A SIMPLE TESTBED FOR COOPERATIVE ROBOTICS

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Abstract— This paper presents a simple, low cost robotic system built from off the shelf sensors and components, designed to perform a series of cooperative tasks in general and *tightly coupled* tasks in particular. A tightly coupled task can only be completed through close interaction of a minimum number of robots (e.g. carrying a box otherwise impossible to a single robot). The several subsystems are briefly described and some experimental results are presented, showing that it is possible to overcome the various restrictions of these platforms and still implement relatively complex cooperative behaviors.

Key Words— cooperative robotics, Lego robots, tightly coupled tasks

1 Introduction

Cooperative robotics usually involves using multiple autonomous agents in coordination to achieve a common goal. The joint action of simple, heterogeneous robots should theoretically produce more efficient results when compared to a single, more complex, specialized robot (Arkin, 1999).

The main goal of a cooperative system is to carry out a task in a way to improve its overall efficiency or even to allow it to be completed at all. *Loosely coupled* cooperation takes place when the main goal can be equally distributed amongst a team of robots, using a strategy similar to divide and conquer. For instance, if the task at hand is to explore an unknown environment, it could be more efficiently accomplished by partitioning the area to be covered among the team members. The failure of one or more robots should not compromise the main goal (but probably increase the total exploration time), provided that there were enough units to finish the job. On the other hand, if a task can only be completed through the interaction of a minimum number of robots, it is called a *tightly coupled* task. For example, a single robot is not able to carry a heavy, large box if it doesn't have enough power or grasping ability. Given the team capabilities, this tightly coupled task could only be satisfactorily completed by close interaction of a number of robots.

There are several advantages of cooperative, multi-robot systems (Parker, 2000). The key features are: better performance, lower individual complexity, possibility to allow remote sensing and information sharing, and fault tolerance through agent redundancy. However, there are also many drawbacks such as: physical collisions during navigation and interaction, difficulty in coordinating distinct, simultaneous actions, and lack of inexpensive, reliable inter-robot communication devices.

Most successful existing systems usually apply advanced, high cost, specialized platforms, with high sensing and processing capabilities. However, cooperative behavior can also be accomplished by simpler, less complex systems, provided a certain degree of sensing and processing capabilities is available.

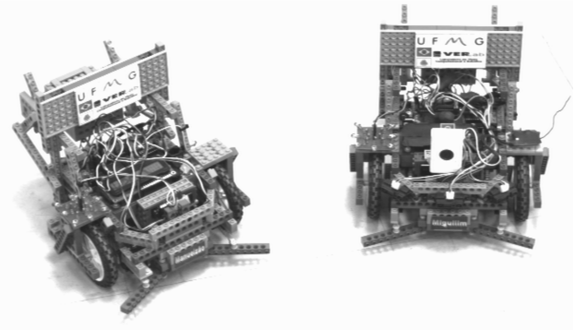

Figure 1. Manuelzão (on the left) and Miguilim, two of VERLab's cooperative mobile robots.

The present work describes a simple testbed for implementing and evaluating a series of cooperative tasks. The system consists of a few 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. Fig. 1 shows two of VERLab's robots, *Manuelzão* and *Miguilim*, named after two famous country side characters immortalized by Guimarães Rosa, a famous Brazilian writer. The development of these devices is described in detail and some control strategies are validated through a series of real world experiments. Moreover, one of the main objectives of this research is to understand and evaluate the limitations imposed by a simpler, restricted system on the performance of cooperative tasks.

The text is organized as follows: Section 2 reviews some of the most relevant related projects currently under development. Section 3 describes the design methodology, with its basic assumptions, advantages and limitations. Section 4 describes the system and each of its individual modules – mechanical assembly, controller, sensors, communications – in detail. Some representative experimental results are discussed in Section 5, and basic conclusions and future directions presented in Section 6.

2 Related Work

There has been significant work in cooperative robotics, with its applications, technological advances and open problems being explored in physical and simulated systems (Parker, 2000). There are not, however, many known systems developed from inexpensive, rapid assembly components as the present one.

