Analyzing Multi-Robot Box-Pushing

Angélica Muñoz Meléndez\textsuperscript{1} and Alexis Drogoul\textsuperscript{2}

\textsuperscript{1} INAOE, Luis Enrique Erro No. 1
72840 Tonantzintla Puebla, México
munoz@inaoep.mx

\textsuperscript{2} LIP6 - UPMC, Case 169 - 4, place Jussieu
75252 Paris Cedex 05
alexis.drogoul@lip6.fr

\textbf{Abstract.} In this paper, various experiments on multiple robot coordination are described. These experiments were conducted to identify experimentally how the use of communication can improve the performance of a box-pushing task by avoiding robot interferences. In these experiments, an intuitive approach consisting in observing and analyzing the outcome of several hypotheses is adopted.

1 Introduction

What is it necessary to constitute a colony of robots? What kind of mechanisms should be designed in order to enable a group of individualistic robots to perform actions jointly?

A mobile robot have to cope generally with highly dynamic environments, in which it is very hard to foresee all the potential situations that the robot may encounter. Specify in advance all the patterns of interaction between a mobile robot and its environment, as well as those patterns among various mobile robots is then, impossible.

Explaining the collective behavior of a group of robots is also complicated. The behavior of a robot colony may have properties that only occur at global level. Then, to derive the global behavior of a group of mobile robots directly from their individual control programs does not seem to be feasible.

For these reasons, we adopt an intuitive approach to research experimentally the elements that are required when designing robot colonies. For that, a very specific problem is formulated and then elements are added gradually to enable the establishment, the demonstration and reformulation of hypothesis. The purpose of this research is to get insight into the design trade-offs of multi-robot coordination. For that, various experiments on box-pushing were conducted using two mobile robots.

The paper is organized as follows, section 2 addresses related work, section 3 and 4 describes and discusses experiments and finally, section 5 concludes with a summary.
2 Related work

The coordination of a group of robots has been analyzed from different perspectives. Todt et al. [13] analyze and compare various methods proposed for multi-robot coordination. These methods deal with the problem of coordination intended to avoid collisions among robots. Collisions are usually avoided by organizing the trajectories that were previously planned by the robots [11].

Jäger [4] reports work on colonies of cooperative cleaning robots. In his experiments, each robot of the colony is controlled by a multi-agent architecture, where agents are in charge of tasks such as tracking objects and navigation. The area to be cleaned is divided into sections and each section is dynamically allocated to one robot. His method relies on local communication and has been tested using simulated robots mainly.

Parker [9] proposes a distributed architecture for multi-robot systems. Her architecture combines action-selection mechanisms and adaptation to enable a group of physical heterogeneous robots to perform cooperative tasks.

There are few works concerning the identification of the aspects and requirements to consider when designing robot colonies. Goldberg and Mataric [3], for example, examine the incidence that interference between robots has in the performance of a control system. They also use this interference as a criterion for evaluation of control systems with interesting results. Hayes [5] for his part, studies performance metrics for robot colonies. He analyses particularly the trade-offs between group size and efficiency in collective search tasks.

Finally, box-pushing is one of the tasks that has been explored by roboticists. Several planning algorithms [1, 2] have been proposed for individual box-pushing in simulated environments. Experiments on box-pushing using two or more physical robots have been reported [6, 7, 12, 15] in cooperative contexts mainly, that is, in situations where several robots push the same object. In this paper, the coordination of two robots that execute individually box-pushing in the same environment is explored.

3 Experiments

This section describes various experiments that were conducted in order to identify experimentally the key elements that are required to achieve multi-robot coordination. Experiments were conducted in such a way that a task, initially in charge of one robot, was gradually complexified towards a multi-robot context.

The research described in this paper is part of the MICRobES\(^\text{1}\) project [10]. The experiments were conducted using two Pioneer 2-DX mobile robots of ActivMedia\(^\text{©}\), provided with odometers, bumpers, sonars, radio modem, video-camera and onboard computer.

\(^1\) MICRobES is an acronym in French for Implementation of Robot Collectivities in a Social Environment.
3.1 Problem and settings

Box-pushing is the application chosen to explore the constitution of a robot colony. In this, robots have to search and move objects from one place to another place of the environment.

