Coordination of multiple mobile robots in an object carrying task using implicit communication

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Abstract— This paper addresses the problem of coordinating multiple mobile robots in a tightly coupled task by means of implicit communication. This approach allows the development of controllers that do not depend on any explicit data flow between the robots, thus relying only on local sensor information. A box-carrying task is used to validate the proposed methodology both in simulation and in real-world experiments. Results show that implicit communication can be used together or replacing explicit communication for the cooperative box carrying task, making the system more robust to faulty communication environments.

Keywords— cooperative robotics, implicit communication, tightly coupled task

1 Introduction

Coordination of multiple mobile robots in tightly coupled tasks has recently been implemented in a distributed way. Rus et al. [1], for instance, use a group of mobile robots to push and place pieces of furniture. Another example is given by Chaimowicz et al. [2], who present an hierarchical architecture to coordinate mobile manipulators in a box carrying task. However, most of the known distributed approaches have been shown to be highly dependent on inter-robot communication, generally used to exchange control messages and local sensorial data.

Communication between cooperative agents can be regarded as either *explicit* or *implicit*. *Explicit communication* is defined as an specific act designed solely to convey information to other robots on the team [3]. Examples of cooperative tasks where this type of communication is used can be found in several papers [1, 2, 4]. On the other hand, *implicit communication* occurs as a side-effect of robots' actions, or through the way they change the environment. Implicit communication offers several immediate advantages over the explicit form. Among them are simplicity, robustness to faulty communication environments, lower power consumption, and stealthiness. Balch and Arkin [5] show that although communication significantly improves the performance of a robotic team, explicit communication is not essential when the implicit form is available. Still, more complex communication strategies offer little or no benefit over low-level communication. Khatib et al. [6] show a cooperative manipulation task in which inter-robot communication is achieved through the interaction forces sensed by each manipulator. Another example of implicit communication is given by Vaughan et al. in [7], where a group of mobile robots performing a foraging task communicates by leaving landmarks in the environment. More recently, Stiwell and Bishop [8] have presented a theoretic approach showing that the amount of explicit communication can be reduced by the use of the implicit form. The framework has been validated using a group of simulated underwater vehicles which maintain tight formation by inferring distances from each other through the acoustic vibrations produced by their thrusters.

This paper addresses the problem of coordinating multiple mobile robots in a box-carrying task. Depending on the robots kinematic constraints, and on the configuration observed between them and the object, complex situations — such as the truck-trailer backing problem [9] — may arise. To avoid this problem, the proposed methodology implements a dynamic leader-follower architecture, where the leading robot — assigned in real-time — is responsible for guiding the group through the environment. Leadership exchanging is dealt via implicit communication, which takes advantage of the controllers full dependency on local sensor information. Experiments with simulated and real robots with restricted communication capabilities show that simple implicit communication strategies provide similar performance levels when compared to robotic teams working with more complex communication systems.

The remainder of the text is organized as follows. Section 2 describes the problem to be tackled in this work. In Section 3, the used methodology is presented. The results of the experiments, both with simulated and real robots are shown in Section 4. Finally, the main points of the paper are summarized and discussed in Section 5.

2 Problem Statement

The more general problem to be tackled here is the coordination and control of multiple non-holonomic mobile

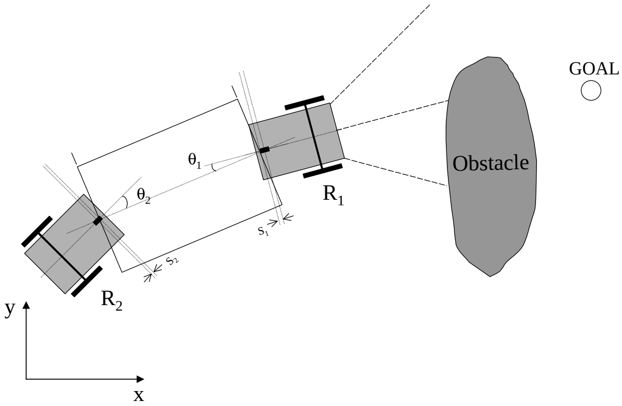

Figure 1: Two nonholonomic robots carrying a box in an unstructured environment. The robots are able to sense both the linear (s_i) and angular (θ_i) box displacements.

manipulators handling rigid objects in an unstructured, dynamic environment. It is also considered that explicit communication among the robots is limited and sometimes even unavailable. Non-holonomicity imposes additional kinematic restrictions to the group when previously unknown obstacles (common to dynamic, unstructured environments) need to be avoided. The use of rigid objects simplifies the problem since deformation does not need to be considered and force information can be directly transmitted from one robot to the others.

