

AN INTEGRATED APPROACH TO SOLVING THE REAL-WORLD MULTIPLE TRAVELING ROBOT PROBLEM

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ABSTRACT

In this study, we analyze the real-world Multiple Traveling Robot Problem (MTRP) and propose an integrated approach to solve this problem in real time. MTRP is a generalization of the well-known Multiple Traveling Salesman Problem and is solved by a multi-robot team. In the MTRP problem definition, target locations should be visited by the robots. Since the real world is beyond the control of robots, in most cases, the OR solutions are not directly applicable due to either robot hardware/software limitations or environmental dynamics. In this paper, we analyze the MTRP from real-world perspectives. In our solution, dynamic task selection, distributed task allocation and contingency handling mechanisms along with the low level robot controllers and the motor and sensory modules are integrated into each other to solve the real world MTRP. Target allocation and route construction is integrated into each other by an incremental assignment approach. Real time situations and contingencies that change the problem instance are handled at the same time. Empirical evaluations of the system performed on the WEBOTS robot simulator reveal the efficiency of the integrated components of our approach.

I. INTRODUCTION

The single robot exploration problem, a variation of the Traveling Salesman Problem (TSP), is to find the minimum cost traversal of a given number of targets without considering the return cost from the last target to the initial location for a single robot [4]. The problem can also be stated as finding the minimal Hamiltonian path on a given fully connected graph with all nodes to be visited. The Multi Traveling Robot Problem (MTRP) or multi-robot multi-target exploration problem is a more general version of the TSP in which there is a team of robots to visit targets at least once (ideally at most once). In the MTRP, besides the quality of the constructed paths of robots, allocation of the targets is quite affective on the overall solution quality.

Different types of complementary objectives to the main goal may be selected to optimize the performance for this problem as in scheduling problems. These objectives may be total path length minimization, time minimization,

average energy minimization, makespan minimization, etc. For example, in the search and rescue operations, the mission is highly challenging with hard time constraints and the success is hugely crucial. In space explorations, the mission is exploring the unknown outer space to collect scientific data. In this domain, robots communicate through the satellite links that are highly prone to communication failures and latency. Instead of optimizing the time, the battery/fuel life of the robots may be optimized in this domain. Based on the selected objective function, the cost evaluation may need to be designed differently.

The optimal results for the MTRP can be obtained using Integer Programming (IP) formulations. However these approaches may become impractical when the size of the mission is even moderate or the cost values change frequently because of the uncertain knowledge, changes in the environment (including failures) or the changing structure of the mission (e.g. online tasks). Robots also have continuous path planning burdens for target sets in dynamic environments. Expensive computational efforts taken to make target allocations may become redundant.

We are in favor of the distributed implementations, where target allocations are made by the robots themselves due to the real world limitations. We propose an incremental task allocation and route construction approach and a contingency handling mechanism integrated into each other on the task allocation layer. Those components are also integrated into the separate low level robot localization, mapping and multi-target path planning layers. Since the schedules are subject to change in the real world during runtime, the incremental allocation approach ensures task allocations are made in an efficient and scalable way reducing redundant calculations. The contingency handling mechanism integrated into target allocation mechanism provides efficiency in detecting and recovering from failures and unplanned events.

The MTRP problem is analyzed in different multi-robot systems by using both combinatorial [1][2] and single

item auction methods in literature. Since we are interested in an efficient implementation and try to reduce the computational and communication efforts, we focus on the single item target allocation approaches. Prim Allocation method [3], one of the easy to implement and efficient single item target allocation methods generates an MSF of the targets and the robots. Each robot offers an auction for a target and one of the targets are allocated at each round in the implementation. Whenever the world knowledge is changed, allocations of the remaining unvisited targets are redone with the same algorithm. As Prim's Algorithm, Prim Allocation method is bounded by $2 \cdot \text{OPT}$ for the MTRP. The Prim Allocation approach offers ways to allocate multiple targets. However, our focus is on integrating both efficient target allocation methods and real robot implementations, and furthermore dealing with the real world ingredients of the MTRP. We compare our approach with Prim Allocation in our earlier work ([7-9]). In this study, we analyze the performance of the integrated components of our proposed approach.

II. PROPOSED APPROACH

Due to the several reasons in practical applications, computing the true optimal solutions is not required [6]. The incorrect modeling of the underlying problem (targets) and lacking of sufficient real-time to find the optimal solution are such reasons. These are the common cases in robot applications besides the failures and the other real world contingencies. To face with all these limitations, we propose a dynamic and distributed task allocation scheme, to coordinate robots in executing different parts of the mission. Distribution is achieved through selecting candidate tasks by each robot. Dynamism is achieved through the incremental selection and allocation of the targets. Since the selection is incremental, the target allocation is interleaved with route construction.