Robots use a cue-based recognition system developed by Viel [14] in order to differentiate visually significant elements of the environment. Both, the objects that robots have to transport and the places where the store and the supplier are located are indicated by cues consisting of bar codes (see figure 1).

The objects that robots have to transport in these experiments are boxes of $20cm \times 30cm \times 23cm$. A robot does not know where these objects are located, but it is able to recognize one of the box faces visually.

Robots have also a repertoire of actions and behaviors that are activated by external stimuli they perceive. Robots are able to execute simple actions such as turn, go forward and go back. More complex actions called behaviors such as vander, line up, surround box, push box towards store, wait and send a message have been implemented in and tested on our robots (for descriptions see the appendix).

Robots are programmed following a situated approach and therefore they do not have detailed information about their environment. They know, for instance, a general description about what an obstacle is from their sonar readings.

Fig. 1. A robot in an environment containing four objects and two bar codes over the wall. Bar codes consist of three black vertical bars on a white background. The patterns of a cue are composed of assembled black or white square-shaped unitary elements.

3.2 Individual box-pushing

A first group of experiments designed to implement and test individual box-pushing is described below.

Experiment 1. Foraging in a corridor. The environment of this experiment is a corridor of $1.70m \times 10m$. At each extreme end of the corridor is placed a bar code, one indicates the supplier and the other indicates the store. Boxes are introduced into the corridor by a human operator in front of the supplier. These boxes are presented in such a way that the bar code side of boxes is oriented towards the robot, leaving enough space between the box and the supplier for the robot. In this environment there are mobile obstacles such as walkers, but there are not fixed obstacles that block the robot movements.
The robot is randomly located in the environment. Its goal is to transport boxes from the supplier to the store. For that, the robot should look for the supplier and stay close to it in order to detect and transport boxes with a minimum delay. Figure 2 shows the Finite State Machine used to control the robot and figure 3 shows a sequence of actions generated by this controller.

![Finite State Machine](image)

**Fig. 2.** Foraging in a corridor

### Table 1. Experiment 1

<table>
<thead>
<tr>
<th>Boxes</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>total collected</td>
<td>waiting</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 1 shows the results of three experiments of individual box-pushing. The total number of boxes that were presented to the robot, as well as the number of boxes that were accurately transported are indicated. Experiments lasted the timed required to transport all the boxes whose total number was known by the robot. A robot takes 2'24", 3'37" and 3'20" to push a box in environments where 1, 2 and 5 boxes were introduced respectively. That is the result of dividing *actual time* (total time − waiting time) into the number of boxes that were transported from the supplier to the store.

![Sequence of actions](image)

**Fig. 3.** Individual box-pushing in a corridor. From left to right, a robot perceives the box, reaches and surrounds it. Next the robot pushes the box towards the bar code located at the extreme end of the corridor

### 3.3 Coordinated box-pushing

A second group of experiments designed to extend individual box-pushing is described below. Through these experiments we inquire answers regarding possible
mechanisms of interaction between two robots that have to complete the same task within the same environment. We want to discover robot requirements in order to perform collectively a task that robots manage to do individually, rather than force robots to coordinate and avoid collisions.

**Experiment 2. Individualistic foraging**

*Hypothesis 1*. A robot that is able to perform a task individually, should be able to perform the same task in a multi-robot context, because no collective effort is required to perform this task.

The environment used in this experiment is exactly the same of experiment 1 but here, two robots are randomly located in the environment. Both robots, whose goals are to push boxes from the supplier to the store, are controlled by the Finite State Machine of figure 2.

As we could have foreseen, the presence of a second robot within the same environment affects the accomplishment of tasks. Because of robots do not have any way to recognize a partner, an important number of collisions happen (see figure 4).

Table 2 gives us an idea of the influence that collisions between robots have in their performance. The number of boxes that were accurately transported is indicated in bold characters. In the best case, a robot succeeded one of two attempts to transport a box. Both robots spent 6'47" and 28'43" to transport respectively 1 and 2 boxes, the sum of actual time for both robots divided into the number of boxes transported from the supplier to the store.

![Fig. 4. Sequence of actions executed by individualistic foraging robots. From left to right, a robot tries to surround a box that is transported by another robot. Robots collide and damage the box, that is finally abandoned](image)

**Experiment 3. Spatially coordinated foraging.** Most collisions in experiment 2 resulted of a spatial conflict produced by two individualistic robots unable to share their environment if designers do not provide them an explicit way to do that. Third experiment is designed to prove a new hypothesis.