Specifically, a simpler situation where two robots must carry a large box from one point to another in an unknown environment is considered. In order to maintain appropriate grasp of the box, the robots must use some force-sensitive mechanism, such as the compliant arm presented in [10]. The robots can localize themselves in the environment through built-in proprioceptive and exteroceptive sensors. Exteroceptive sensors such as vision or sonar rangers are also used to detect close obstacles. Figure 1 depicts this scenario.

The kinematics of the robot-box-robot configuration shown in this figure is very similar to the multiple degree of freedom, mobile robot with compliant linkage system implemented by Borenstein [11]. The box, the displacements (s_1 and s_2) and the angles (θ_1 and θ_2) can be viewed as the compliant linkage between the robots. In his work, Borenstein points out that the centralized control of the whole system is rather difficult, mainly because it involves adjusting the link length by controlling four independent motors. Other authors such as Kosuge and Oosumi in [12] and Sugar and Kumar in [4] have addressed similar problems in a distributed way, showing that the distribution of the control laws makes the problem easier to be solved.

Perhaps, one major difficulty to control the mobile manipulators in an unknown environment is obstacle detection and avoidance. Depending on the configuration, the group may not be able to fully avoid the obstacle without dropping the box. In such situations, the robots must move backwards mainly due to the sensors' limited range and the ensemble kinematics. If the leading robot (R_1 in Figure 1) detects an obstacle and simply moves backwards without first communicating its intention to the other robot (R_2 in Figure 1), the control problem degenerates to the truck-trailer backing problem, which is a known open-loop unstable system [9]. A simple way to avoid that problem is to adopt a dynamic leader-follower architecture such as the one presented in [2]. Using such an approach, robot R_1 is initially set as the team leader, being able to transfer the leadership every time the group needs to move backwards. The truck-trailer backing problem is avoided, since the leading robot is always moving forward.

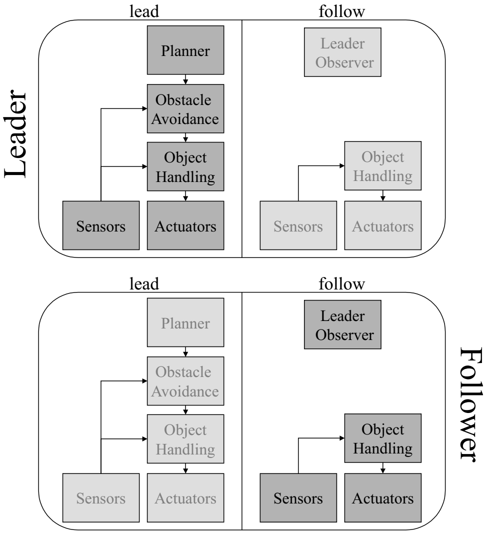

Figure 2: System architecture. The darker side represents the active robot controller. When the *lead* controller is active, the robot guides the ensemble. On the other hand, the *follow* controller is only concerned with the box grasping.

The main contribution of this paper is the development of a hierarchical methodology where the leadership exchanging is achieved by means of implicit inter-robot communication.

3 Methodology

The methodology presented here is based on a hierarchical architecture composed by one leader, that commands the team towards a predefined target, and the followers, that try to keep an appropriate grasp on the object. For the specific situation of two robots carrying a box, it is assumed that only the *Leader* knows the target position. Thus, in order to complete the task, the same robot must start and finish as team leader. The *Follower*[1] only leads the group during short time periods when the ensemble must move backwards. Hence, a new concept of *leadership lending* can be observed: the *Leader lends* the authority to the *Follower*, which must *return* it after

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[1] Through the remaining of the text, the innate leader (R_1 in Figure 1) will be addressed as the *Leader*, while the other robot as the *Follower* — both in italic with initial capital letters.