Rybski et al. (1998) present a group of simple, Lego^{TM} based robots, with limited sensing capabilities, used in a search and retrieval task. The ability of the system to complete the task in a limited amount of time is quantitatively evaluated with regard to the number of robots, complexity of the environment, and distribution of targets. Although loosely coupled cooperation exists, the robots are not explicitly coordinated in order to better perform the task, nor do they use any kind of communication to exchange useful information. Lego^{TM} based robots were also used during the RoboCup Jr. competition (Lund and Pagliarini, 2000), where user-guided behavior-based controllers allowed inexperienced users to create complex behaviors for a robot soccer competition. Primitive behaviors were previously integrated in the system enabling fast development of working robots by non-experts.

Cooperative tasks, such as the ones explored in this paper, have been extensively explored. Loosely coupled tasks usually deal with cooperative mapping, exploration and localization. Alur et al. (2000) presented a team of mobile robots with considerable processing capabilities performing several tasks such as localization, target acquisition, cooperative mapping and formation keeping in unstructured environments. The only sensor used by each agent is an omnidirectional on board camera, through which they could estimate their position relative to each other and to nearby obstacles. Cooperation between highly heterogeneous robots was also reported for pose estimation tasks (Vaughan et al., 2000), where an autonomous helicopter uses its vision system to detect a moving ground robot. Based on GPS pose information sent by the ground robot, the helicopter captures two different instances of the ground robot's trajectory to estimate its own current location.

Tightly coupled cooperation is usually verified in tasks such as object transportation. Sugar and Kumar (1999) presented two heterogeneous robots capable of coordinately carrying a large, heavy box while maintaining a specified formation. One of the robots – the follower – has a force sensitive manipulator while the other – the leader – only relies on a fork-lift arm with no force sensing. While the follower is built on a non-holonomic platform, the leader is an omnidirectional robot (Nomad XR4000), which highly increases the group maneuvering flexibility. The robots communicate their trajectories via a wireless Ethernet with the follower compensating dead reckoning errors by adjusting the forces applied by its compliant arm. A third robot can be added to the team to act as a scout, locating nearby obstacles and communicating improved trajectories to the carriers.

In this paper, some experiments somewhat related to the above research have been implemented, in order to evaluate the impact of simple non-holonomic platforms on the overall system capability.

3 Methodology

The application of simple, in-house built solutions to build relatively complex systems is one of the main motivations to this work. The devices presented here evolve from the authors' previous experience in projects such as robotic soccer, and undergraduate robotics competitions. The MIneiROSOT (Campos et al., 1998) robotic soccer team, uses simple mobile robots remotely coordinated by a vision-based control system running in a workstation. Further, internal robotics competitions allow undergraduate students to rapidly build small robot systems using Lego^{TM} components, simple processing units and off the shelf sensors and actuators. The tasks involved usually require a certain knowledge of structural mechanics, instrumentation and basic control theory.

This background motivates building somewhat more complex robots, using better sensors, actuators and devices available in the laboratory, to implement cooperation and other complex behaviors. The key idea is to evaluate control strategies previously implemented in complex, robust robotic systems (Chaimowicz et al., 2001), on much simpler Lego^{TM} based platforms. Furthermore, it is this research's objective to verify what aspects of cooperative behavior may be observed on simpler, low cost platforms, and what is the influence of the limitations of this restricted systems on the overall task performance.

4 System Development

This section briefly describes the system implementation and its main modules: mechanics, controller, sensors, vision, communication and vision based ground-truth. Initially, two 30×25 cm mobile robotic platforms were constructed, each with some of the characteristics described in the following subsections. Although the robots are both based on the same mechanical design, their use of on-board sensors is quite different, allowing for some degree of heterogeneity, at least at the sensors level.

4.1 Mechanics

As mentioned before the robots were assembled using Lego^{TM} building blocks. The blocks offer the possibility of rapid assembling and high flexibility, which makes them ideal candidates in proof-of-concept designs. Furthermore, a certain level of robustness and mechanical precision can be achieved. Although there are many design possibilities, the robots described here are based on wheeled differential driven platforms. The kinematic and dynamic models for these platforms can easily be derived similarly to the way discussed by Pereira et al. (2000).

