

Ad Hoc Networks of Cooperative Robots

A First Impression of a New Research Project

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Isaac Asimov's Three Laws of Robotics

1. *A robot may not injure a human being, or, through inaction, allow a human being to come to harm.*
2. *A robot must obey the orders given it by human beings except where such orders would conflict with the First Law.*
3. *A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.*

Introduction

Robots can be used in a wide variety of scenarios, including hostage situations and search and rescue missions. They are particularly suitable to deal with dangerous tasks such as the investigation and disposal of explosive materials. The use of robots reduces risk to human soldiers, especially in urban warfare. Therefore, the US military spends some 340 million dollars every year on ground-based robots [Source: United Press International 2007].

There are many definitions of what is called a robot. These definitions range from “machines that can perform complicated tasks automatically or by remote control” to “devices that are capable of performing a number of human tasks”. Although robots that are human-like or soldier-like may be very useful, and probably will participate in fighting on battlefields in the near future, our current research focuses on robots that are *not* human-like. Simple robots that move by wheels can in most cases do simple jobs equally well as complicated and expensive human-like robots.

The well known Asimov’s Three Laws of Robotics may be very useful for general purpose robots, but for military applications we want to replace these laws by the following laws:

Three Laws of Robotics in Military Applications

1. *A robot may only injure a human being if that human being poses a threat to “us” (the owner of the robot) or our allies. [Note, however, that international laws forbid robots to use arms autonomously.]*
2. *A robot must obey the orders given it by the proper authorities.*
3. *A robot must protect its own existence as long as such protection is needed to fulfil his current assignment.*

We define robots as devices that are able to perform certain tasks *autonomously*, that are able to *communicate* with other robots and that are able to *build a certain model of their environment*, based on their own sensory observations and on observations obtained from other robots. The tasks that robots perform are based on their model of the environment and on orders the robots have been given by the proper authorities. Industrial “robots” that assemble cars for instance, do not fit this definition.

Ad hoc networks

One might think that robots that fit the above definition are very complex robots. It is our intention, however, to make the robots as simple as possible, and to incorporate any desired complex problem-solving capabilities by means of ad hoc networks that are formed by a (possibly large) number of robots. The minimum requirements for the (mobile) robots are that they must be able to accept an order from the proper authorities, to sense their environment, to find the place where they are needed, to fulfil a simple dedicated task, to report the success (or failure) in achieving the task and to share their observations with the other robots that are involved in the mission. A robot will have one type of sensor only or a suite of sensors that can easily be combined.

Compared to multipurpose robots, there are several advantages of using multiple dedicated robots that are specialized in a small number of tasks only:

- such robots can be small, cheap, robust and consume little energy;
- if another sensor is needed other robots can be brought into the scene. There is no need to modify any of the existing robots;
- if a robot is lost, only a few sensors are no longer available;
- some robots may need special protection, for instance against chemical agents. There is no need to protect all other robots;
- some tasks may be inherently too complicated for a single robot to accomplish.

A severe disadvantage is that these simple robots must be able to communicate. This makes them vulnerable because the communication signals may be intercepted or disturbed. For this reason the robots or groups of robots must be capable of working on their own for a longer period of time to avoid extensive long-range communication. So it is evident that the units must be able to act autonomously.

Cooperative robots

Several definitions of “cooperative robots” are possible (see eg. [CAO et al., 1997]). We adopt the definition of [Barnes and Gray, 1991] “joint collaborative behaviour that is directed toward some goal in which there is a common interest or reward”. Collective behaviour of robots is not the same as cooperative behaviour. In our view robots *decide to* behave collectively if that is needed to accomplish their current mission.

The scientific challenge is to design a system that is flexible enough to process data from all kinds of specialized robots, where the configuration may change all the time and even new robots may come into play. These new robots may have sensors that were even not known at the time of development of the system. This behaviour is very similar to computer networks (for instance the Internet), so a number of problems involving robots that appear in or disappear from a scene already have been solved in network theory. For an extensive overview and in-depth analysis of networks and structures of networks see [Newman, 2003]. The current research focuses on this aspect of the multi-robot systems. The networks of cooperating robots should try to build a common ontology, based on the observations of the robots. (An ontology is a model of the world; in this case a model of

the direct environment in which the robots operate). This is a challenging problem, because different robots may have sensors that measure completely different aspects of the real world, for instance some robots may detect chemical weapons while other robots may detect magnetic anomalies. Although this contribution concerns material robots, many mechanisms, such as coordination [Storms and Grant, 2006], are the same for networks of software robots (or better: software agents).