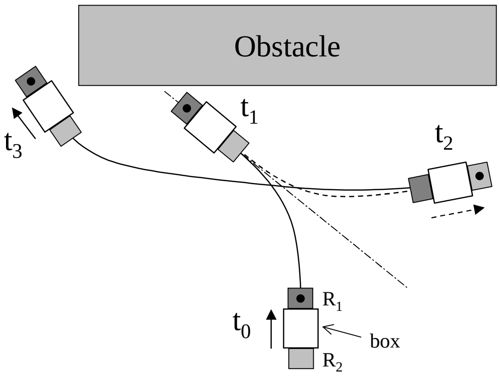

Figure 3: The *Follower's* (R_2) trajectory shown when it is driving the group (dashed line) and when it is not (solid line). The darker robot is the *Leader* and the lighter is the *Follower*. The robot with the black dot is the one currently driving the group. In t_1 the *Leader* lends the leadership, and in t_2 the *Follower* returns it. Observe that the heuristically determined mirrored trajectory traced by the *Follower* helps the group to avoid the obstacle.

a given time period or when *requested* by the *Leader*. The proposed architecture is shown in Figure 2. It can be seen that each robot has two basic control modes: *lead* (on the left) and *follow* (on the right). The switching between these two modes will be discussed later.

In recent box carrying methodologies, the controllers of the followers are highly dependent on the leader's position and velocity, which are transmitted via a wireless communication link. In the present work, communication is considered to be rather limited or sometimes unavailable, motivating the robots' controllers to be fully dependent on local sensor information. Hence, in the box carrying task, robot motion can be controlled as a function of its interaction with the object. In this way, the leading robot drives in a determined direction while the other robot tries to maintain the forces and torques applied to the object constant. Initially, the object is in equilibrium since the summation of the forces applied to it equals zero. When the *Leader* begins moving, the resultant vector points towards the direction of movement. At the same time, the *Follower's* controller commands it to move in a way to keep the force summation null. It can be seen from Figure 2 that the proposed architecture does not consider any explicit data flow between the robots: the basic controllers do not depend on each other.

Since the target position is unknown to the *Follower*, when it receives the leadership it does not know which direction to take. However, by having observed the *Leader's* path prior to leadership exchanging, the *Follower* may choose a "reasonable" trajectory. A simple heuristic which has experimentally proven to be rather efficient is to move through a mirrored trajectory of the *Leader* (Figure 3), which significantly improves the group's obstacle avoidance process. A good approximation to the *Leader's* trajectory is the *Follower's* own trajectory, since both robots are tightly coupled through the box. This trajectory can be easily estimated by local odometry. If this is not possible, due to some robot restriction (e.g. lack of memory or processing), to store the *Leader* trajectory, the follower can simply move backward maintaining its current absolute orientation. Although this may not lead to the optimal action, the ensemble would eventually avoid the obstacle.

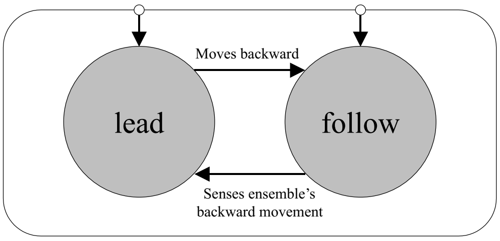

Figure 4: Implicit leadership exchanging mechanism between the two discrete modes.

Leadership lending is the most difficult task to be performed without explicit communication. Usually, common obstacle avoidance algorithms force the robot to move backwards when it is impossible to avoid an obstacle. Since this is the case at hand, when the *Follower* detects this movement pattern, it assumes that the *Leader* has temporarily resigned the leadership. A similar situation occurs when the *Follower* must relinquish the group's control. This mechanism is actually a form of implicit communication. Nevertheless, it can also be seen as a simple non-confirmation explicit protocol, since the robots may intentionally pass the leadership by moving backwards. However, this communication protocol is rather limited, since other messages such as leadership request are difficult to be conveyed. Movements to transmit leadership information other than those which compress the box might actually drop it. The robots behavior can be modeled as two basic discrete modes (Figure 4), each with particular controllers (Figure 2).

