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Multi-Robot Simultaneous Coverage and Mapping of Complex Scene - Comparison of Different Strategies

Laetitia Matignon\textsuperscript{1,2} and Olivier Simonin\textsuperscript{1,3}

Abstract— This paper addresses the problem of optimizing the observation of a human scene using several mobile robots. Mobile robots have to cooperate to find a position around the scene maximizing its coverage. The scene coverage is defined as the observation of the human pose skeleton. It is assumed that the robots can communicate but have no map of the environment. Thus, the robots have to simultaneously cover and map the scene and the environment. We consider an incremental approach to master state-space complexity. Robots build an hybrid metric-topological map while evaluating the observation of the human pose skeleton. To this end we propose and evaluate different online optimization strategies exploiting local versus global information. We discuss the difference of the performance and cost. Experiments are performed both in simulation and with real robots.

I. INTRODUCTION

Research in complex scene observation by mobile robots has recently gained significant attention and practical interest. A key direction of this research aims at coordinating robots to explore the environment and at optimizing their positioning so as to maximize the quality of the scene observation. This is especially challenging when human activities must be observed, or monitored, in complex structured environments. This concerns for instance cobotics and rescue tasks.

In this paper, we focus on observing a person carrying out an activity in a specific area. Several robots have to deploy themselves around the person to fully observe its pose (i.e., identify its skeleton pose). As the environment is unknown to the robots and cluttered, robots have to explore it in order to find the best joint observation. We assume that robots are homogeneous, can communicate and know the relative position of the scene to observe.

Several strategies have been proposed to coordinate robots in tracking a set of targets. They range from very simple local rules to heuristic-global approaches, see review [1]. However these solutions generally consider that the environment is free of obstacles, or they are too few to obstruct the observation.

In this paper we address multi-robot scene observation in unknown cluttered environment. This raises new questions: how to map the environment while searching for an optimal positioning? how to limit the state space to map and to explore? how to represent the quality of observation from each location visited by the robots?

To this end we build an approach which extends the coverage (observation) of the targets by considering to simultaneously map the environment. Then we tackle another issue which is the trade-off between exploitation and exploration, that is moving to optimize the observation versus exploring the environment to find new interesting observation positions.

In response to these questions we propose an incremental mapping that refines the representation and the information in areas where the quality of observation is promising. We also introduce a circular topology adapted to the continuous observation of the scene while robots move around. Then we propose different algorithms relying on local versus global observation, leading to solutions with different computational costs. We conduct a set of experiments in simulation and with real robots allowing to evaluate the different approaches.

The paper is organized as follows. In Section II we discuss related works on the tracking of targets with mobile robots. Section III formalizes the problem and defines the coverage and mapping tasks. Then we propose in IV different algorithms relying respectively on random decisions, meta-heuristics and brute-force search. Section V presents a simulator and some experiments comparing the performances of the different approaches. Finally, we conclude and draw some perspectives to this work in section VI.

II. RELATED WORK

The last decade have seen a growth of the research on network of fixed cameras to detect, track and recognize objects or persons [2], [3]. However, a set of static cameras cannot deal with non-covered zones or occlusions. That’s why recent works in the field of active perception are interested in using mobile cameras that can move to adequate places to cover blind spots or to react to changing conditions as lighting or dynamic obstacles.

Cooperative active perception considers multiple decision makers that cooperate and merge information from their sensors. In the URUS\textsuperscript{1} project [4], the objective is to assist and guide people in urban settings. Active cooperative perception has been here considered only between one mobile robot and a set of fixed surveillance cameras. In Giusti et al. work [5], distributed visual recognition of hand gestures is carried out with a group of mobile robots. They use a distributed consensus protocol to decide, between individual

\textsuperscript{1}Ubiquitous Networking Robotics in Urban Settings.
classifications made by each robot, the issued gesture. In this work, the navigation and coordination of the robots is very simple and is not used to improve the recognition. Indeed, although the robots are mobile, once they are positioned uniformly in a semi-circular arc centered on the target scene, they maintain this formation. Moreover, the environment is assumed to be without obstacles, which facilitates the navigation and the observation.

