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Fault-tolerant gathering of asynchronous oblivious mobile robots under one-axis agreement ☆

S. Bhagat [a], S. Gan Chaudhuri [b], K. Mukhopadhyaya [a,*]

[a] ACM Unit, Indian Statistical Institute, West Bengal, India
[b] Department of Information Technology, Jadavpur University, West Bengal, India

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ABSTRACT

This paper addresses *gathering*, a fundamental coordination problem for multi-robot systems, for $n \geq 2$ asynchronous, oblivious mobile robots in the presence of f faulty robots. Earlier work has reported that the asynchronous robots cannot gather at a point without having some assumptions on multiplicity detection or total agreement in coordinate axis or constant amount of persistent memory bits. This paper shows that gathering is possible by agreeing only on one axis. Traditionally the robots have been assumed to be transparent. This work proves that gathering is achievable under one axis agreement even if the robots have *obstructed visibility*. In both the cases, deterministic fault-tolerant algorithms have been presented, for any initial static configuration of the robots. This paper is the first attempt at studying the gathering problem under the combination of three realistic model specifications (i) agreement in one axis (ii) obstructed visibility (iii) arbitrary number of faulty robots.

1. Introduction

In distributed computing, the mobile entities are sometimes referred to as *robots* or *agents*. Introduction of swarms (groups) of robots have changed the notion of solving problems by traditional robots where normally, a large complex machine (robot) is used to solve one single problem. It has got the standard advantages of a distributed system over centralized one. Cooperative behavior is the main strength of swarm robotics. The robots act in collaboration to execute a common task. This approach makes the system of swarm robots scalable and fault tolerant. Robots are usually represented as points moving on the 2D plane. The robots are anonymous, identical and they act autonomously in an asynchronous manner. They do not communicate with each other by passing explicit messages. They sense (observe) their surroundings and locate the positions of the other robots. Based on the set of locations, a robot determines its destination and moves their. The robots are oblivious. After reaching their respective destinations, they flush all past information.

The distributed system of mobile robots aims at using the minimum amount of capabilities while trying to solve a problem. It makes designing an algorithm more difficult. For example if we had a *synchronous* system of robots, then designing the algorithm becomes easier. However, maintaining a synchronous system is not easy. The crux of swarm robotics is to have cheap, mass producible robots which can be easily replaced when a few are damaged. The fields of application for such a distributed system of robots are also versatile. One can use the robots to search for objects in a hazardous environ-

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* Corresponding author.
E-mail addresses: sbhagat_r@isical.ac.in (S. Bhagat), srutiganc@it.jusl.ac.in (S. Gan Chaudhuri), krishnendu@isical.ac.in (K. Mukhopadhyaya).

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ment [31], which typically include disaster hit areas. The robots can even work together to build a complex 3D structure [26]. Other applications include mining in hazardous areas, agricultural tasks like foraging etc. Multi-robots systems are also used in defense. A large number of robots can act as an autonomous army. The U.S. Navy has created a swarm of boats which can track an enemy boat, surround it and then destroy it [30].

Gathering, (i.e., collecting the robots to a point not defined in advance) is a fundamental coordination problem for a group of mobile robots. In this paper, we have addressed this problem in presence of some faulty robots under limitations of capabilities in terms of agreement in coordinate system and visual obstruction. The robots obey the framework described in the following subsection.

1.1. Framework

General characteristics. The robots are distributed in nature, i.e., they have their own computational unit and they act independently. They do not communicate by sending or receiving messages. The robots are indistinguishable by their appearances. They perform a given task cooperatively.

Geometric representation. The robots are represented by points on a 2D plane. Each robot treats its own position as its origin in its local coordinate system. They agree on the direction and orientation of any one axis (Y axis/direction of north and south, for this paper). However, they do not have any agreement on the orientation of the other axis (X axis, for this paper).

Computation cycle. At any point of time, a robot may be active or inactive. When the robots are active, they operate by executing a cycle repeatedly. A robot has following three states:

- *Look*: In this state, the robot senses or observes the positions of the other robots in its surroundings with the help of some sensing device. The robot plots the positions of other robots in its local coordinate system.
- *Compute*: Depending upon what the robot has observed and the requirement of the given task, the robot computes a destination to move to.
- *Move*: The robot moves to the computed destination. This movement is nonrigid i.e., the robot may stop before reaching its destination. However, in order to get some guarantee that the movement would eventually be completed, it is assumed that there is a prefixed minimum distance that the robot travels if it stops prematurely.

A robot cannot differentiate between a static robot and a moving robot.

Activation scheduling. The operation cycle is scheduled asynchronously, i.e., at any point of time a set of robots may be in look state while some other sets of robots are computing or moving.

Obliviousness. The robots are oblivious, i.e., at the end of a cycle, the robots remove all computed data of that cycle.

Fault. Some of the robots may crash or become faulty i.e., they stop their activity forever. The faulty robots are still visible to others. However, the robots cannot decide whether a robot they see is functional or defective.

No multiplicity detection. The robots cannot detect if more than one robot lie at a single point.

Obstructed visibility. The robots are not transparent. Let r_i, r_j and r_k be three collinear robots such that r_k lies between r_i and r_j. r_k blocks the visibility between r_i and r_j, i.e., r_i and r_j are mutually invisible.

We propose a distributed algorithm that will gather all non-faulty robots (under the above model), starting from any arbitrary set of initial positions, to a point not fixed in advance, in a finite number of cycles.

1.2. Earlier works

Gathering is one of the most active research topics [4,8,6,7,13,16,19,22,23,25,28] in the domain of the multi-robot systems. The primary aim of these investigations is to find out sets of minimum capabilities which the robot should have to be able to gather at a point in finite time.[1] Depending on the activation scheduling, the system of robots have mostly been viewed under the following two models; (i) CORDA [27]: under this model the robots are asynchronous, i.e., they independently execute the phases of the cycles; (ii) SYm (Suzuki, Yamashita model [32]): the robots are semi-synchronous, i.e., a set of robots is active at some time and performs the phases of the cycles simultaneously. There is also a third type, called *fully synchronous*, where all the robots are active and perform the phases of the cycle at the same time. Gathering is possible without any extra assumption in *fully synchronous* model [18]. Prencipe [28] proved that, deterministic gathering of $n > 2$ robots is impossible in CORDA and SYm model without the assumption on multiplicity detection (the robots can detect a point consists of multiple robots). If there is no agreement about the coordinate system, gathering of even two robots is not possible without remembering the past. The result continues to hold even with multiplicity detection. Flocchini et al.

[1] There is some variation of gathering such as, convergence [9]; where the robots come as close as possible but do not gather at a single point. However, in this paper we only discuss gathering at a single point.