Besides the locomotion subsystem, robot mechanics includes a supporting device with a platform and two force sensors which will be detailed in Section 4.3. This device is used when the robots must maintain an appropriate grasp on an object to be cooperatively transported throughout the environment (See Section 5.3).

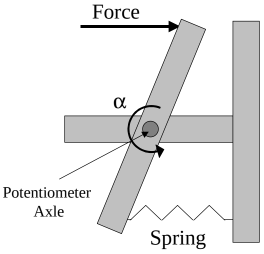

Figure 2. Force sensor implemented with a spring and an angular potentiometer.

4.2 Controller

The robots' control system is implemented on a Handy Board^{TM}. This board is based on a 52-pin Motorola MC68HC11 processor with 32K static RAM, a 16x2 character LCD, four PWM outputs and 7 analog and 9 digital sensor inputs. The board runs Interactive C, which is a multitasking version of the C programming language.

4.3 Sensors

Several types of sensors are installed on the robots, both for localization and interaction with the environment. They are:

- Proximity Sensors – off the shelf Sharp GP2D15 infrared emitter/receiver sensors that enable obstacle detection in a range between 10 to 60cm.
- Contact Sensors – common microswitches mounted on Lego^{TM} blocks, used to detect obstacles that for some reason (e.g. size, dynamics) could not be detected by the proximity sensors.
- Shaft-encoders – optical incremental shaft encoders, with 16 counts per turn, used both for dead reckoning and to determine the robot's velocity. The encoders were connected approximately midway in the gear train, to account for higher resolution and precision (more counts per wheel revolution).
- Ground Feature Detection Sensors – two infrared sensors located at the bottom of the robots, are used to detect landmarks on the floor, enabling the robot to determine its global position and orientation in the environment.
- Force Sensors – force sensitive devices used when the robot must carry, push or pull objects. These sensors were assembled using springs and angular potentiometers, as shown in Fig. 2.

4.4 Vision

The vision system adds many possibilities to the platforms, such as performing visual servo control, using natural or artificial features in the environment for pose estimation, visual tracking and monitoring, and teleoperation (when working together with a radio control module). The system uses a monochromatic battery powered microcamera to capture the scene in front of the robot. Since the Handy Board lacks the desired requirements for efficient real-time image processing, the robot uses a radio frequency link to send the video signal to a remote computer that further processes the data and sends back to the robot the required information (e.g. control commands, position and orientation). This is achieved by using a 900MHz audio/video transmitter on the robot and a receiver connected to a frame grabber in the remote computer.

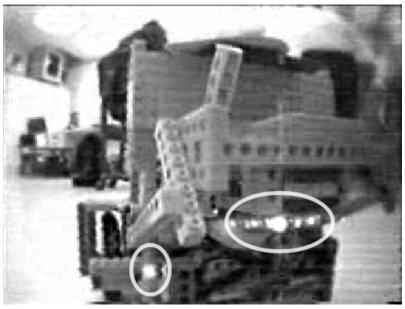

Figure 3. One robot as "seen" by the other. The elipses show both the infrared proximity sensor reflection (left) and the infrared communication transmitter (right) perceived by the microcamera's CCD.

Fig. 3 shows a single frame of a leader following task (see Section 5.1), where the follower is able to "see" and track its leader. It is interesting to notice that the microcamera's CCD is sensitive to infrared frequencies, allowing the human eye to perceive the infrared communication pulses, as well as the reflection of the infrared proximity sensor on the leader robot (bright spots in Fig. 3).

4.5 Communication

There are currently three communication modalities implemented in the platforms: 1) unidirectional radio link between a remote host computer and the robot, 2) bidirectional infrared, and 3) bidirectional wired serial links between the robots.