Exploration and mapping of cluttered environments with autonomous mobile robots have been intensively studied since two decades. The objective is to explore as quickly as possible all the area of the environment in order to build a complete map. Using a fleet of robots instead of a single one allows to divide the task, leading to a gain of time, robustness and accuracy, see e.g. [6], [7], [8], [9]. However, these works do not consider that the mapping has to be conducted in order to help the positioning and coordination of robots so as to optimize the observation of a scene, which is our problem.

Approaches using the navigation and coordination of multiple robots to perform cooperative active perception can be found in works about the observation of moving targets with moving sensors. Most of these approaches are classified and discussed in a recent review [1]. Among these, the CMOMMT (Cooperative Multi-robot Observation of Multiple Moving Targets) framework, introduced by L. Parker [10], aims to dynamically position robots to maximize the number of targets under observation and the duration of observation of each target. An on-line and distributed heuristic approach is proposed to solve the CMOMMT problem using weighted local force vector control. However this approach assumes uncluttered environments with either no or simple obstacles. Moreover it is supposed that the navigation behaviour is only influenced by the obstacles, and not by the perception of the targets. This means that the robots observe the targets even if there are obstacles and they do not observe the targets only when they are too far from them. So this approach is not adapted to our context where robots have to evolve in an unknown cluttered environment composed of obstacles affecting the navigation and the observation of the scene. However we build our approach as an extension of the CMOMMT model, and we use its formalism to define our problem in the following section.

III. PROBLEM DEFINITION

In this section we formally define the generic task of the multi-robot observation of a human activity in an unknown environment. We consider in this paper a person carrying out an activity in a quasi-static location. The observation is defined as identifying the human body pose, that can be characterized by a set of skeleton joints. We give general definitions before refining the mapping and the coverage tasks by considering a specific circular navigation topology, more adapted to the observation around a scene.

A. Coverage and Mapping

We formalize the complex scene observation problem as an extension of the CMOMMT framework [10]. This framework aims to dynamically position robots to maximize the coverage of mobile targets, i.e. the number of targets under observation and the duration of observation of each target.

Definition 1. The CMOMMT model [10] is defined as a tuple \( < S, V, K > \) where:

- \( S \) a two-dimensional, bounded spatial region;
- \( K(t) \) a set of \( n \) targets, where \( k_{i,j}^t \) is a target, that is located within region \( S \) at time \( t \); in our case, the human scene to observe is composed of a set of \( n \) skeleton joints;
- \( V \) a team of \( m \) mobile robots, where \( v_{i,j} = 1, \ldots, m \) is a robot with observation sensors that are potentially noisy and of limited range.

Observing human(s) activity in an unknown and structured environment requires the robots to build a map. The map will allow the robots to locate themselves, to share information, to plan paths among obstacles, and to learn worst versus best observation locations. Thus we complete the CMOMMT framework and its coverage task with a simultaneous mapping task.

To master the complexity of the state space, we propose a discrete representation of the environment and the robots’ positions. We define a grid of \( D \times C \) contiguous cells where \( C \) is the number of concentric circles around the scene, divided in \( D \) sectors. Then the robots move in discrete-circular topology by following the \( C \) circles or changing of circle, as it is illustrated in Fig. 1.

Definition 2. The position of a robot \( v_i \) at time \( t \) is defined by \( x_i^t = (d_i(t), \sigma_i(t)) \) with \( d_i \) the distance of the robot \( v_i \) to the scene, and \( \sigma_i \) the angle between a reference line and the line connecting the scene to the robot (cf. Fig. 1).

Definition 3. At any position of a robot \( v_i \) at time \( t \) is associated a unique cell \( c_i^t \) such that \( d_i(t) \in [d_a, d_b] \) and \( \sigma_i(t) \in [\sigma_a, \sigma_b] \). The position of a cell \( c \) is \( ((d_a, d_b); [\sigma_a, \sigma_b]) \).
This concentric topology allows the robots to maintain their direction of observation towards the scene while they move along circles. This also reduces dramatically the number of position of observation. Some of these positions can be unreachable when occupied by obstacles or other robots.

B. Observation data and Actions

Skeleton observation: In the considered observation problem, a target is a skeleton joint. A joint is observed when a robot is able to identify the joint with its sensor.