A few examples of recent military applications

Today, there are already many military applications for autonomous robots. There is a growing interest in cooperative robot systems. A well known underwater “robot” is the REMUS (Remote Environmental Monitoring Units) which is an autonomous unmanned submarine. The REMUS can carry a variety of sensors to meet the mission requirements. More than one REMUS can be used, all with different sensors if desired. In the near future, the REMUS will be equipped with technology that will allow the submarines to communicate with each other using underwater acoustic modems. A new philosophy of the US Navy and many other navies is to develop lots of cheap unmanned undersea vehicles (UUVs), because with many cheap UUVs it is not so bad if a few are lost during a mission. There is a growing interest in cooperative UUVs as well [Wernli, 2000].

Unmanned ground vehicles (UGVs) are already used for mine clearance and urban reconnaissance, but usually they are operated from distance (“teleoperation”). However network-centric autonomous ground vehicle systems are in development and already at the demonstration stage (e.g. see [Committee on Army Unmanned Ground Vehicle Technology, 2002]).

This year, a special issue of the International Journal of Robust and Nonlinear Control [Rasmussen and Schumacher, 2008] appeared, filled with papers on cooperative unmanned aerial vehicles (UAVs) in a military context. Combinations of cooperative UGVs and UAVs may prove to be very useful in unknown hostile environments.

An in-depth study of collaborative core technologies used in networks of autonomous robots together with many possible military applications can be found in a report of [Singh and Thayer, 2001].

Our current research

Within our research, we want to develop and test new algorithms and paradigms rather than constructing a completely new operational system. Therefore, it is not necessary to build full scale robots. Instead, our current research uses miniature robots and computer programs that emulate robots. Many of the problems that may occur with real, full scale robots can be solved and tested by simulations and by using miniature robots. By limiting ourselves to small scale robots and simulations, we are able to obtain many of the desired results much faster and cheaper than would be possible with full-scale robots. The current research started at the end of 2007, so we are not able to present scientific results yet. However, we have already implemented a working system for the determination of

mutual distances and orientations of the robots. This localization system is described in more detail after the next section.

The next step in the development of the system hardware will be the addition of sensors that can detect obstructions. Moreover, one of the robots will be equipped with a stereo-vision system so it will be able to explore the 3D world in its immediate neighbourhood.

Educational relevance

This research project is very well suited to be used for bachelor thesis projects of our Military Systems and Technology education. In particular the project assignment that is scheduled for the third year. Over the past two years, we have already had two groups of students working on a project involving cooperative robots. They used miniature mobile robots, so-called Boe-Bots (“Board of Education Robots”), which are software compatible with the so-called ARobots we use. The students equipped their robots with several sensors and communication provisions. They were able to develop software in several computer languages to make it possible for the robots to communicate wirelessly with another robot, with a personal computer notebook and even with a handheld computer. In the future, very interesting project assignments are possible, for instance projects where as part of a strategic scenario Boe-Bots must try to disturb the mission of the ARobots or try to help the ARobots. These kinds of “strategic games” are particularly interesting if the two groups do not know each others intentions. During these projects student can gain experience on Artificial Intelligence, Wireless Communication, microprocessors and in writing realistic computer programs.

Localization system

At the moment, we are building a number of test robots (see Fig. 1). These robots are equipped with a system to determine the position of the robots by means of sound. This is very similar to the determination of the position of submarines by sonar. Although in many cases a GPS system may be available, we must consider the possibility that this is not the case at the battlefield. Our tests with the model robots will often be conducted indoors, so we certainly cannot use GPS. GPS signals are too weak to penetrate buildings and standard GPS is insufficiently accurate for use with small robots outdoors.

The reason for the use of sound instead of radio waves, is purely because with the current state of the art in electronics it is impossible to obtain the time-resolution that is needed for centimetre-resolution using cheap and small electronics. When larger robots in the open field are used, it will be no problem to use radio waves, because for most real-world applications a position accuracy of several decimetres will be sufficient. Furthermore on larger robots the antennae can be placed at a larger mutual distance, thus increasing the time differences between the arrivals of the waves. In fact, radio waves in many ways will be simpler to use, for instance because very much higher update frequencies can be used and the speed of electromagnetic waves is much more constant than that of sound.

