $Zone_1$ and $Zone_2$, respectively, as shown in Fig. 1(f). Note that the different atomic tasks would have the same task requirement matrix if they require the same capabilities. In the simulation, two task requirement matrices are defined as shown in Table V. Each of the atomic tasks in the mission uses either $T_1^{req}$ or $T_2^{req}$ where $T_1^{req}$ is used as the task requirement matrix of $task_1^A$, $task_2^A$, $task_5^A$, $task_6^A$ and $task_7^A$, which requires either block collecting

TABLE IV
DESCRIPTIONS OF COMPOUND TASKS

| Compound task | Description |
|---|---|
| $Task_1^U$ | Move blocks in rooms on $Tray_1$ |
| $Task_2^P$ | Carry $Tray_1$ to $Hall$ |
| $Task_3^U$ | Sort black and white blocks |
| $Task_4^S$ | Open the gate |
| $Task_5^U$ | Carry trays to zones |

TABLE V

TASK REQUIREMENT MATRICES

| | | LOC | COL | MOB | GRP | CAR |
|---|---|---|---|---|---|---|
| $T_1^{req}$ | $h_1$ | 1 | 1 | 1 | 1 | 0 |
| | $w_1^q$ | 0.5 | 0.8 | 0.6 | 0.8 | 0.0 |
| $T_2^{req}$ | $h_2$ | 1 | 0 | 1 | 0 | 1 |
| | $w_2^q$ | 0.8 | 0.3 | 0.6 | 0.0 | 0.8 |

or block sorting capability, and $T_2^{req}$ is used as the task requirement matrix of $task_3^A$, $task_4^A$, $task_8^A$, $task_9^A$ and $task_{10}^A$, which requires tray carrying capability.

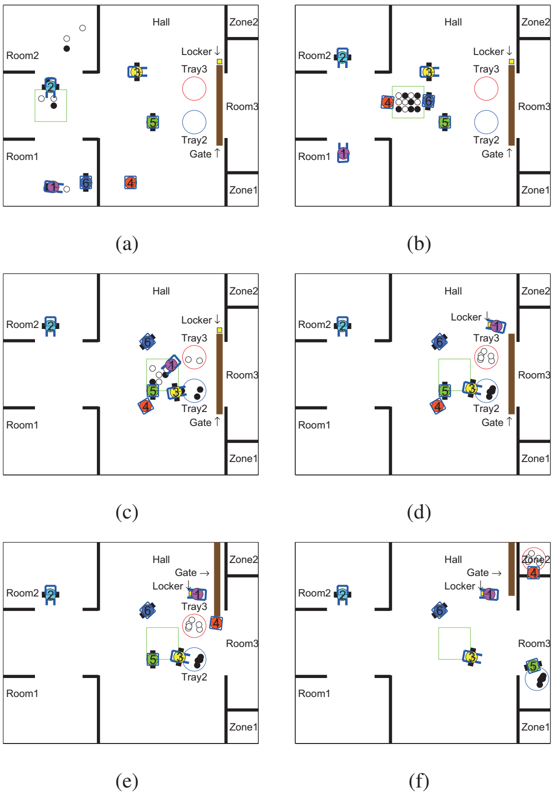


Fig. 1. (a) Robots collect blocks on $Tray_1$. (b) Robots carry $Tray_1$ to $Hall$. (c) Robots sort black and white blocks on $Tray_1$. (d) One robot unlocks the gate by pulling out the locker. (e) One robot opens the gate of $Room_3$. (f) Robots carry $Tray_2$ and $Tray_3$ to $Zone_1$ and $Zone_2$, respectively.

## C. Preference Degree Sets

To demonstrate the preference-based task allocation of the proposed framework, four preference degree sets are defined based on the relative preference between each pair of the bid elements as shown in Table VI. Based on the preference degree sets, the preference weights of the bid elements are calculated as shown in Table VII and Fig. 2. In case of $W_1^{Set}$, the preference weight for the task quality is the highest among the other cases, and the preference weights for the task cost and task time are less than a half of those for the task quality and task distance. In case of using $W_2^{Set}$, the preference weight for the task cost is almost five times higher than the other cases. Instead, the preference weights for the task quality and task time are much lower than the other cases. For $W_3^{Set}$, the preference weight for the task distance is the highest among the other cases, and the preference weight for the task time is the highest when $W_4^{Set}$ is used.