The following section presents results of several experiments executed in order to validate this methodology.

4 Experiments

In both simulated and real experiments, the robots move from an initial position to a goal carrying an object and avoiding obstacles in their path. As explained in the previous section, due to kinematic constraints and sensors limitations, the robots must exchange the leadership using explicit or implicit communication, in order to avoid the obstacle.

4.1 Simulated Robots

Before experimenting with real robots, a simulator(MuRoS [13]) was used to evaluate the task performance as the reliability of the communication system varies. MuRoS is a multi-robot simulator developed for simulating various types of cooperative tasks, ranging

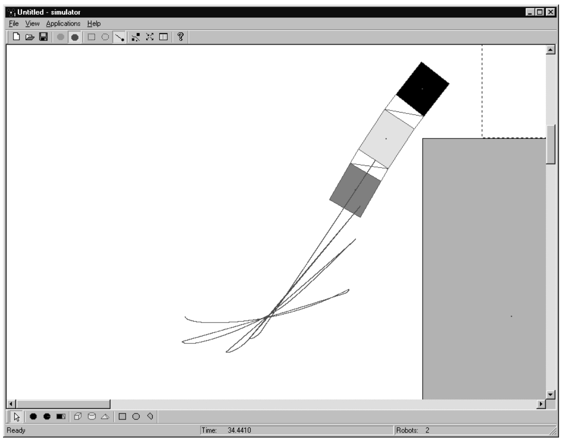

Figure 5: Snapshot of the box carrying simulation

from loosely coupled to tightly coupled. Implemented using object orientation in the MS Windows environment, MuRoS can be easily extended with the development of new classes and the implementation of new robots, controllers and sensors.

In the box carrying task, two non-holonomic robots equipped with a compliant arm (similar to the one presented in [10]) were simulated. Figure 5 shows a snapshot of the simulation, where the *Leader* is the black robot and the *Follower* is the dark gray one. A trace of the box position is also shown. The goal is located at the right corner of the screen, inside the dashed rectangle.

The communication models are the following: in the explicit communication, the robots exchange asynchronous messages, and failures are simulated by "losing" a percentage of these messages during transmission. An acknowledgment message is sent to confirm that a message was received and in case of failure, the sender transmits the message again after a timeout period. Using implicit communication, the leading robot simply starts to move backwards with constant velocity during a given period of time. The follower senses this movement through the compliant arm, and automatically takes the leadership.

The simulation time for two robots to carry a box from an initial position to the goal was measured. Both implicit and explicit communication were used and communication failures were simulated by increasing lost messages rate during execution. Figure 6 shows the task completion time using implicit and explicit communication, increasing the rate of failures in the transmission from 0 to 90%. For each point of the graph, 200 runs were executed and the arithmetic mean and standard deviation were computed.

As expected, the execution time increases when communication failures are also increased. As the robots use an acknowledgement/timeout mechanism, the total waiting time will be significant in faulty communication situations. Another important result is that the completion time using implicit communication is constant and similar to the time using explicit message exchange in a reliable environment. In this case, the performances are similar because explicit communication is used only to pass the leadership. No other additional information that could increase the performance, such as trajectory direction or leadership requests, are transmitted by the leader. Also, failures in implicit communication that could degrade the task overall performance are not being considered. In spite of these restrictions, the results show that implicit communication can be used together or replacing explicit communication in a cooperative box carrying task.

