UNIVERSITY OF LIVERPOOL

ANNUAL PROGRESS REPORT

Distributed Navigation

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1 Introduction

The focus of this work is on a study of structural properties of network environments with the aim of developing new efficient deterministic or randomised algorithmic techniques which will be applicable to distributed computation and communication. To achieve the aims of this project, two primary areas in relation to network exploration and communication mechanisms have been identified for investigation.

1.1 Rendezvous and gathering of mobile agents

This area primarily focuses on the *Rendezvous Problem*. Alpern [1] introduces the rendezvous problem as what occurs when two people are placed randomly in an environment they are unfamiliar with, and are required to meet each other. In the most likely scenario, they are unable to communicate with each other. At Liverpool Poster Day 2011, the scenario of two naive tourists agreeing to meet *at* Central Park[1] was discussed.

The rendezvous problem can be identified in various scenarios where there is a mobile agent (virtual or physical) which must attempt to find an object that is either immobile (e.g., sink vertex) or mobile (e.g, another agent). In the presence of multiple agents we very often assume that they are identical (anonymous) and they all use the same algorithm. This strong assumption leads to the problem of symmetry breaking. When a randomised protocol is allowed, symmetry can be easily broken, however, in deterministic solutions it is far harder to break symmetry. A very simple though very intuitive example of the symmetry breaking problem occurs when two identical agents are located on a symmetric ring, and both operate under a deterministic protocol. In this example, the agents perform a sequence of identical (either synchronised or controlled by an adversary in asynchronous models) steps, s.t., the agents are locked into chasing each other unable to ever meet. [10] provides a very in-depth look at rendezvous in the ring and provides the best known algorithmic solutions to various situations when certain information (ring length, agent distance, ability to mark vertices, etc.) is available to the agents.

1.2 Efficient multi-agent distributed communication

Another interesting aspect of this work refers to developing new alternative approaches in time and energy efficient distributed communication. Imagine, e.g., an agent/token in a network at a vertex s (source) that is destined for another vertex, t. If the topological structure of the network is unknown one of the simplest though possibly inefficient methods of routing the agent/token is by utilising the *random walk* principle, whereby the agent at each vertex selects a neighbouring vertex at random and traverses towards it. This process is repeated until t is reached. Apart from the routing time that is likely to be excessive, either the agent or the network nodes (even in static networks) must have access to a random number generator.

Two major and interesting alternatives to the random walk are the *rotor-router* (or *Propp machine*) [2, 3, 14] and the *basic walk* [9]. In many previous approaches, focus has been on the performance of one agent performing graph exploration, however, relatively little is currently known in the case where multiple agents are expected to collaborate within these models. The initial focus of this part of the work is on the ***random** basic walk*.

The significant feature of the basic walk is it allows for the formation of multiple directed cycles with at least one cycle of a size linear to $|V|$. The basic walk is performed on the network formed of a graph $G(V, E)$ where V is a set of vertices and E is a set of directed edges, and specifically the graph should hold the property that it is undirected. The network G is seen as a digraph where each vertex v has a set of incoming edges $v_{\overleftarrow{E}} \subset E$ and a set of outgoing edges $v_{\overrightarrow{E}} \subset E$. To enable the basic walk to be performed by an agent, each vertex must label each of its own $\overrightarrow{e}$ with a random unique label (port number) from the set of integers $\{0 \ldots deg(v)\}$.

[1]The difficulty being that the tourists did not specify any specific landmark within Central Park, they only agreed to meet at Central Park; a park with over 40 entrances and covering $3.42km^2$.

To initiate the process, an agent first selects an outgoing edge $v_{\overrightarrow{u}}$ to a neighbouring vertex u (at random or through some other method) and traverses to the neighbouring vertex arriving through $u_{\overleftarrow{v}}$ ($v_{\overrightarrow{u}} \equiv u_{\overleftarrow{v}}$). At u, the agent must identify the associated port number i of the edge $u_{\overrightarrow{v}}$, i.e. that of the port number associated with the outgoing edge to v. Following this the agent can then select the next vertex to traverse to by identifying the $u_{\overrightarrow{e}}$ associated with the port number $(i + 1)$ MOD $\deg(u)$.