TABLE VI

DESCRIPTIONS OF PREFERENCE DEGREE SETS

| Preference degree set | $p_{12}$ | $p_{13}$ | $p_{14}$ | $p_{23}$ | $p_{24}$ | $p_{34}$ |
|---|---|---|---|---|---|---|
| $W_1^{Set}$ | 5.0 | 3.0 | 8.0 | 0.3 | 0.5 | 5.0 |
| $W_2^{Set}$ | 0.2 | 0.3 | 2.0 | 0.5 | 8.0 | 5.0 |
| $W_3^{Set}$ | 5.0 | 0.3 | 0.2 | 0.2 | 0.5 | 3.0 |
| $W_4^{Set}$ | 5.0 | 3.0 | 0.3 | 0.5 | 0.3 | 0.2 |

TABLE VII

PREFERENCE WEIGHTS

| Preference degree set | $w_1$ | $w_2$ | $w_3$ | $w_4$ |
|---|---|---|---|---|
| $W_1^{Set}$ | 0.54 | 0.06 | 0.29 | 0.10 |
| $W_2^{Set}$ | 0.11 | 0.47 | 0.36 | 0.06 |
| $W_3^{Set}$ | 0.23 | 0.07 | 0.41 | 0.29 |
| $W_4^{Set}$ | 0.35 | 0.08 | 0.13 | 0.45 |

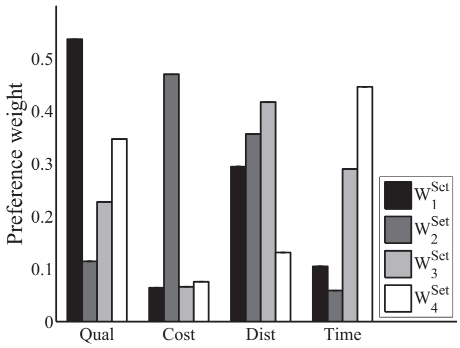


Fig. 2. Preference weights of the preference degree sets.

## D. Simulation Results

The cleaning mission was repeated five times for each of the preference degree sets and initial positions of robots were randomly selected for each time. In the simulation, compound tasks were initially distributed randomly to robots and the robot which had the first compound task, $Task_1^U$, auctioned the task first when the mission started. After completing the first compound task, the robot which had the second compound task, $Task_2^P$, auctioned the task. Likewise, the rest of the compound tasks were auctioned to the robots. The execution order of the compound tasks was informed to the robots in advance. The simulation results with different preference degree sets are shown in Fig. 3, where the mission quality, the mission cost and the mission distance are the total sum of the task qualities, the task costs and the task distances of robots, and the mission time represents the completion time of the cleaning mission. In case of using $W_1^{Set}$, the

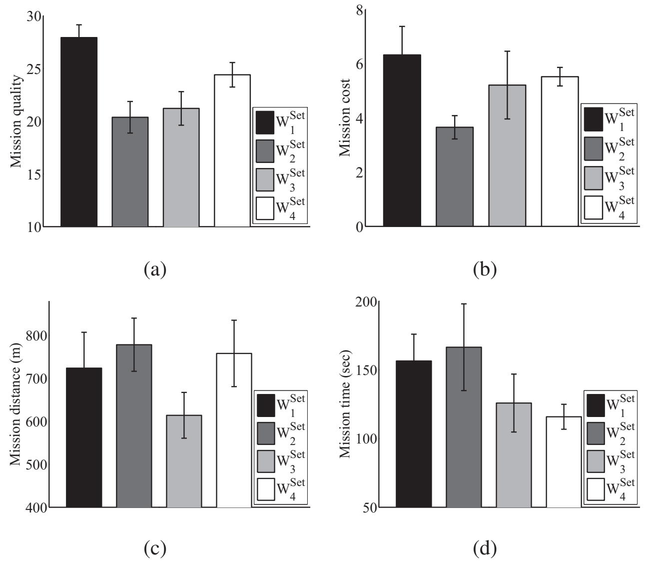


Fig. 3. Simulation results with different preference degree sets. (a) Mission quality. (b) Mission cost. (c) Mission distance. (d) Mission time.

robots were able to perform the mission with the highest quality and relatively lower mission distance. However, they had to spend more cost than other cases. The results were caused by the high preference weight for the task quality and task distance, and the low preference weight for the task cost. On the other hand, the robots with $W_2^{Set}$ were able to minimize the mission cost since the preference weight for the task cost was the lowest among the other cases. In case of using $W_3^{Set}$, the mission distance was the lowest, and the mission time were lower than the case of using $W_1^{Set}$ and $W_2^{Set}$. It was because the preference weights of the task distance and the task time are relatively higher than the other preference weights in $W_3^{Set}$. In case of using $W_4^{Set}$, where the preference weight of the task time was the highest, and the preference of the task quality was also higher than the cases of $W_2^{Set}$ and $W_3^{Set}$, the robots were able to complete the mission with minimum completion time and relatively higher mission quality than the results from $W_2^{Set}$ and $W_3^{Set}$.