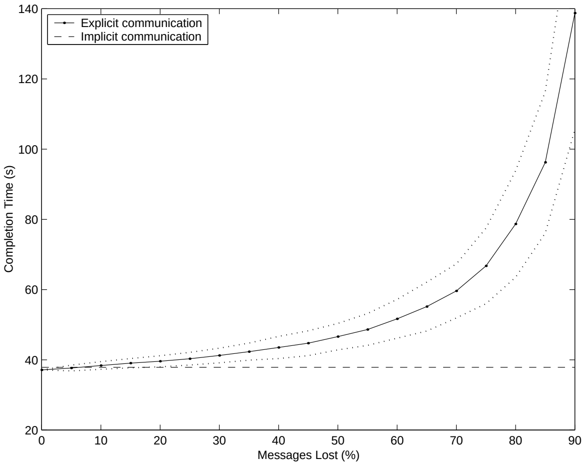

Figure 6: Mean completion time for implicit and explicit communication (solid line) and its variation (dotted lines), represented by the standard deviation.

4.2 Real Robots

The testbed consists of two small robots built from commercially available assembling blocks (Lego^{TM}), equipped with common off the shelf sensors, and low cost, simple, in-house-built imaging and communication systems. Figure 7 shows the VERLab's robots, *Manuelzão* and *Miguilim* named after two famous countryside characters immortalized by Guimarães Rosa, a famous Brazilian writer.

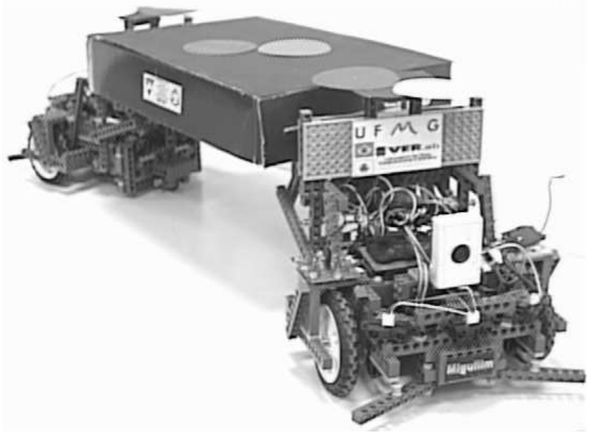

Figure 7: Miguilim and Manuelzão in a box carrying task.

The robots' control system runs on the Handy Board^{TM}. This board is based on a 52-pin Motorola MC68HC11 processor with 32K static RAM, four PWM outputs and 7 analog and 9 digital sensor inputs. Several types of sensors are installed on the robots, both for localization and interaction with the environment:

- Proximity Sensors – off the shelf Sharp GP2D15 infrared emitter/receiver sensors that enable obstacle detection in a distance range of 10 to 60cm;
- Contact Sensors – micro-switches mounted on Lego^{TM} blocks, used to detect obstacles that were not detected by the proximity sensors;
- Shaft-encoders – optical incremental shaft encoders, with 16 counts per turn, used for dead reckoning;
- Force Sensors – two force sensitive devices used when the robot is carrying objects. These sensors were assembled using springs and angular potentiometers, as shown in Figure 8.

Explicit communication between the robots is accomplished by a serial cable connecting the Handy Board serial ports in each robot. A cable is used in order to assume error free communication. This wired serial link can be used in tasks where the robots maintain approximately constant poses relative to each other, within a close distance, as is the case in this work, since the cable does not interfere with the ensemble dynamics. More details about the platforms can be found in [14].

In the experiments presented here, the robots were programed to transport a box from the origin of the coordinate system to the goal at position $(2.0\,\text{m}, -1.5\,\text{m})$ (see Figure 9). Furthermore, an obstacle was placed in order to create a typical avoidance situation. The proposed implicit communication methodology was compared to when the robots can communicate through a reliable, bidirectional point-to-point channel. The same box grasping algorithm was used in both cases. The main differences are that, with explicit communication, the *Leader* can inform the *Follower* the path to be followed and also request the group leadership when it is able to resume its task. Figure 9 shows the box trajectory with the robots using implicit communication. The data was obtained through an overhead vision-based ground-truth system. Notice in this figure, the presence of two situations of leadership lending.

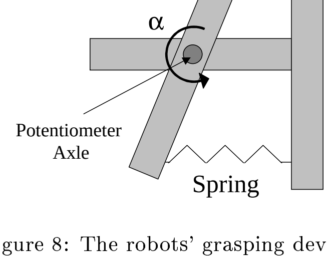

Figure 8: The robots' grasping device.