Definition 4. The observation vector \( o_i(x^t_i) \) of a robot \( v_i \) at time \( t \) is defined as a binary vector of size \( n \) such that:

\[
o_i(x^t_i) = [o_{ij}(x^t_i)]_{j=1..n} = [o_{i1}(x^t_i), ..., o_{in}(x^t_i)]
\]

where:

\[
o_{ij}(x^t_i) = \begin{cases} 1 & \text{if robot } v_i \text{ is observing target } \kappa^t_j \text{ from its position } x^t_i \\ 0 & \text{otherwise.} \end{cases}
\]

Definition 5. The individual observation quality \( q_i(x^t_i) \) made by a robot \( v_i \) at time \( t \) is defined as:

\[
q_i(x^t_i) = \frac{1}{n} \sum_{j=1}^{n} o_{ij}(x^t_i).
\]

The quality \( q_i(x^t_i) \) is the percentage of skeleton joints accurately tracked by the robot \( v_i \) at \( t \).

Definition 6. The observation matrix \( O \) of the team \( V \) at time \( t \) is defined as:

\[
O(x^t_1, ..., x^t_m) = [o_i(x^t_i)]_{i=1..m} = [o_{ij}(x^t_i)]_{i=1..m,j=1..n}
\]

Definition 7. The joint observation quality \( Q \) made by the team \( V \) at time \( t \) is defined as:

\[
Q(x^t_1, ..., x^t_m) = \frac{1}{n} \sum_{j=1}^{n} g_j(O(x^t_1, ..., x^t_m))
\]

where:

\[
g_j(O(x^t_1, ..., x^t_m)) = \begin{cases} 1 & \text{if } \exists i \in V \text{ such that } o_{ij}(x^t_i) = 1 \\ 0 & \text{otherwise.} \end{cases}
\]

To quantify the individual contribution of each robot to the joint observation, we introduce the notion of marginal contribution. This refers to the marginal contribution of a player to a coalition in the Shapley value [11].

Definition 8. The marginal contribution \( w_i \) of a robot \( v_i \) in the joint observation of the team, at time \( t \), is defined as:

\[
w_i(x^t_1, ..., x^t_m) = \frac{1}{n} \sum_{j=1}^{n} o_{ij}(x^t_i) \land (o_{ij}(x^t_i) \lor g_j(O(x^t_k,k\neq i)))
\]

with \( \land \) the exclusive disjunction.

The marginal contribution corresponds to the part of the observation that robot \( v_i \) is the only one to see. It depends on the positions of all the robots of the team.

Coverage criterion example: The objective is to maximize the joint observation quality \( Q \), i.e. the number of targets observed by the team. Notice that maximizing \( Q \) is not decomposable into maximizing \( q_i \) for each robot, which could lead to redundant information. For instance, consider the following example with \( n = 3 \) robots and \( n = 7 \) targets. Observation vectors, individual qualities and marginal contributions of each robot at time \( t \) are:

\[
\begin{align*}
o_1^t &= [0, 0, 0, 1, 1, 0, 0], & q_1^t &= 0.29, & w_1^t &= 0.29 \\
o_2^t &= [1, 1, 0, 0, 1, 1], & q_2^t &= 0.57, & w_2^t &= 0 \\
o_3^t &= [1, 1, 1, 0, 0, 1, 1], & q_3^t &= 0.71, & w_3^t &= 0.14
\end{align*}
\]

Even if Robot \( v_2 \) has a high individual observation quality, its contribution is low because it observes the same targets as another robot. Conversely, \( v_1 \) has a low individual quality, but it is the only one to observe some targets, so its contribution is the highest. This illustrates that the objective of maximizing \( Q \) requires to find the most complementary information.

Map data: In each cell \( c \) of the map we compute the following data:

- an obstacle occupancy probability (computed from the robots’ SLAM\(^3\) function);
- a number of visits (considering all the robots);
- the set of observation vectors done so far from that cell.

The size of this set is equal to the number of visits.

From this, we can compute\(^4\) the mean and rounded mean observation vector \( \bar{o}(c) \).