The proposed approach can efficiently respond to real-time events and the solution quality is maintained simultaneously with the real time task execution by the cooperative processing of the integrated components of the system. We propose a general mechanism for multi robot cooperation on the MTRP but not necessarily specific heuristic functions to solve the problem although their success is validated previously [9].

DYNAMIC TASK SELECTION AND INCREMENTAL ALLOCATION

Since there is a tight connection between route generation and allocations, in our approach, this consideration is implemented by generating rough routes by robots. Therefore each robot (r_j) selects its most suitable target among the targets in the route target set (T_{Rj}). T_{Rj} is constructed by selecting the targets close to the robot r_j , among unvisited targets (T_U) according to Eq. (1), where

$dist$ function returns the Euclidean distance between two points. Targets in T_{Rj} are considered as the candidate targets for robot r_j . Therefore, before selecting the most suitable target, each robot constructs these rough route sets. This heuristic does not compel an actual commitment, and the targets in the rough routes are not necessarily assigned to the corresponding robots in future auctions. Instead, it provides a global view to obtain near optimal results from a local perspective.

$$reldist(r_j, t_i) = dist(r_j, t_i) - \min(dist(r_k, t_i)), \{\forall k \neq j\} \quad (1)$$

$$T_{Rj} = \cup t_i, reldist(r_j, t_i) < 0, \forall t_i \in T_U$$

We use the simplest cost function to evaluate the targets in T_{Rj} for each robot. This cost function for robot r_j and target t_i is simply evaluated as in Eq. (2) by considering the distance between the target and the robot.

$$c_{ji} = dist(r_j, t_i), t_i \in T_{Rj} \quad (2)$$

The rough schedule generation is implemented by Algorithm 1. The robot then selects the most suitable candidate task (t_S), the top most suitable target among the rough schedule targets, to perform.

Algorithm-1. Rough Schedule Generation, r_j

```

name: MTRP-FormRoughSchedule
input:  $T_U$ , output:  $T_{Rj}$  and  $t_S$ 
 $T_{Rj} = \phi$  (a heap with task cost as the key)
 $t_S = \phi$ 
while ( $T_U \neq \phi$ )
    if  $t_i$  is in the rough schedule region
        evaluate  $c_{ji}$  and insert  $t_i$  into  $T_{Rj}$ 
if  $\|T_{Rj}\| > 0$ 
     $t_S = top(T_{Rj})$ 

```

Algorithm-2. Incremental Task Selection, r_j

```

name: MTRP-DPTSS
input:  $T_U$ , output: action to be performed
 $[T_{Rj}, t_S] = \text{MTRP-FormRoughSchedule}(T_U)$ 
if  $t_S \neq \phi$ 
    if  $t_S$  is the current task
        continue with current execution
    else
        if  $t_S$  is an available task
            offer an auction
        else
            switch executing the awarded task
else
    stay idle

```

Algorithm 2 forms the main loop for incremental task allocation and it is called in the beginning of mission execution and whenever the world knowledge of the robot is changed. Each robot implements the same algorithm in a distributed fashion until the end of the mission when all traversable targets are visited. The given algorithm may be used to allocate all targets from scratch. However, an incremental approach eliminates the redundant allocations for dynamic environments. The cost function design can be determined based on the capabilities of the robot. The cost function that we use can be successfully implemented for very small robots as in our experiments.

DISTRIBUTED TARGET ALLOCATION

After selecting the most suitable target for itself, each robot announces its intentions by a single item auction. Selection of the best robot for a task is performed by using the Contract Net Protocol (CNP) in our approach. Although CNP presents the formalism on the relationships between managers and contractors, some simple decisions are left to the designer. Most auction based task allocation schemes offer solutions for allocating one/subset of tasks of the overall mission. However there is usually little information about when task announcements and reassignments are made.

Algorithm-3. Main Asynchronous Procedures for some events, r_j

```

if auction negotiation deadline is reached
  end auction
  award the best bidder or begin execution
if an auction message for  $t_k$  from  $r_l$  is received
  Perform the corresponding MTRP-Response
  (Path/Time)
if an award message is received and  $\|T_{R_j}\| = 0$ 
  begin executing the task
if the world knowledge is changed affecting  $T_{R_j}$ 
  cancel auctions or executions

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Algorithm-3'. Response from r_j for the auction of t_k to the auctioneer r_l - Path Minimization

```

algorithm: MTRP-Response-Path
if auction/execution is in progress and  $c_{ji} > c_{lk}$ 
  cancel auction/execution
if  $c_{ji} < c_{lk}$ 
  send bid value for  $t_k$ 

```

Algorithm-3''. Response from r_j for the auction of t_k to the auctioneer r_l - Time Minimization