Once this process has been repeated until an edge previously visited is found, a unique directed cycle will have been discovered. Should this process be repeated on all remaining unvisited edges, it will lead to the partition of a graph into a series of directed cycles (rings). This leads to the motivation of this work which is to apply the basic walk to any unknown general graph and reduce it to a series of rings, up on which more efficient algorithms can be utilised.

2 Thesis Plan

My final submission date is **December 2013**, however, my funding will terminate earlier, in **August 2013**. For this reason my plan is as follows, for the remaining duration of 2012, further experimental and theoretical research will be continued. Predominately, the goal is to continue experimental work on the *basic walk* and prepare the existing results for writing up and publishing. Further, as will be mentioned in **Future Areas**, it is possible other publications may be produced within this period.

At the start of **February 2013** I plan to commence the write up of the thesis, with the goal of completing it by no later than than **June 2013**. This plan may be revised due to the distance from the point of writing this to the expected start date. Further it may be affected by employment opportunities arising.

3 Proposed Table of Contents

Abstract Short description of tthe project motivation, its importance and results.

Introduction Introduction and overview of the thesis, explains the the two main themes in the thesis and their relation to each other. With further introduce the models used for mobility and commucation, the related work and my personal contribution to the field.

Location aware rendezvous Introduction to the rendezvous problem, and also an introduction to two of the branches of rendezvous.

- **Synchronous rendezvous** The first subsection will be focused specifically on synchronous rendezvous, specifically [6].

- **Asynchronous rendezvous** The second subsection will be focused on asychronous rendezvous, specifically [7].

Network Patrolling This section will focus on a derivitive (and perhaps even application) of rendezvous, network patrolling and specifically the work within [8].

Efficient multi-agent distributed communication Introduction the basic walk and specifically its difference to a random walk. This section will further discuss the results obtained through experimental work and discuss theoretical understanding that has been gained, specifically with relation to [5]

Software Development A discussion on the software development that was completed in order to perform the experimental work on the basic walk. Further this section will highlight the capabilities of the software and any interesting algorithms developed for the purpose of rendering graphs (c.f. **Future Areas**).

Conclusions Final discussion on the work completed within this project and discussions on future directions for both the rendezvous and basic walk sections.

Bibliography Bibliography and references.

Appendix If required.

Index Index to the contents of the thesis.

4 Written Papers

Attached with this document are three papers, the abstracts for the three papers follow, and further an abstract of a draft paper as well as some future directions

4.1 Tell me where i am so i can meet you sooner: Asynchronous rendezvous with location information

In this paper we study efficient rendezvous of two mobile agents moving asynchronously in the Euclidean 2D space. Each agent has limited visibility, permitting it to see its neighborhood at unit range from its current location. Moreover, it is assumed that each agent knows its own initial position in the plane given by its coordinates. The agents, however, are not aware of each others position. The agents possess coherent compasses and the same unit of length, which permit them to consider their current positions within the same system of coordinates. The cost of the rendezvous algorithm is the sum of lengths of the trajectories of both agents. This cost is taken as the maximum over all possible asynchronous movements of the agents, controlled by the adversary.

We propose an algorithm that allows the agents to meet in a local neighborhood of diameter $O(d)$, where d is the original distance between the agents. This seems rather surprising since each agent is unaware of the possible location of the other agent. In fact, the cost of our algorithm is $O(d^{2+\varepsilon})$, for any constant $\varepsilon > 0$. This is almost optimal, since a lower bound of $\Omega(d^2)$ is straightforward. The only up to date paper on asynchronous rendezvous of bounded-visibility agents in the plane provides the feasibility proof for rendezvous, proposing a solution exponential in the distance d and in the labels of the agents. In contrast, we show here that, when the identity of the agent is based solely on its original location, an almost optimal solution is possible.

An integral component of our solution is the construction of a novel type of non-simple space-filling curves that preserve locality. An infinite curve of this type visits specific grid points in the plane and provides a route that can be adopted by the mobile agents in search for one another. This new concept may also appear counter-intuitive in view of the result from stating that for any simple space-filling curve, there always exists a pair of close points in the plane, such that their distance along the space-filling curve is arbitrarily large.