Definition 9. The mean observation vector \( \bar{o}(c) \) of the cell \( c \) at time \( t \) is the sum of the observation vectors done so far, divided by the number of visits of that cell until \( t \).

Definition 10. The rounded mean observation vector of the cell \( c \) at time \( t \) is the mean observation vector where each element of the vector is rounded to 1 or 0 according to its comparison to 0.5.

Incremental division of cells: To master the time to explore the environment, we propose an incremental division of cells based on a quadtree structure. The idea is to have at the beginning a coarse representation of the environment.

---

\(^3\)Simultaneous Localization and Mapping

\(^4\)Incremental averaging is used.
with few initial cells. A leaf cell can be split into four sub-
cells (sub-cells become the new leaf cells), and recursively, 
sub-cells can be split until the max depth of the quadtree 
is reached. This is illustrated in Fig. 2. The objective is to 
refine the discretization only in interesting areas of the 
environment. Thus the number of cells to explore is reduced 
while refining the joint observation quality over time as the 
robots split interesting cells.

Robots actions: Robots can execute two kind of actions:
- split its current cell; then the robot goes randomly to 
one of the four children cells;
- move to a cell: move to an adjacent cell or compute 
a path to a specific cell. Robots are moving on cells 
which are leaf nodes of the quadtree.

Cell’s data are updated following probabilistic quad-tree 
principle [12]. When a cell is split, all the data of the children 
cells are initialized with the data of their parent node, except 
the obstacle occupancy probability that is computed from the 
occupancy grid map.

Exploration-Exploitation compromise: The problem is 
defined as two concurrent tasks, which are mapping the 
environment and covering the scene. The objective is to reach 
as soon as possible a robots’ joint position that maximises 
the coverage criterion. The exploitation consists in using 
the information gathered by robots in each cell, i.e. in the map, 
to find this joint-position.

In all cases, we need to explore at the beginning of the 
task to acquire and gather cells data. Then, a compromise 
between exploration and exploitation is required. The 
compromise is between the quality of the found solution (the 
more we explore cells and gather data, the more cells data 
will be pertinent), and the time to find a good solution (how 
long do we need to explore to gather pertinent enough data).
Especially if the scene is dynamic and the targets are moving, 
robots do not have a lot of time to find a solution.

IV. ALGORITHMS

In this section we present different strategies for the 
simultaneous exploration of the environment and coverage 
of the scene. In each strategy, or algorithm, robots/agents 
are homogeneous and supposed at least to communicate their 
location and split actions. These algorithms do not exploit 
the same data and do not compute/store the same information. 
We discuss in the end of the section their differences in term 
of computational and memory cost, before comparing their 
performances in the next section.

A. Heuristics algorithms

Consider the state space that \( m \) robots have to explore 
in order to find the best position. This set is bounded\(^5\) 
by \((C \times D)^m\) if robots are heterogeneous. If robots are 
identical\(^6\), the size of the state space goes down to \( (C \times D)_{\frac{m}{m}} \).

Given the obstacles, it does not reduce to \( \binom{D}{\frac{m}{m}} \) as it is 
not sufficient for the robots to explore the cells situated 
the closest to the scene as they are not guaranteed to be 
reachable. To handle this complexity we combine the 
incremental mapping with heuristics algorithms to guide 
the exploration of the state space.

In general, exploration consists in moving to unknown 
cells to gain new information and to avoid possibly the team 
remaining in a local optimum; while exploitation consists 
in moving to known cells to optimize the joint observation. 
Here exploration consists for a robot in moving to one of 
its unvisited adjacent cells. If there are no unvisited adjacent 
cells, the robot tries to move to adjacent cells by choosing 
first the less visited ones. Exploitation consists for a robot in 
moving to its best adjacent cell, or split its current cell if it is 
already the best one or if moving is not possible\(^7\). The 
best adjacent cell is defined for a robot as the cell that, among 
the current cell of the robot and its adjacent cells, maximizes 
the joint quality given the current cells of the other robots.

The rounded mean observation is used to compute the joint 
quality and especially, to infer the observations made from 
the adjacent cells.