The unidirectional radio link is basically used to send data (e.g. commands, pose information) to the robots from an external host computer. This system is built from R/C model components with one additional microcontroller (Microchip PIC16F86) used as an interface for the R/C radio signal. The information is encoded at the source using Pulse Width Modulation (PWM) and is sent by the R/C transmitter in continuous pulse streams. However, due to time restrictions of the microcontroller in the interface between the remote computer and the radio transmitter, the data is quantized into 256 values. At the robot, another device based on the same microcontroller extracts the pulses from the radio receiver and makes them available to the Handy Board. The host computer and the transmitting microcontroller communicate through the RS232 standard protocol, while the Handy Board and the receiving microcontroller use a simple synchronous parallel protocol. A block diagram of this subsystem is shown in Fig. 4.

The bidirectional infrared system is used as a point-to-point communication link between two robots or as a broadcast channel from one robot to the group. The built-in infrared sensor component of

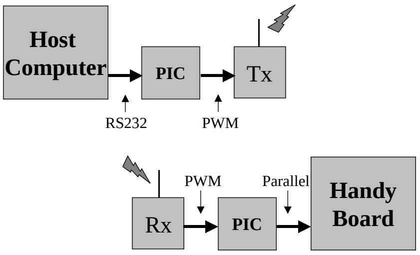

Figure 4. Radio communication system block diagram.

the Handy Board is used as the receiver, while the transmitters are constituted by a set of eight infrared LEDs disposed omnidirectionally on a printed circuit board. Each robot is equipped with two sets of transmitters, one at the front and another at the back of the structure, in order to overcome line-of-sight problems inherent to wireless infrared transmission. Furthermore, in order to improve the communication efficiency, the emitters are powered by an independent 9V battery pack, which offers higher power than the built-in Handy Board power source.

The wired serial link can be used in tasks where the robots maintain approximately constant poses relative to each other, within a close distance. It simply uses a serial cable connecting the Handy Board serial ports in each robot to create a reliable, bidirectional point-to-point communication channel. Virtually any data type can be sent through this link, what makes it an important feature when tightly coupled cooperation, physical interaction and a higher degree of coordination are involved.

4.6 Vision based ground-truth

In order to validate the models and experiments, reliable global localization is needed to supply ground-truth information. The system used here is composed by a color CCD camera and real-time vision software, developed at VERLab (Campos et al., 1998). The vision software receives as input a sequence of images containing the robots, which are identified with a specific mark (see Fig. 5). The software firstly determines the center of each color circular patch and then computes the orientation of their centroids. The system is then able to output the position (in pixels) and orientation of the robots, at frame rate (30 Hz).

One disadvantage of this system is the limited field of view of the camera. Although the robots are free to move about an extended region, during the supervised tests their working space must be limited to approximately 4.0 m^2 (which is the camera's effective viewing area for the maximum height allowed in the lab), so that the software may be able to continuously keep track of them.

4.7 System Restrictions

One of the goals of this project is to understand and quantify the influence of sensor, processing and mechanical limitations on the ability of the robots to perform the proposed tasks. All of them have some impact on the overall flexibility and efficiency of the platforms.

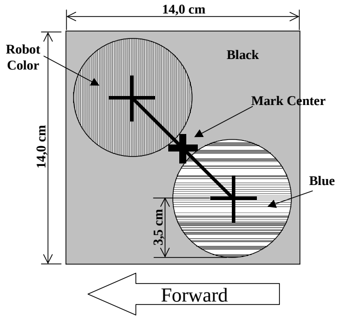

Figure 5. Mark used by the vision based ground-truth system.

The Lego$^{\text{TM}}$ structure, although easy to assemble and modify, is rather elastic, allowing high clearances on the mechanisms, gears and axes. This may imply on unpredictable modeling errors, specially when dead reckoning techniques are used for robot localization.

The bidirectional infrared communication system is rather unreliable, even with the improvements described in Section 4.5. Its short range, low power link has very limited bandwidth and the infrared signal is sensitive to lighting conditions and interference. Still, infrared transmission will always need an occlusion-free line-of-sight to enable point-to-point communication.

The Handy Board lacks memory space, specially if one wants to keep track of the robot's previous states and variables. Also, its low frequency sampling rate makes it difficult to implement basic controllers which depend on higher frequency data, such as motor mounted shaft encoders.

Nevertheless, as it will be shown next, the platforms are able to effectively perform several cooperative tasks and implement relatively complex behaviors, which are normally accomplished with high end mobile robots.