```

algorithm: MTRP-Response-Time
if auction/execution is in progress and
 $c_{ji} > c_{jk} \parallel c_{ji} > c_{lk}$  and  $t_k$  or  $r_l$  is close to  $T_{R_j}$ 
  cancel auction/execution
if  $c_{ji} < c_{lk}$ 
  send bid value for  $t_k$ 

```

In our proposed approach, multiple auctioneers and winners for different tasks are allowed depending on the optimization objective. Algorithm 3 presents the responsive behaviours for asynchronous events as distributed target allocation procedures. For the total path length minimization objective, ending one auction at the same time results in better performance when there is relation between targets. When robots receive task execution intention messages as auctions, they either send their cost values as bids for the announced targets or send warning messages to the sender robots by the system consistency procedures as explained in the following section.

III. PLAN B PRECAUTIONS

The contingency handling mechanism in the proposed approach is used to detect failures or contingencies and to recover from them. Contingency handling is provided as an integrated component to the target allocation mechanism to ensure robustness. It is formed by two components: *The Model Update Module* and *The System Consistency Checking Module*. *The Model Update Module* uses incoming information and perceptual information and own motivations to update the world model of the robot. *The System Consistency Checking Module* provides the warning messages to keep the consistency. Related to the contingent situations, appropriate consistency checking and update procedures are activated to either correct the models, or initiate recoveries.

REPRESENTATION OF THE SYSTEM MODEL IN EACH ROBOT'S WORLD KNOWLEDGE

Each robot keeps the models of the system tasks and other robots in its world model. Models of different robots may become inconsistent because of the uncertainties, incomplete knowledge, assumptions, etc. It is not always possible to share a common world knowledge in decentralized systems as in the case of ours. Task models are stored as FSMs where each task can be in a different state. The FSMs for task states are illustrated in Figure 1. The state transitions are activated by the *Model Update Module*. Different task states that tasks can be represented as follows:

- *available*: This is initial state of tasks that are neither in execution nor in auction.
- *invalid* (interpreted as state *available*): This state is activated whenever there is incomplete information regarding a task which is previously being *auctioned* or *executed*.
- *self_auctioned*: A task in this state is under auction negotiation process managed by the corresponding robot as an auctioneer.
- *others_auctioned*: A task in this state is under auction negotiation process managed by another robot as an auctioneer.

- *awarded*: A task is being represented with this state, if the robot either selects itself or being awarded at the end of an auction negotiation process.
- *self_inexec*: A task in this state is being executed by the corresponding robot in a coalition and synchronized or the coalition involves only the robot itself.
- *others_inexec*: A task in this state is being executed by other robots.
- *achieved*: This is the final state of the tasks that are achieved.
- *unachievable*: This state is used for tasks that are not traversable or achievable.

Robot models are also stored in FSMs where each robot model has a state which is assumed by the corresponding robot. Robot states are:

- *idle*: A robot is assumed to be in this state when it is believed that it does not execute any task.
- *executing*: A robot is assumed to be running properly and executing a task whenever there is recent evidence.
- *failed*: A robot is assumed to be failed when there is no evidence on it is running properly for a long time.
- *auctioneer*: A robot is assumed to be auctioned for a task when there is recent evidence.

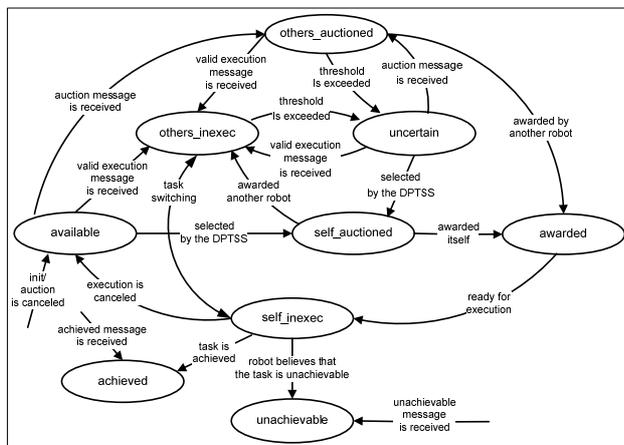


Figure 1. States of the FSMs for Task Models

MODEL UPDATES AND DUTIES FOR KEEPING THE SYSTEM CONSISTENCY

Recovery operations may include warning other robots about the problem or changing the model accordingly. Inconsistencies usually arise when robots are not informed about tasks that are achieved, under execution or auction in real-world operations. To keep the system consistency, robots use explicit communication and broadcast the following information:

- new discovered online tasks which are unachieved yet,
- task execution messages containing the updated cost value and estimated task achievement

deadline information in predefined time periods as clues for the executor robot is still alive and the task is under execution,

- task achievement message, when the task is achieved,
- cancellation message, if task execution is cancelled,
- task invalidation message, when invalidities are detected.