We propose different algorithms based on two major steps:
- The first one is the selection of which robots must 
move at each decision step. The proposed heuristic is to move 
only the robots with the lowest marginal contributions. Keeping static the robots with high con-
tributions still offers several advantages: minimizing the 
decay in the current joint quality, maintaining the group 
configuration stable, and detecting potential changes in 
the scene (activity change).
- The second one is to determine which action must be 
done by these selected robots. To this end we study 
different strategies:
  - RandomAction chooses to split the current cell 
of the robot with a probability of 0.5, and otherwise 
to move to one of the adjacent cells of the robot 
chosen randomly;
  - SimulatedAnnealing (SA) [13] chooses an 
action of exploration according to a probability 
\( \tau \), and an action of exploitation otherwise. This 
temperature parameter is gradually reduced by a 
decreasing rate \( \alpha \in [0; 1] \) at each decision step \( t \) 
according to:
    \[ \tau_t = \tau_{t-1} \times (1 - \alpha) \];
  - TabuSearch (TS) [14] always performs an action 
of exploitation, but forbids the visit of the cells that 
are in the tabu list. The tabu list keeps tracks of a 
short-term set of the last visited cells.

Two main algorithms are obtained combining the op-
tions at each step. Algorithm 1 chooses randomly which 
robots to move at each step, and their actions are also 
selected randomly. Algorithm 2 gathered various algorithms

\(^{5}\)It can be reduced if some cells are inaccessible because of obstacles and 
if only one robot per cell is allowed.

\(^{6}\)Two robots can be arbitrarily swapped without changing the joint 
observation of the scene.

\(^{7}\)A move is not possible if the target cell is an obstacle or is already 
occupied by another robot.
where only the robots with the lowest marginal contributions move at each step. In Algorithm 2, each moving robot can choose its action according to RandomAction (it gives the RandomWithContribution algorithm) or meta-heuristics. In particular, using meta-heuristics as TS or SA leads to a behaviour where the cells that are potentially interesting for the observation of the scene are divided and explored more accurately.

Algorithm 1: One step of Random search

Data: The set of \( m \) robots, the number of moving robots \( \delta \in [1..m] \)

for \( i \in [1,...,m] \) do
  Update \( o_i \)
  // 1- Choose which robots to move
  movingRobots ← choose randomly \( \delta \) robots among \( m \)
  // 2- Choose an action
  for \( r \in [1,...] \) do
    \( c_i \) ← current cell of the robot \( movingRobots[i] \)
    \( movingRobots[i] \) executes RandomAction\((c_i)\)

Algorithm 2: One step of search common to RandomWithContribution and meta-heuristics (TS, SA)

Data: The set of \( m \) robots, the number of moving robots \( \delta \in [1..m] \), a ChooseAction function \( \in \{ \text{RandomAction, SimulatedAnnealing, TabuSearch} \} \)

for \( i \in [1,...,m] \) do
  Update \( o_i \)
  // 1- Choose which robots to move
  for \( i \in [1,...] \) do
    Compute \( w_i \)
    weakRobots ← the \( \delta \) robots with lowest \( w_i \)
    // 2- Choose an action
    for \( i \in [1,...,\delta] \) do
      \( c_i \) ← current cell of the robot \( weakRobots[i] \)
      \( weakRobots[i] \) executes ChooseAction\((c_i)\)

B. Exhaustive search (brute-force)

To compare our heuristic algorithms with a brute-force approach, we propose an exhaustive combination algorithm. It aims to find the best joint position around the scene by computing the qualities of all the possible joint positions, given the cells already visited by the robots.

1) Combination definitions: A combination from the set \( m \) is defined as a set of \( m \) different leaf cells and noted \( \lambda \). It represents a joint position for the \( m \) robots. The quality of a combination at step \( t \) is defined as the joint quality computed with rounded mean observations of the cells.

2) Algorithm: Algorithm 3 details each step of the exhaustive combination algorithm. At the beginning of each step, the algorithm has the set of already visited leaf cells \( L \), and the set of all possible combinations at this step \( \Lambda \). \( \Lambda \) contains all the \( m \)-combinations of cells from the set \( L \) (also noted \( \binom{L}{m} \) ). \( \Lambda \) is shared among all agents.