*Hypothesis 2*. An explicit division of the environment should be enough to avoid collisions between robots performing the same task within the same environment.
For this experiment, the environment described in experiment 1 is divided in two sub-corridors and each one is allocated to one robot. In the extreme ends of the corridor, bar codes indicating the supplier and the store are placed. In the middle of the corridor, a double faced cue hangs from a string situated 60 cm from the floor. This cue indicates the store for the robot situated in the first sub-corridor and the supplier for the robot situated in the second one.

The robots' goal is to push boxes through the corridor, where each robot is in charge of one sub-corridor. Boxes are introduced into the environment by a human operator who is placed in the extreme that corresponds to the supplier.

Table 3 summarizes the results of three experiments where robots p03 and p01 were in charge of sub-corridors. In the best case, robots succeeded one of five attempts to transport the same box. A success was here a box accurately transported to the second store. Two robots in a divided corridor spent 10'38" and 14'41" to transport the same box, of a total of 2 and 3 boxes respectively. Robots got a slightly better score but they still had problems of coordination.

The line that divides the corridor is a critical zone which robots cannot deal with. It happens often that the second robot reaches and tries to push a box that is been pushed by the first robot. Indeed, the controller of the second robot triggers the action go forward when a box is perceived, producing a collision (see figure 5). This situation could be solved if go forward was triggered once the box is perceived under a fixed threshold. This solution is however partial, because the calculation of distances to mobile objects is always approximate.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image5}
\caption{Sequence of actions executed by robots foraging in a divided corridor. From left to right, robot p03 pushes a box while robot p01 waits in front of its own supplier. p01 tries to reach the box before than p03 finished, producing then a collision.}
\end{figure}

\section*{Experiment 4. Spatio-temporally coordinated foraging.} Last experiments were based on the same control mechanism. We wanted to explore the possibilities of individual box-pushing and test the robustness and weakness of a general behavior in a multi-robot context.

We have seen that, even though an explicit division of the environment was introduced, robots were not always able to coordinate their actions. Previous results showed that robots acting within the same environment need an explicit mechanism for coordination.
**Hypothesis 3.** An explicit mechanism for synchronization is required for multi-robot coordination.

In this experiment, synchronization is achieved through a simple mechanism of direct communication between robots. Robots’ controller is here modified by introducing a behavior that enables one robot—the server—to send a message to another robot—the client—(see figure 6).

The robot in charge of the first sub-corridor, the server, behaves more or less in the same way described previously; however this robot sends here a message to its partner once it has completed its task. The robot in charge of the second sub-corridor, the client, does not longer executes wander as its first action. It waits and only starts to move if it receives a message of its partner indicating that a box is waiting in the middle of the corridor.

Table 4 shows the results of our last experiments. From the number of boxes that were collected, in bold characters, we confirm that robots have improved their performance. They succeeded, in the best case, two of five attempts to transport the same box. This improvement is due to their competence to communicate directly with each other, that enables them to avoid the collisions produced in experiment 3. The sum of actual time for both robots divided into the number of boxes transported from the supplier to the store was 6'36” to transport 1 box; 7'45” and 9'30” to transport 2 boxes of a total of 2 and 3 boxes respectively.

<table>
<thead>
<tr>
<th>Total Robot boxes</th>
<th>Boxes detected collected</th>
<th>Time wait. exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 p01</td>
<td>1</td>
<td>0 00&quot; 145&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>2</td>
<td>0 00&quot; 147&quot;</td>
</tr>
<tr>
<td>2 p01</td>
<td>2</td>
<td>2 20&quot; 456&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>2</td>
<td>0 48&quot; 459&quot;</td>
</tr>
<tr>
<td>3 p01</td>
<td>5</td>
<td>1 14&quot; 1446&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>5</td>
<td>0 36&quot; 1447&quot;</td>
</tr>
</tbody>
</table>