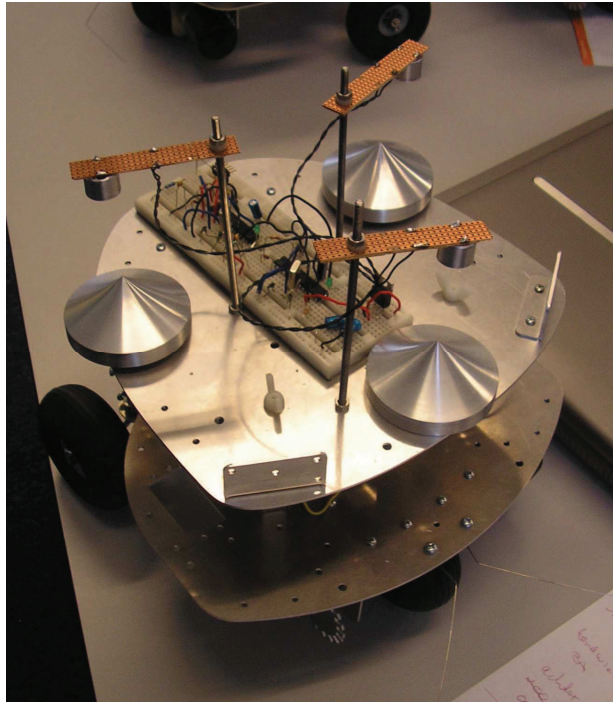


Figure 1. One of our – partially assembled – robots with three parabolic “ears”

A serious disadvantage in our employment of sound signals, compared to radio signals, is that sound can only be used if the robots move strictly on a plane surface. This is because most of the sound intensity produced by cheap 40 kHz transducers is confined to a cone of about 30° across, so many transducers would be needed to direct the sound intensity into all directions. This would make the system very complex and too energy-consuming. It is rather easy to direct the sound into all directions within one (horizontal) plane by using a reflective parabolic cone (see Fig. 2). Tests have shown that with this simple provision the sound intensity is still enough to be used up to about 10 m, which is about the maximum distance between the robots we will be using in our indoor test environments.

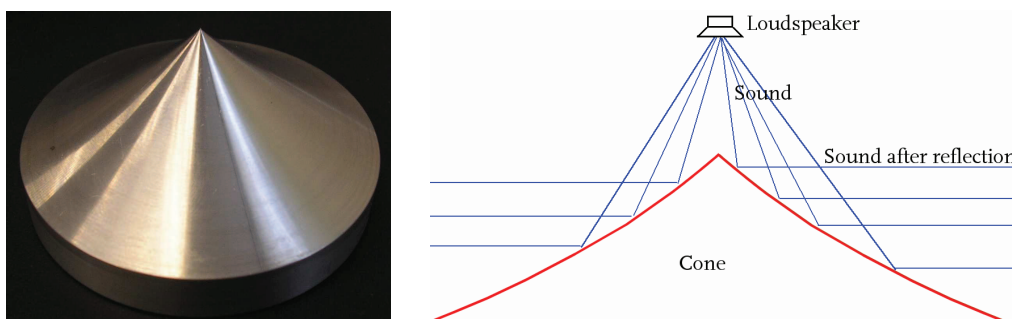


Figure 2. Left: parabolic cone made of hard alumina, used to spread the sound sideways. Right: principle of operation.

In the real world, there are several ways a robot can determine its absolute position, all of which may not be available when needed the most. If GPS is available things are simple, but the GPS can be jammed by the opposing force at any time or the signal may be lost when the robots for instance enter a dense wood. The position can also be deduced from the visual environment, for instance by cameras carried by the robots, or provided by an unmanned air vehicle. Sometimes it may be possible to make use of radio beacons as well.

We shall start developing a system that consists of an accurate sound beacon and “ears” on the robots to determine the position and heading with respect to the beacon or to another robot. The robots cannot determine their absolute position, but they can determine the relative position of other robots or beacons by the ultrasound system. If one of these objects is able to determine its absolute position all robots can calculate their absolute position as well.