Most of the contingencies are detected by checking models, and the corresponding model updates are implemented. One standard way of detection of robot failures is sending heart-beat signals. However in our approach, incoming messages from other robots are taken as clues for being marked as running properly. More complicated prediction models may be used for more accurate failure prediction. Some misleading beliefs such as setting state of a robot as *failed* although it is running properly may cause parallel executions. This is a desired feature for the mission completion point of view. Designed precautions resolve these kinds of inconsistencies if communication resources permit in later steps.

Note that, information is not assumed to be complete in our approach; robots allocate and execute tasks in a distributed fashion. The model updates are implemented in each robot's world model in a completely distributed fashion. If communication is available, the system can take advantage of it to ensure the system consistency. Current implementation use explicit communication to detect conflicts and contingencies. However failures in communication can also be handled by precaution routines.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Our real-time dynamic simulation experiments are conducted on the professional mobile robot simulation software, Webots [5]. It contains a rapid prototyping tool to create 3D virtual worlds with robots and objects having physics properties [10]. In our simulation experiments, each environment is represented as a 5m by 5m 3D virtual world where 70mm-size simulated Khepera II robots and objects are located. The environments are randomly generated VRML files containing the robots, the objects and the MTRP targets. Communication is achieved through the wireless links. Emitters in the simulator are configured as having baud rate 9600 and the buffer size 1024B as in the receiver modules.

Robot kinematics calculations are done on the low level design of the robots by using the odometry information coming from the encoders for both simulation and real world experiments. Robots perform mapping of the environment by using occupancy grid approach simultaneously with online localization. In the simulator, slipping and encoder errors are simulated whereas the real

world has its own uncertainties. Due to the slipping errors, as expected from differential wheel robots, there are usually odometry errors. Different modules on the task allocation layer are integrated with the low level Sensory Interface, Motor Interface, Motion Model and Mapping modules in the multi-threaded structure.

In the first set of experiments, the scalability of the system for different number of robots is evaluated. Since the proposed approach in this paper is for an efficient multi-robot team, we expect to see a linear decrease in the total path length traversed by the robots with the increasing number of robots as in Figure 2. These results validate our expectations. The overall performance of the total path length traversed by the robot is evaluated in [7,9] with promising results.

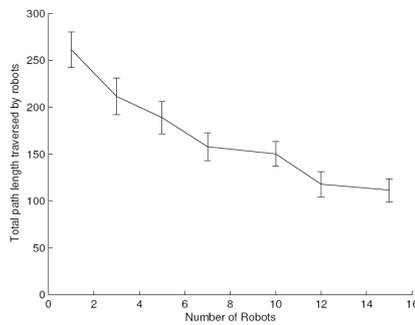


Figure 2. Scalability Analysis for different number of robots

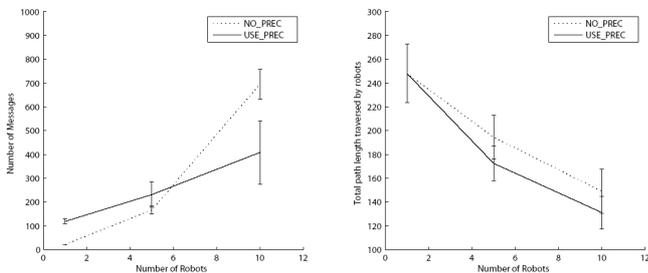


Figure 3. Contingency Handling Mechanism performance results

In the second set of experiments, the contingency handling mechanism performance is evaluated as in Figure 3. NO_PREC method does not use the contingency handling mechanism capabilities, while USE_PREC method uses. In the left figure the total number of messages that are sent by the robots can be seen. The surprising result here is the increasing number of messages for the NO_PREC case. Although our contingency handling mechanism seems to inject additional messages in the system at first glance (for ensuring the system consistency), as these results reveal, it also eliminates the redundancy in the number of messages for multiple bids and auctions. The right figure shows the total path length traversed by the robots. The path length is presented by quantized values (one unit is 70mm each). Using the contingency handling mechanisms reduce both

the number of messages sent and the total path length traversed by the robots. The results show the efficiency of integrating the contingency handling mechanism into the system.

V. CONCLUSION

Our solution to the real world MTRP is integrating the distributed target allocation, simultaneous route construction, real-time contingency handling and low level robot procedures to make robots contribute to the overall team objective by visiting target locations. The target allocation decisions are made by the robots themselves in a distributed fashion. Target allocation and route construction is integrated into each other by an incremental assignment approach. Furthermore, real time situations and contingencies that change the problem instance are handled at the same time. Empirical evaluations of the system are performed on the professional Webots simulator. Experiments reveal the success of the approach as a whole with its integrated components and its applicability even very simple and small robots like Khepera II.

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