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Fault-Resilient Cooperation of Autonomous Mobile Robots with Unreliable Compass Sensors

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Abstract

Continuous advances in technology have made possible the use of several robots in order to carry out a large variety of cooperative tasks that are dangerous or undesirable for humans to complete. These tasks include, surveillance, inspection of sites that are inaccessible to humans, e.g., tight spaces, hazardous environments or remote sites, and search and rescue tasks, such as rescuing human beings trapped under piles of debris in an earthquake disaster or searching for victims of a flood. Following this idea, we are interested in systems with no prior infrastructure (e.g., unlike Global Positioning System), where robots are deployed in adverse environments, and where they are required to cooperate and self-organize to build such an initial infrastructure. For instance, robots may need to exchange information on their states (positions, trajectories, orientation, etc.) to construct a complete configuration of the team in order to cooperate. However, robots may not initially agree on a common coordinate system. Therefore, providing a way for robots to agree on a common coordinate system is useful in exchanging geographical information, for instance. Subsequently, reaching agreement among these robots is one of the most essential issues in distributed robotic systems. Besides, as the number of robots increases in the system, the issue of resilience to failure becomes prominent.

In this dissertation, we consider a system that consists of a group of mobile robots roaming in the two-dimensional plane. Each robot occupies a point in the plane, and is equipped with sensors to observe the positions of the other robots. Each robot proceeds by repeatedly (1) observing the environment, (2) computing a destination based on the observed positions of robots, and (3) moving toward the computed destination. Also, robots are unable to communicate directly, and can only interact by observing each others' positions. Finally, all robots execute the same deterministic algorithm, and they are oblivious (i.e., stateless), meaning that they can not remember their previous states, their previous actions or the previous positions of the other robots.

In this model, we address the problem of coordination between these robots from a computational viewpoint, aiming to identify the fundamental limits of what autonomous mobile robots can do in the presence of unreliable sensors. In particular, we focus on a basic coordination problem, namely the gathering problem, where robots must self-organize, and meet at some location not determined in advance, and without the help

of some global coordinate system. While being very simple to express, this problem has the advantage of retaining the inherent difficulty of agreement, namely the question of breaking symmetry between robots. Among other things, solving the gathering problem is interesting because it provides a way for robots to agree on a common origin.

Prior work has shown that gathering oblivious mobile robots in the plane cannot be achieved deterministically without additional assumptions. More specifically, if robots can detect multiplicity (i.e., count robots that share the same location), gathering is possible for three or more robots. Alternatively, prior work has also shown that gathering can be achieved with any number of robots if they share the knowledge of a common direction (e.g., north as given by some compass). However, that result holds only if all compasses are perfect, in the sense that they all agree perfectly on a common direction.

In this dissertation, we define a model in which compasses may be unreliable, and we study the solvability of gathering oblivious mobile robots using different classes of unreliable compasses, and under different models of synchrony. More specifically, we describe two classes of unreliable compasses, namely the class of eventually consistent compasses, and the class of compasses with bounded errors. Then, we present several results of possibility and impossibility for solving the gathering problem deterministically under these classes.

This dissertation makes four major contributions:

In the first contribution, we address the problem of gathering with eventually consistent compasses, that is compasses that are unstable for some unknown periods, with the guarantee that they stabilize eventually to show the correct direction. However, the time of stabilization is unknown to robots. In particular, we address the problem in the semi-synchronous model, where robots are oblivious and they have limited visibility. Especially, we provide an algorithm that solves the problem, in finite time, in a system where compasses are unstable for some arbitrary long periods, provided that they stabilize eventually.

The algorithm can solve gathering probabilistically when the compasses are inconsistent, and deterministically after compasses have stabilized for a sufficiently long period. Our algorithm is guaranteed to recover from any arbitrary configuration when the compasses of robots eventually stabilize. We can argue that our algorithm is intrinsically self-stabilizing and offers protection against any number of transient failures in the compasses.

In the second contribution, we study the solvability of gathering in the asynchronous model under eventually consistent compasses, where robots are oblivious and have limited visibility. In particular, we propose an algorithm that gathers up to four robots, in finite time, relying on eventually stabilizing compasses. In addition, we show that our gathering algorithm developed for the semi-synchronous model solves gathering for up to three robots, when they are equipped with eventually consistent compasses.

Alternatively, we show that it is impossible to achieve the gathering of a large number of asynchronous mobile robots, when they are equipped with compasses that are unstable for some arbitrary periods, they are oblivious and have limited visibility. In particular, we show that there exists no oblivious algorithm that solves the gathering problem for nine or more robots.

In the third contribution, we focus on the solvability of the gathering of autonomous mobile robots with inaccurate compasses. In particular, we provide a self-stabilizing algorithm to gather, in finite time, two asynchronous oblivious robots equipped with compasses that can differ by as much as 45°. In addition, we argue that our algorithm is also correct if we consider robots with volume, that is, robots are not represented by points, but they occupy some space in the plane.

In the fourth contribution, we extend our work on gathering with inaccurate compasses by proving a tight bound on the degree of divergence of robots' compasses for solving the gathering problem. More specifically, we present a self-stabilizing algorithm to gather, in a finite time, two oblivious robots equipped with compasses that can differ by an angle strictly less than 180°, and this is obviously a tight bound, since two compasses that can differ by an angle of up to 180° provide no information at all.

Finally, as a secondary contribution, we have completed a prior work on the circle formation problem by developing complete and rigorous proofs of correctness of a previous distributed circle formation algorithm. In particular, we studied the problem when robots are disoriented, i.e., share no knowledge of a common coordinate system, and they are oblivious. The algorithm allows a group of mobile robots to self-organize and move to form a circle in the semi-synchronous model. The proposed algorithm ensures that robots deterministically form a circle in a finite number of steps, and converges to a situation in which all robots are located evenly on the boundary of the circle. Among other things, the ability to form a circle means that the robots are able to agree on an origin and unit distance.

Key Words: **Distributed computing, Mobile computing, Autonomous robots, Distributed algorithms, Cooperation, Control, Implicit communication, Gathering, Point formation, Rendezvous, Circle formation, Fault-tolerance, Unreliable compasses, Unstable compasses, Eventually consistent compasses, Inaccurate compasses, Bounded error compasses, Self-stabilization.**