Published at ICALP 2010: [6]

4.2 Synchronous rendezvous for location-aware agents

We study rendezvous of two anonymous agents, where each agent knows its own initial position in the environment. Their task is to meet each other as quickly as possible. The time of the rendezvous is measured by the number of synchronous rounds that agents need to use in the worst case in order to meet. In each round, an agent may make a simple move or it may stay motionless. We consider two types of environments, finite or infinite graphs and Euclidean spaces. A simple move traverses a single edge (in a graph) or at most a unit distance (in Euclidean space). The rendezvous consists in visiting by both agents the same point of the environment simultaneously (in the same round).

In this paper, we propose several asymptotically optimal rendezvous algorithms. In particular, we show that in the line and trees as well as in multidimensional Euclidean spaces and grids the agents can rendezvous in time $O(d)$, where d is the distance between the initial positions of the agents.

The problem of location-aware rendezvous was studied before in the asynchronous model for Euclidean spaces and multi-dimensional grids, where the emphasis was on the length of the adopted rendezvous trajectory. We point out that, contrary to the asynchronous case, where the cost of rendezvous is dominated by the size of potentially large neighborhoods, the agents are able to meet in all graphs of at most n nodes in time almost linear in d, namely, $O(d \log^2 n)$. We also determine an infinite family of graphs in which synchronized rendezvous takes time $\Omega(d)$.

Published at DISC 2011: [7]

4.3 Optimal patrolling of fragemented boundaries

A set of mobile robots is deployed on a simple curve of finite length, composed of a finite set of "vital segments" separated by "neutral segments". The robots have to patrol the vital segments by perpetually moving on the curve, without exceeding their maximum speed. The quality of patrolling is measured by the idleness, i.e., the longest time period during which any vital point on the curve is not visited by any robot. Given a configuration of vital segments, our goal is to provide algorithms describing the movement of the robots along the curve so as to minimize the idleness.

Our main contribution is a proof that the optimal solution to the patrolling problem is attained either by the cyclic strategy, in which all the robots move in one direction around the curve, or by the partition strategy, in which the curve is partitioned into sections which are patrolled separately by individual robots. These two fundamental types of strategies were studied in the past in the robotics community in different theoretical and experimental settings. However, to our knowledge, this is the first theoretical analysis proving optimality in such a general scenario. Throughout the paper we assume that all robots have the same maximum speed. In fact, the claim is known to be invalid when this assumption does not hold.

Submitted to ESA 2012: [8]

4.4 Random supersize tours in spatial communication networks

We study an efficient randomised construction of cyclic traversal and communication routes in spatial networks modeled by two dimensional grids and random Unit Disk Graphs (rUDG). A system of routes can be used to connect distant parts of the network during a communication process such as broadcasting or routing or, e.g., in network patrolling performed by a team of mobile agents.

Our randomised construction is fully distributed and it is based on communication-less local computation at the network nodes. The system of routes does not impose any extra space requirements on the network. The structure of routes is encoded via appropriate ordering of the list of neighbours at each node. Similar deterministic constructions were used earlier to support periodic network traversal. However, these constructions required fully centralised solutions.

We first provide a fully comprehensive analysis of this novel randomised approach in flat two dimensional grids. Later we focus on more general spatial networks when we show that the structure of system of cyclic routes resembles properties of random graphs. Finally, we discuss how the new method can be used to support communication in ad hoc distributed networks.

In preparation: [5]

4.5 Other Research Activities

Currently their is a number of possible future areas that can be investigated, some as continuations and others that are new. Firstly, with one paper pending peer review, and a further in the preperation stage, there is a possibility for continuation work in future should these two papers receive positive reviews or interesting feedback.

Secondly, the university is in the process (and hopefully will have completed) the formation of an agreement between the university and Dollywagon. The agreement will commit myself and other members of the department to the production of developing new tools and performing research into the area of social network analysis. Specifically, the goal will be to investigate network significance within social networks as well as further investigate methods of graph drawing. Some of the reports already generated as part of this project are already published in *Research Live*[2] and available at [11–13].

Thirdly, an EPSRC funded vacation bursary has been awarded to Miss K. Williams, an undergraduate within the department. The goal of the project will be to assist in the development of new force directed algorithms for the drawing of graphs. While it is not expected that in the short duration of the internship anything publishable will be produced, it is however possible that this will provide an opportunity to trial and test new ideas that could lead to some interesting algorithms later on.