5 Experiments

A set of experiments has been devised to verify the ability of the proposed system to implement basic, cooperative behaviors. Some examples of both loosely and tightly coupled cooperative tasks are presented, such as simple leader following and box pushing with remote sensing, and box carrying with obstacle avoidance, respectively. The robot's local sensors are used as inputs to the controllers and the vision based system is applied to validate the models.

5.1 Leader following

Although it may look rather simple, the correct execution of this kind of task is very demanding in control and sensory issues. It can be very useful in practical applications, where heterogeneous robots may use their teammates' information to determine or even improve their own state estimate (Vaughan et al., 2000; Roumeliotis and Bekey, 2000). In this experiment it is assumed that one of the robots has a global localization scheme (leader), while the other

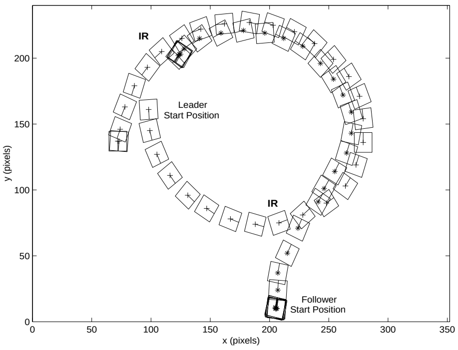

Figure 6. The leader following task. The leader is marked with crosses (+) while the follower is marked with asteriks (*). Infrared communication, performed at the "IR" symbol, is used by the leader to start and finish the task.

can only rely on its local sensors (follower). Whenever the follower wants to go to a specific location, it has to follow the leader, who actually has the ability to locate the goal. The leader function is played by Manuelzão, who is able to globally localize itself in the environment with the ground feature detection sensors. Miguilim acts as the follower, only relying on its infrared proximity sensors to keep the right distance to its teammate.

Robust tracking systems are usually vision-based (Hanek and Schmitt, 2000; Jung et al., 1998) and are able to extract several useful information from the scene. Here, however, all the tracking will be performed through the readings of the three infrared proximity sensors on the follower. This (much) simpler scheme lacks the ability to distinguish the leader from other objects within the follower's sensors range. Yet, this drawback can be improved by simply having the robots communicate their intentions of movement, which is subject to future work.

Fig. 6 shows the trajectories executed on the leader following task, with the follower holding still until the leader passes by it and sends an infrared message to begin the movement. The leader then follows its desired heading with the follower keeping up within a certain distance. This process goes on until the leader reaches the goal and informs the follower, that stops at the desired position. As said before, a view of the follower's on-board camera at the exact moment of infrared communication is shown in Fig. 3.

5.2 *Box pushing with remote sensing*

In this task, a large, heavy box must be pushed from a start position to a specified location in the environment. The box can be pushed by a single robot, but due to its heavy mass (compared to that of the robot) there is significant slippage on the pusher's wheels. This makes the use of dead reckoning techniques prohibitive, and suggests the implementation of some other way to evaluate the pusher's position.

To achieve the goal, the pusher needs help with its localization process. This help is provided by an *observer* robot, whose main function is to maintain itself aligned to the box, within a close distance. This time Manuelzão acts as the pusher, and Miguilim as the observer. As the pusher tries to lead the box to the desired position, the observer remains close enough to follow approximately the same path as its teammate. The pusher cannot rely on its encoders, but the ones in the observer should provide a reasonable approximation of the team's location. As the observer travels the desired distance, it sends an infrared message to the pusher, and both stop at the goal (which would be otherwise impossible to be accomplished by the pusher alone).

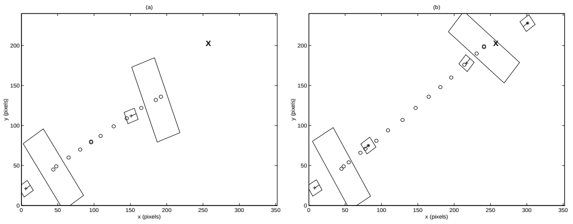

Figure 7. The box pushing task with (a) one robot alone, and (b) the help of a remote sensor. The pusher is marked with crosses (+) while the observer is marked with asteriks (*). The circles represent the box trajectory and the X represents the target.