The exhaustive combination algorithm first searches the best combination \( \lambda^* \) in \( \Lambda \). The best combination \( \lambda^* \) is the combination with the optimal quality and the lowest cost given the current position of the robots. So \( \lambda^* \) defines a joint position that gives an optimal observation on the scene. If \( \lambda^* \) is found, the robots move to the corresponding cells of \( \lambda^* \). Otherwise, the robots explore the map to complete and update the set of combinations. The exploration consists in moving to unvisited cells in priority, otherwise trying to split and in last resort, moving to less visited cells.

Algorithm 3: One step of Combination search

Data: The set of \( m \) robots, the set of combinations \( \Lambda \), the set of unvisited leaf cells \( Unvisited \), the set of leaf cells sorted by their number of visits \( Lessvisited \)

for \( i \in [1,...,m] \) do
  Update \( o_i \)
  \( \lambda^* \) ← the best and closest combination \( \in \Lambda \), given positions of the \( m \) robots
  if \( \lambda^* \) exists then
    AStarMove\((m,\lambda^*)\) // Move the robots to \( \lambda^* \)
  else if \( Unvisited \neq \emptyset \) then
    AStarMove\((p,Unvisited)\) // Move \( p \leq m \) robots
  else if Agents with no assignment can split then
    Agents not assigned try to split
  else if Agents with no assignment cannot split then
    AStarMove\((AgentsNotAssigned,Lessvisited)\)
  for \( i \in [1,...,m] \) do
    Update \( \Lambda \)

3) Combination set updates and complexity: At the beginning of each step, \( \Lambda \) is the \( m \)-combinations of cells from
the set $L$ so it is composed of $\binom{L}{m}$ combinations. To find the best combination, algorithm 3 must look over all these combinations.

The set of combinations $\Lambda$ is also updated and can increase at each step given the actions of the robots.

- If a robot moved to a cell never visited before, $\Lambda$ is increased with $\binom{L}{m-1}$ new combinations formed with the new cell and all the combinations of the already visited cells $L$ (the new cell is not considered in $L$ here).
- If a robot splits a cell, all the combinations in $\Lambda$ where the split cell is are modified to replace the split cell by one of its children (the one where the robot has chosen to move).

C. Local vs. Global approaches

Table I summarizes the four proposed algorithms given different characteristics. In each algorithm, robots are supposed at least to share the obstacle map characteristics. This means that they build a cooperative obstacle quadtree, i.e. they all have the same quadtree structure decomposed in cells, and obstacle occupancy associated to these cells (but observation data are not required). Observation communication characteristic requires the robots to communicate at each time step their current observation vectors. This is an assumption of all the algorithms that compute the marginal contribution to choose which robots to move at each step. Observation map is when the algorithm requires the robots to build a full cooperative quadtree, with all the cell data detailed in the Map Data (cf. subsection III-B). Finally, the space search characteristic defines if the robots are searching in a local space (adjacent cells around their current cells) or in a global search (all leaf cells of the quadtree).

This table allows to underline which approaches rely on local vs. global information leading to different computational cost. Among them two extreme solutions are proposed: i) the random action selection, having a null cost in computation and memory, ii) the exhaustive search having an exponential complexity and requiring to store all observation vectors obtained in each cell. Between the two we examine how the selection of robots to move, depending on their marginal contribution, could improve dramatically the performances. Then we aim to study how meta-heuristic exploiting local information compares to the exhaustive search approach, while requiring few computational expenses.

V. COMPARISON OF PERFORMANCE AND COST

A. Simulator

To perform experiments, we developed a simulator that allows to run a large quantity of experiments in order to test the validity of our approach. A main feature of our simulator is that its main parts (data structures, e.g. cell, quadtree, decision algorithms, interface) are used both for the simulation and for the control of our robots during real experiments. For the simulation part, specific modules have been developed to simulate in the most accurate and realistic way key features of real mobile robots, environments and scene. A video presenting the simulator interface, the exploration and incremental mapping with simulated and real robots can be found at https://liris.cnrs.fr/crome/wiki/doku.php?id=videoaamas2018.