The principle we use for the determination of the relative position is based on the successful Maxelbot Trilateration Project of the University of Wyoming (see for instance [Heil, 2004]). In short the system works as follows: a robot broadcasts a radio signal, containing one or several codes. The codes can be used for instance for an identification code or to address other robots. One of the robots reacts by immediately sending an ultrasonic beep signal. The first robot measures the differences between the arrival times of the beep at his three ears and the time the radio signal was broadcasted. With simple triangulation the first robot can find the position of the second robot. Then the first robot sends this position to the second robot, together with the radio signal. Although this robot now knows where it is according to the first robot, he still measures the position of the first robot with respect to itself.

Since both robots measure all positions with respect to their own coordinate system, the coordinates that the two robots find for each other’s position will be completely different. However, in the ideal case, these coordinates should describe the same *vector* in space, apart from a minus sign (see Fig. 3). So, by exchanging the measured position of the other robot in their own coordinate system, both robots are able to determine the position of each other’s coordinate system. If we take the positive X-axis always along the symmetry axis in the direction of the front every robot can make a fair guess about the heading of the other robots. There may be some small deviations because of inaccuracies and because of the small difference between the moments the measurements take place. Preliminary experiments show that an accuracy of about 1 cm is feasible using cheap electronic components.

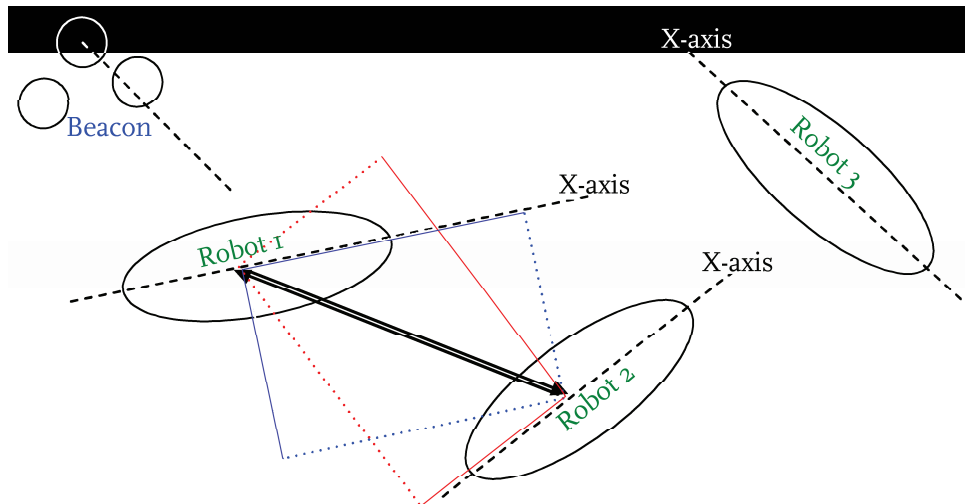


Figure 3. The dashed lines indicate the X-axis of each object. The relative coordinates of Robot 1 determined by Robot 2 (red solid lines) have no relation to the coordinates of Robot 2 determined by Robot 1 (blue solid lines). However knowing that the resulting position vectors must be exact opposites (black arrows), they both can calculate the direction of the X-axis of the other robot.

Now that the robots know not only their own position, but also each other's coordinate system it is possible to:

1. Recalculate everything to a generic coordinate system. This might be the coordinate system obtained from a beacon, or they may use their own system as a reference.
2. Robots that cannot hear the beacon, but can hear other robots may be able to know their position with respect to the beacon if there is a chain of robots, where each robot can hear its neighbour or the beacon. With an accuracy of 1 cm and a distance between the robots of about 10 m, simulations show that about 100 m away from a beacon the robots will still be able to know their absolute position (that is the position relative to the beacon) with an acceptable accuracy, provided the chain is available and works properly. In practice this will only be reliable if more robots are present in the neighbourhood of the chain. Once the chain is broken the robots may never be able to find the other robots again, because they then do not have a clue about their absolute position.

Conclusions

The research on cooperative robot systems of the Combat Systems section is still at a preliminary stage. A system for the determination of the relative position of robots has already been built and tested. With this system, together with computer simulations it will be possible to test many scenarios and principles quickly and without the need for expensive devices. Next, the focus of this research project will shift to the formation of ad hoc networks of cooperating robots and to technologies to share non-compatible information (from different sensors) between robots. At the same time we must implement methods to share a common model of the environment between robots that participate in ad hoc networks.

In the near future many interesting and challenging educational projects involving students from the bachelor-level degree programme Military Sciences and Technology can be done in cooperation with this research project.

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