The cooperation is thus achieved at sensor level, as the pusher uses the observer's encoders to localize itself. Fig. 7 shows the initial and final positions of both the pusher alone and the team during this goal directed box pushing task. It can be easily noticed that the task is correctly accomplished with the help of the observer robot.

5.3 *Box carrying with obstacle avoidance*

Carrying a box is considerably more complex than simply pushing it to the goal, since there must be coordination between the robots while moving in a unstructured environment, performing some level of obstacle avoidance and still keeping the appropriate support to the object. All maneuvers are restricted by the readings of the force sensors, specially considering that both platforms are non-holonomic, as opposed to previous work by Sugar and Kumar (1999), where one of the robots is omnidirectional.

The leading robot (Miguilim) guides the team through the area, using its infrared proximity sensors to avoid nearby obstacles, with the helper (Manuelzão) simply trying to keep up, controlling its orientation and velocity to maintain its force sensor readings aligned above a certain threshold. The leader limits its heading corrections by the values of its force sensors, to better accommodate the box. On the other side, the helper uses a highly reactive controller, always trying to keep the box safely supported.

Fig. 8 shows the group trajectory through the constrained environment, smoothly dodging nearby obstacles. It is important to notice that simply avoiding obstacles does not present much of a challenge for the leader alone. A highly constrained environment could easily be traversed by its reactive controller. What makes this task difficult is that the leader's reactions are limited to certain values to avoid dropping the box. A typical configuration for this task is shown in Fig. 9.

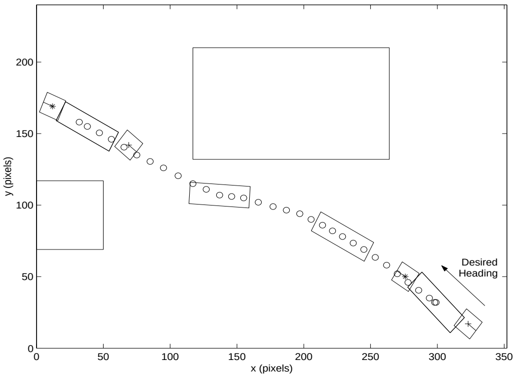

Figure 8. Two robots carrying a box while avoiding nearby obstacles. The leader is marked with asterisks (*) and the helper is marked with crosses (+). The circles represent the box trajectory.

6 Conclusion

This paper presented simple, low cost mobile robotic platforms able to perform a series of cooperative tasks. When compared to powerful, complex, commercial systems, one may see that the proposed testbed performs well in the applications evaluated here, even with the (various) known limitations. It may be stated that by improving sensor characteristics, memory capability and communication features, it may be possible to overcome some of these drawbacks.

The authors are currently working on visual servo control on one of the robots, with remote processing being performed by either a workstation or the Nomad 200 mobile robot. In this task the cooperation would be achieved at the processors level. The Nomad 200 could also be involved in tasks of cooperative localization, where the small robots would try to improve their pose estimates by using their teammates's own estimates, and the knowledge of relative position obtained by the Nomad 200 vision system. By relying on the serial wired communication link, it might be possible to implement robust layered architectures for tightly coupled cooperation and dynamic role assignment as the one proposed by Chaimowicz et al. (2001).

The full details of the platforms and the experiments presented here, including compressed video files, are available in the homepage of the project: `www.verlab.dcc.ufmg.br/coop`.

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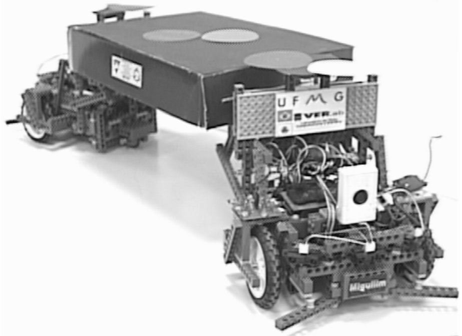

Figure 9. Miguilim helped by Manuelzão carrying a large box.

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