We assume that robots’ motion around the scene is perfect, i.e. robots can move along circles without trajectory errors, and robots are equipped with sensors allowing them to remotely detect nearby obstacles. Communications between robots are also supposed to be instant and errorless.

To simulate a scene, we use real data obtained from real human captures with Kinect RGB-D sensor. These captures were made from different human poses (standing, sitting, crouching), with or without occlusions\(^8\) (cf. fig. 3). For each scene, multiple captures were made from a set of point of views along a circle centred on the scene. Skeleton data obtained from OpenNI and NITE skeletal tracking library [15] have been imported in the simulator to generate the observation vectors\(^9\) for each sector.

To generate an environment in the simulator, one can choose where to put obstacles or to randomly distribute them. Concerning observations from each cell, it is possible to choose random ones or observations obtained from a human pose generated from real data. Then we use a ray tracing [16] technique starting from the scene to assign to each cell of a same sector a common observation until reaching obstacles. Cells behind an obstacle have a null observation.

Once the reference environment has been generated, it is used in all runs. Fig. 4 shows two reference environments containing different obstacles (black cells). They also show

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Obstacle Map</th>
<th>Observ. Comm.</th>
<th>Observ. Map</th>
<th>Space search</th>
</tr>
</thead>
<tbody>
<tr>
<td>random</td>
<td>x</td>
<td>-</td>
<td>-</td>
<td>local</td>
</tr>
<tr>
<td>random-contrib</td>
<td>x</td>
<td>x</td>
<td>-</td>
<td>local</td>
</tr>
<tr>
<td>meta-heuristic</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>local</td>
</tr>
<tr>
<td>exhaust-search</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>global</td>
</tr>
</tbody>
</table>

TABLE I

CHARACTERISTICS OF THE FOUR COMPARED ALGORITHMS. x MEANS THAT THE CHARACTERISTIC IS REQUIRED.

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\(^8\)Occlusions are not in the navigation space, i.e. they are in the space between the scene and the most inner circle of the navigation model.

\(^9\)I.e. skeleton information composed of 15 body joints.
Fig. 4. (a) - (b): Two different environments used in the simulator. (c): Real environment with three robots around a human scene (reading phone) and a cluttered environment.

<table>
<thead>
<tr>
<th></th>
<th>Env. A</th>
<th>Env. B</th>
</tr>
</thead>
<tbody>
<tr>
<td># Targets</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td># Circles</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td># Sectors</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td># Leaf cells</td>
<td></td>
<td>192</td>
</tr>
<tr>
<td># Obstacles</td>
<td></td>
<td>27</td>
</tr>
<tr>
<td># Possible joint positions</td>
<td>1,661,853</td>
<td>1,616,586</td>
</tr>
</tbody>
</table>

**TABLE II**

Characteristics of env. A and B with 3 robots. Possible joint positions are all the combinations of non-obstacle, leaf and non-leaf cells. This number is not the same, as non-obstacle non-leaf cells are not the same in A and B.

To simulate noise in camera sensor and occlusions due to other robots, we add noise to the perception from a cell. A noise parameter \( \beta \) defines the probability for each value of an observation vector to be flipped (compared to the reference values). Robots occlusion is simulated as a noise inversely proportional to inter-robot distance. This operation is computed each time a robot asks for an observation over the environment. Thereby, the perceived observation from cells of a same sector may vary.

**B. Experimental setting**

We perform our experiments in two different environments, presented in fig. 4, using 3 robots and 3 initial cells. Simulation of the scene is done using real data captured from different human poses. Table II provides some information concerning the state space of each environment and the number of optimal joint positions for each pose, illustrating their complexity. In the following, common parameters used are the number of agents \( m = 3 \), the number of moving agents at each time step \( \delta = 2 \), the size of the tabu list is 5, the temperature for SA algorithm is set once to 0.6 at the beginning of each experiment, and decreases at each step according to \( \alpha = 0.01 \), but is never reset until the experiment ends.