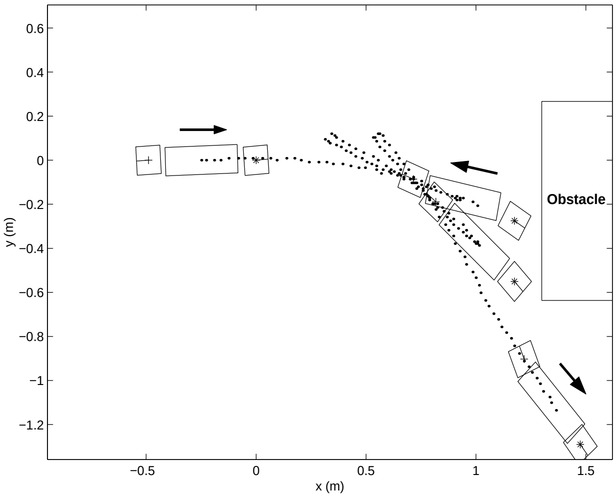

Figure 9: The robots negotiating obstacles using implicit communication. The points represent the box trajectory.

Table 1: Tests results

Communication	Successes (%)	Locks (%)	Failures (%)
Explicit	100	0	0
Implicit	80	12	8

Table 2: Completion Time

Communication	Time of Success (sec)
Explicit	(54.50, 1.37)
Implicit	(55.49, 1.53)
t-test	t=1.76, ν=26

Table 3: Localization Error

Communication	Localization error (cm)
Explicit	(12.70, 6.85)
Implicit	(8.20, 14.53)
t-test	t=1.11, ν=30

Table 1 shows the results for this test. It can be seen that, with explicit communication, the robots successfully complete the whole task in all trials. On the other hand, the implicit communication case presented *locks* and *failures*. Locks occur when none of the robots sense the backward movement, therefore leaving the ensemble with no appointed leader. In this case, the (innate) *Leader* assumes the leadership after some time and drives the group to the goal, but the completion time is compromised. Failures occur mainly due to the *Follower's* poor estimation of the *Leader's* trajectory, which makes the group to move in a wrong direction. It is important to notice that, despite the unsuccessful situations, the box is not dropped.

Table 2 shows the completion times with both explicit and successful implicit communication cases. The data is expressed as (mean, standard deviation). The bottom line represents the results of the Student t-test performed on the above pair. This statistical test is used to evaluate whether two groups of data are significantly different according to their means. The null hypothesis of the test proposes that the implicit and explicit communication results do not differ significantly, while the alternative hypothesis proposes that the results produce different distributions. The computed t rejects the null hypothesis with a confidence level of 0.95 ($t_{0.95} = 1.72$), indicating that explicit communication presents slightly better results.

The results presented in Table 3 are relative to the robot's positioning error at the end of the task. Those measurements were made in order to shown that implicit communication does not hinder the group from completing the mission. The t-test shows that both methods have similar distributions with a confidence level of 0.95 ($t_{0.95} = 1.70$).

Results from Tables 2 and 3 show that in the absence of failures in the implicit communication form, its performance is similar to the explicit one. It is also important to notice that in lock situations, the task was still completed, although with a higher completion time. Thus, only in 8% of the trials (failures) the robots did not complete the task, due to poor trajectory estimations. If completion time is not a severe restriction, the ensemble could simply move straight backwards during the maneuvers, and then avoiding such failure situations. These results show that implicit communication can successfully replace the explicit form, for the box carrying task.

5 Conclusion

This paper addressed the problem of coordinating multiple mobile robots in a tightly coupled task by means of implicit communication. The concept of leadership lending was introduced and used in order to simplify the control problem. Results from both simulated and real-world experiments showed that implicit communication can be used together or replacing explicit communication for the cooperative box carrying task, making the system more robust to faulty communication environments. However, it is important to notice that this replacement could only be done for this specific task because only simple information is exchanged between the robots. In other situations where more complex data must be transmitted, implicit communication mechanisms may be harder or even impossible to implement. Future works include investigating the applicability of this methodology for other tightly coupled tasks (e.g. object pushing, assembling).

Acknowledgments

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