## VII. CONCLUSIONS

This paper proposed a preference-based task allocation framework for market-based multi-robot systems. The proposed framework dealt with the task allocation for three types of compound tasks considering the preference of the mission planner. The robot capability matrix and the task requirement matrix were defined to explicitly represent the capabilities of the robot and the required capabilities for the task. For trading tasks, four types of bid elements were defined to represent the characteristics of the bidder on the auctioned task. To calculate the utility of a bidder considering the preference of the mission planner, the pairwise comparison matrix was employed. Based on the preference weights and the bid elements, the auctioneer calculated the utility of the bidder. The proposed framework was applied to the cleaning mission and the results with four types of preference degree sets were compared in a simulation experiment. The experimental results demonstrated that the framework was able to allocate tasks effectively considering the preference of the mission planner.

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## REFERENCES

[1] M. B. Dias, N. Kalra, R. Zlot, and A. Stentz, “Market-based multi-robot coordination: A survey and analysis,” *Proceedings of IEEE*, vol. 94, pp. 1257-1270, 2006.

[2] M. B. Dias and A. Stentz, “A free market architecture for distributed control of a multirobot system,” in *Proc. Int. Conf. Intell. Auton. Syst.*, pp. 115-122, 2000.

[3] M. Nanjanath and M. Gini, “Repeated auctions for robust task execution by a robot team,” in *Robot. Auton. Syst.*, vol. 58, pp. 900-909, 2010.

[4] R. Zlot and A. Stentz, “Multirobot control using task abstraction in a market framework,” in *Proc. Int. Conf. Collab. Tech. Alliances*, 2003.

[5] R. Simmons, D. Apfelbaum, D. Fox, R. P. Goldman, K. Z. Haigh, D. J. Musliner, M. Pelican, and S. Thrun, “Coordinated deployment of multiple, heterogeneous robots, in *Proc. Int. Conf. Intell. Robot. Syst.*, pp. 2254-2260, 2000.

[6] R. Jensen and M. Veloso, “OBDD-based deterministic planning using the UMOP planning framework,” *The AIPS-00 Workshop Model-Theoretic Approaches to Planning, AAAI Press*, pp. 26-31, 2000.

[7] L. E. Parker, “ALLIANCE: An architecture for fault-tolerant multirobot cooperation,” *IEEE Trans. Robot. Autom.*, vol. 14, pp. 220-240, 1998.

[8] P. Nebot, D. Gomez, and E. Cervera, “Agents for cooperative heterogeneous mobile robotics-a case atudy,” in *Proc. IEEE Conf. Syst. Man Cybern.*, pp. 557-562, 2003.

[9] T. Huntsberger, P. Pirjanian, A. Trebi-Ollennu, H. D. Nayar, H. Aghazarian, A. J. Ganino, M. Garrett, S. S. Joshi, and P. S. Schenker, “CAMPOUT: A control architecture for tightly coupled coordination of multirobot systems for planetary surface exploration, *IEEE Trans. Syst. Man Cybern.*, A, vol. 33, pp. 550-559, 2003.

[10] M. B. Dias, “Traderbots: A new paradigm for robust and efficient multi-robot coordination in dynamic environments,” Ph.D. dissertation, Robotics Institute, Carnegie Mellon University, 2004.

[11] B. P. Gerkey and M. J. Mataric, “Sold!: Auction methods for multi-robot coordination,” *IEEE Trans. Robot. Autom.*, vol. 18, pp. 758-768, 2002.

[12] T. L. Saaty, “Decision making with the analytic hierarchy process,” *Int. Journal. Service. Science.*, vol. 1, pp. 83-98, 2008.

[13] B. P. Gerkey and M. J. Mataric, “A formal analysis and taxonomy of task allocation in multirobot systems,” *Int. Journal. Robot. Research.*, vol.23, pp.939-954, 2004.

[14] M. G. Lagoudakis, E. Markakis, D. Kempe, P. Keskinocak, A. Kleywegt, S. Koenig, C. Tovey, A. Meyerson, and S. Jain, “Auction-based multi-robot routing,” Robotics: Science. Syst., Cambridge, USA, pp. 343-350, 2005.