**C. Performance comparison**

First we plot the current joint quality found by the robots at each step with the different algorithms in Figure 5. It shows that with the Random algorithm, the current joint quality fluctuates a lot, contrary to the other algorithms. This illustrates that the heuristic that consists in moving only the robots with the lowest marginal contributions at each step is a good solution to maintain a stable view on the scene. Indeed, this heuristic is used with all algorithms except the Random. Maintaining a stable view on the scene is particularly interesting to detect potential changes in the scene, as in case of a dynamic scene.

Second we compute for each algorithms, the distance that the robots have to travel before covering optimally the scene, i.e. being on a joint position with the best possible joint quality. We do not count the number of algorithm steps, because one time step of the algorithms can last for variable time in real experiments. Indeed with random algorithms or meta-heuristics, robots can only move to their adjacent cells at each time step, so the distance travelled by each robot is relatively small and the duration of the steps is roughly of the same order. But with the Combination algorithm, each robot can move to any cells of the map at each step. And this move is done by following the circular topology (cf. §III-A).

So one step in the Combination algorithm can last much longer than one step with the algorithms where robots are moving only to their adjacent cells. This is why we use the distance instead of the number of steps to fairly compare all the algorithms in simulation. This is equivalent to compare the time taken by real robots before covering optimally the scene in case of real experiments.

Fig. 6 shows this distance for different environments and human poses. We can see that in all cases, TS meta-heuristic is the fastest in term of distance to cover optimally the scene. Combination algorithm shows various results. Indeed it needs to explore all the unvisited cells before being able to
split. In occluded environments, the best joint position can require several split, which increases the number of cells to potentially explore before finding a combination with the best quality. These results highlight the importance of the use of the marginal contribution to the search process. They also show that strategies based on local information and meta-heuristic obtain better results than the exhaustive exploration / combination algorithm, especially considering the time to find a best joint quality. This time is an important factor in our context where we want to observe human scene that could be dynamic and so avoid long processes of exploration.

D. Real robot experiments

We performed experiments using 3 Turtlebot2 robots equipped with a RGB-D camera (Kinect) for the skeleton tracking, a low-cost 360° and 4 meters laser rangefinder (RP-Lidar) for local metric mapping and navigation, a netbook with Ubuntu/ROS connected to the mobile base and to the rangefinder for the decision and navigation part, and an Intel NUC mini-PC with Windows connected to the Kinect for the human observation part. ROS gmapping-package is used as particle filter SLAM algorithm. The decision algorithms (cf. §IV) are embedded in ROS nodes. They request skeleton data to a server running on the NUC. Data exchanged between robots use TCP/IP socket between netbooks.

These experiments were realized with the same modules (data structures (e.g. cell, quadtree), decision algorithms, interface) as the one used in the simulator. The additional components used with real robots are: (i) an hybrid mapping mixing high-level data of the quadtree map and low-level data of the metric map; (ii) a communication module between the robots, (ii) a distributed architecture for the algorithms presented in §IV; this architecture relies on asynchronous communication and topological quadtree maps cooperatively constructed by the robots. We tested SA and TS strategies and obtained similar results than with the simulator. Videos presenting these experiments are available at https://liris.cnrs.fr/crome/wiki/doku.php?id=videoaamas2018.

VI. CONCLUSION

We formally defined the generic task of the multi-robot observation of a human activity in an unknown cluttered environment as a simultaneous problem of coverage and mapping. The objective is to optimize the robot joint-observations of a human scene while exploring the environment. We proposed an incremental mapping based on a quadtree structure and a concentric navigation topology allowing to manage the state space complexity of the task. Then we proposed and evaluated different strategies showing that considering each agent marginal contribution is essential to the search process, while approaches based on local information and meta-heuristic optimizations obtained better results than the exhaustive exploration/combination algorithm.

As a perspective, we plan to extend our work to dynamic scenes, i.e. when the person is doing a sequence of activities. In this context, the robots will have to detect the change and adapt their positions at each new activity. This refers to a coverage problem of multiple moving targets. To perform this fast adaptation, keeping some map information about obstacles and occluded cells could be helpful. Another perspective is to extend our approach to soft confidence values for body joints. This would require to redefine observation and marginal contribution in a probabilistic framework.

REFERENCES


Fig. 6. Mean distance (meter) and standard deviation travelled by the robots before finding the best possible joint quality for the first time (50 experiments).