Futhermore, and on a much more less research orientated note away from the main body of research of this project, a university funded vacation bursary has been awarded to Mr. D. Hamilton, also an undergraduate within the department to work on a continuation of the teaching tool [4] developed for COMP526. While it remains to be seen where this will lead, there is the possibility of producing a more refined product for use in other departments as well as show casing it at more education orientated events.

On a similar note the project management system developed for M.Sc. projects seems to now be well received by the users of the B.Sc. final year projects and there is further interest for its adoption with the B.Sc. group projects. Further from this there may be opportunities to finalise the project as a solution for use in other departments or universities and can be show cased through similiar education orientated events.

References

[1] S. Alpern. The rendezvous search problem. *SIAM Journal on Control and Optimization*, 33(3):673–683, 1995. doi: 10.1137/S0363012993249195. URL http://link.aip.org/link/?SJC/33/673/1.

[2] E. Bampas, L. Gąsieniec, N. Hanusse, D. Ilcinkas, R. Klasing, and A. Kosowski. Euler tour lock-in problem in the rotor-router model. In I. Keidar, editor, *DISC*, volume 5805 of *Lecture Notes in Computer Science*, pages 423–435. Springer, 2009. ISBN 978-3-642-04354-3.

[3] E. Bampas, L. Gąsieniec, R. Klasing, A. Kosowski, and T. Radzik. Robustness of the rotor-router mechanism. In *OPODIS*, pages 345–358, 2009.

[4] A. Collins. Improving transparency through automating verification. Available from: http://www.csc.liv.ac.uk/~acollins/papers/AutomatedVerifierCOMP526.pdf, 2011.

[5] A. Collins, L. Gąsieniec, E. Kranakis, and R. Martin. Random supersize tours in spatial communication networks.

[6] A. Collins, J. Czyzowicz, L. Gąsieniec, and A. Labourel. Tell me where i am so i can meet you sooner: Asynchronous rendezvous with location information. In *37th International Colloquium on Automata, Languages and Programming (ICALP 2010)*, pages 502–514, 2010.

[7] A. Collins, J. Czyzowicz, L. Gąsieniec, A. Kosowski, and R. Martin. Synchronous rendezvous for location-aware agents. In *25th International Symposium on Distributed Computing (DISC 2011)*, pages 447–549, 2011.

[8] A. Collins, J. Czyzowicz, L. Gąsieniec, A. Kosowski, E. Kranakis, D. Krizanc, and R. Martin. Optimal patrolling of fragmented boundaries. In *Submitted to 20th European Symposium on Algorithms (ESA 2012)*, 2012.

[2]Research Live is the online counterpart of the *Research Magazine*, the market leading magazine for market research. Research Live has highest number of registrants and viewing statistics globally for the market research industry, more than all comparable sources. Specifically they have over 17,000 registrants from 120 countries and over 60,000 unique visitors and 150,000 page views every month.

[9] J. Czyzowicz, S. Dobrev, L. Gąsieniec, D. Ilcinkas, J. Jansson, R. Klasing, I. Lignos, R. Martin, K. Sadakane, and W.-K. Sung. More efficient periodic traversal in anonymous undirected graphs. In *Proc. 16th Colloquium on Structural Information and Communication Complexity (SIROCCO 2009)*, pages 174–188, 2009.

[10] E. Kranakis, D. Krizanc, and E. Markou. *The Mobile Agent Rendezvous Problem in the Ring*. Synthesis Lectures on Distributed Computing Theory. Morgan & Claypool, 2010.

[11] B. Tarran. Research live: Best of the web – april 2012. Available from: http://www.research-live.com/features/best-of-the-web---april-2012/4007378.article, Apr. 2012.

[12] B. Tarran. Research live: Best of the web – may 2012. Available from: http://www.research-live.com/comment/best-of-the-web---may-2012/4007535.article, May 2012.

[13] B. Tarran. Research live: Follow the leaders. Available from: http://www.research-live.com/features/follow-the-leaders/4007467.article, May 2012.

[14] V. Yanovski, I. A. Wagner, and A. M. Bruckstein. A distributed ant algorithm for efficiently patrolling a network. *Algorithmica*, 37(3): 165–186, 2003.