**Table 2. Experiment 2**

<table>
<thead>
<tr>
<th>Total Robot boxes</th>
<th>Boxes detected collected</th>
<th>Time wait. exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 p01</td>
<td>1</td>
<td>0 24&quot; 343&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>1</td>
<td>0 24&quot; 348&quot;</td>
</tr>
<tr>
<td>2 p01</td>
<td>2</td>
<td>1 00&quot; 510&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>3</td>
<td>0 00&quot; 528&quot;</td>
</tr>
<tr>
<td>3 p01</td>
<td>5</td>
<td>2 42&quot; 905&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>4</td>
<td>2 47&quot; 905&quot;</td>
</tr>
</tbody>
</table>

**Table 3. Experiment 3**

<table>
<thead>
<tr>
<th>Total Robot boxes</th>
<th>Boxes detected collected</th>
<th>Time wait. exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 p01</td>
<td>2</td>
<td>0 00&quot; 419&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>1</td>
<td>1 58&quot; 415&quot;</td>
</tr>
<tr>
<td>2 p01</td>
<td>3</td>
<td>1 26&quot; 606&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>2</td>
<td>2 59&quot; 604&quot;</td>
</tr>
<tr>
<td>3 p01</td>
<td>3</td>
<td>2 00&quot; 602&quot;</td>
</tr>
<tr>
<td>p03</td>
<td>2</td>
<td>2 31&quot; 559&quot;</td>
</tr>
</tbody>
</table>

**Table 4. Experiment 4**

Fig. 6. Foraging with communication
4 Discussion

Even though the competences of robots involved in previous experiments are not exactly the same, we can compare and discuss their results. The purpose of this comparison is to figure out the role that communication has in multi-robot interaction.

Figures 7, 8 and 9 illustrate the behaviors that were executed by robots during the foraging of three boxes in experiments 2, 3 and 4 (rows 5 and 6 of tables 2, 3 and 4). These experiments lasted for 14'47", 9'05" and 6'02".

In experiment 2 according to figure 7, the number of fails -the triggers of behavior line up and push box that did not succeed- is important. There are less attempts that did not succeed in experiment 3 as indicated in figure 8. In addition to the problems of coordination that were discussed, a robot may loose boxes for other reasons such as an instability problem caused by box placements and boxes out of the sight of robots.

Collisions between robots disappeared in experiment 4 when we introduced communication, as we can see in figure 9. This figure shows also that synchronization avoids useless movements of p03.

Is communication essential to achieve multi-robot coordination? In experiments where robots did not communicate, when an individualistic foraging robot met a partner, it reacted as if it were an obstacle. However, when they met while pushing a box they ignored themselves and collide.

A thorough coordination of the actions executed by robots may avoid these situations, as we can see in experiment 3. We think, however, that parameters tuning should ease by communication. Thus, we conclude that communication is desirable for achieving collective actions, even if communication is not necessarily achieved in a direct form.

5 Conclusions

We described our research in collective robotics applying an intuitive approach. Four experiments of foraging robots in single and multi-robot contexts were presented. We conducted these experiments naively, a problem was defined and a number of hypothesis -apparently obvious- were formulated, explored and demonstrated experimentally, analyzing the outcomes of several tests.

We consider that this approach is useful when analyzing multi-robot coordination strategies. The main contribution of our experiments is that the requirements of a multi-robot system were detected experimentally, rather than imposed a priori by designers.

Future work will focus on extending our box-pushing mechanisms to deal with collective box-pushing, a task involving the joint efforts of a robot colony.

Appendix

Description of behaviors used in the experiments (for more details see [8]):
**Fig. 7.** Behaviors of two individualistic foraging robots

**Fig. 8.** Behaviors of two spatially coordinated foraging robots

**Fig. 9.** Behavior of two spatio-temporally coordinated foraging robots
- **Wander.** The robot explores its environment randomly avoiding obstacles. Robot moves at a speed of $250 \text{mm/sec}$.
- **Line up.** The robot aligns itself with a bar code and stands in line.
- **Push towards store.** The robot pushes a box detected in front by its sonars. Robot pushes in a straight line at a speed of $100 \text{mm/sec}$ until it is at a given distance from a given bar code.
- **Wait.** The robot remains at the same position.
- **Surround box.** The robot goes towards a box and moves to the opposite side of the bar code side. Robot moves at a speed of $200 \text{mm/sec}$.
- **Send a message.** The robot sends a message to a given robot. Robots communicate via sockets, transmitting simple messages such as “box”.

**References**