A Bio-Inspired Transportation Network for Scalable Swarm Foraging

EXTENDED ABSTRACT

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I. INTRODUCTION

A scalable foraging system should be effective in swarms ranging from tens to thousands of robots without reducing foraging performance per robot. In Central Place Foraging (CPF), robots search for dispersed resources from a foraging arena and consolidate them in a centrally-placed collection zone [1]–[3]. Two major problems limit the scalability of CPF. First, larger swarms produce more inter-robot collisions. Second, large foraging arenas require that robots travel further distances to find resources and transport them which leads to “diminishing returns” [4]. The Multiple Place Foraging Algorithm (MPFA) [5]–[7] improves scalability using multiple collection zones dispersed in a foraging arena. Foraging Algorithm (MPFA) [5]–[7] improves scalability using multiple collection zones dispersed in a foraging arena. However, it still has diminishing returns when the arena size is very large. Here we propose the bio-inspired hierarchical branching transportation network (MPFA* ✓) based on resource transportation networks in plants and animals. We derive scaling relationships for a 2D foraging area (rather than a 3D animal volume). We use this scaling law to predict the transportation infrastructure required to maintain constant per-robot foraging rate with increasing swarm and arena size.

II. RELATED WORK

Most studies in scalability of robot swarms find diminishing returns in large swarms. [8] shows dramatic reductions in per robot foraging rates. In [1], foraging performance per robot decreases 70% going from 1 to 768 robots. In the Distributed Deterministic spiral Search Algorithm (DDSA) [9], for swarms with between 20 and 30 robots, the performance drops below that of the Central Place Foraging Algorithm (CPFA) [1] due to crowding. The use of adaptive and dynamic mobile depots increases the scalability of MPFA up to 30% with 96 robots in a 50 × 50 m arena. [10], [11] demonstrated that partitioning strategies can provide a scalable and robust foraging robot swarm. We build on earlier work by introducing mobile depots for the transportation task, separate from searching robots that search for resources.

III. SCALING LAWS FOR FORAGING SWARMS

The transportation of resources through the cardiovascular system from the heart to dispersed cells in 3D space of an animal body is the inverse problem of transportation of dispersed resources to a central collection zone in 2D robot swarms. We derive scaling predictions for foraging robot swarms using the following definitions and simplifying assumptions, translated from [12]. 1) Each region (R) is a specified area Ar with a collection zone in its center. The number of regions is Nr so that Ar = NrA. 2) Resource density (Dr) is the number of resources (Nr) in Ar, Dr = Nr/A. To maintain constant resource density, another resource is placed uniformly when a resource is collected. 3) Foraging rate (F) is the number of resources collected in the central collection zone per unit time. The foraging rate in a region i (Fi) is the number of resources collected and transported to the regional collection zone per unit time, 4) Geometric similarity: since the arena A is a square with edge length l, then A ∝ l2. 5) Robot searching velocity (vs) is constant across all experiments. The delivery velocity of depots (vd) can vary for each foraging model and experimental setup. 6) The capacity of searching robots is always one resource. The capacity of depots (C) can vary for each foraging model and experimental setup. 7) The number of resources in transit is in steady state and Nr ∝ A. The density of resources in transit is the same across arena sizes. 8) Delivery rate (D) matches foraging rate (F). For each collection zone (j), the rate of dropoff equals the rate of pickup Dj = Fi and the delivery rate to the central collection zone equals the total foraging rate: D = F.

Fig. 1a shows idealized paths of mobile depots in the MPFA in an explosion network and Fig. 1b shows the hierarchical branching transportation network of the MPFA*. Prior work [12] showed that these two networks have the same scaling, in an idealized case without collisions. In the explosion network, Nr ∝ nNr, where Nr is the number of routes from collection zones to the central collection and n is the average number of resources in transit per route. So, Nr ∝ Nr ∝ F and n = lrt/vd, where lrt is the average length of a route and lrt ∝ A1/2 by Assumption 4. If vd is constant, we have Prediction I: F ∝ A1/2. Thus, region length l ∝ (A/Nr)1/2 ∝ A1/4. If vd is not constant, following [12], we have Prediction II: F ∝ A2/3, and consequently, l ∝ A1/6. This leads to the following prediction for the required number of depots Nd:

$$N_d = \begin{cases} \frac{2F}{vdC} (A - A^{3/4}) & \text{if } vd \text{ is constant} \\ \frac{2F}{vd^2} (A - A^{2/3}) & \text{if } vd \propto A^{\frac{1}{2}} \end{cases} \quad (1)$$

Biological systems are limited to sublinear scaling. However, we can use biological scaling principles to design a scale-invariant foraging swarm in which the total foraging rate is linear with arena size and swarm size. If we increase

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Fig. 1: The explosion network in the MPFA and the hierarchi- 
cal branching transportation network in the MPFA\(_T\).

the capacity \(C\) on each level by \(ab\) from level \(L-1\) to 0, then Eqn. 1 will have a constant \(\frac{2b}{3}\) in each level \(i\) collection zone. Then **Prediction III**: \(F \propto N_c \propto A\). So, the total number of robots is \(\frac{2b}{3}N_r - \frac{10}{3}\), therefore linear with \(N_r\) and \(A\).

IV. EXPERIMENTAL SETUP

We conducted three experiments to test the three predic-
tions for scalability of the CPFA, MPFA, and MPFA\(_T\). In Set I, we test the 1/2 scaling in Prediction I. The depot velocity and capacity are constant (\(v_d = 0.16m/s\) and \(C = 4\)), but the region length \(l \propto A^{1/4}\). In Set II, we test the 2/3 scaling in Prediction II. \(C = 4\), but \(v_d \propto A^{1/6}\) and \(l \propto A^{1/6}\). The number of depots \((N_d)\) in Set I and II is calculated in Eqn. 1. In Set III, we test the linear scaling Prediction III. \(l = 5m\), \(v_d\) is constant, and the depot capacity \(C\) is scaled by \(ab\) on each level as described in Section III.

The number of depots \((N_d)\) is 4 robots per collection zone \((N_d = 4N_c)\). For a fair comparison, we use the same number of robots in each set. In addition, we use the same number of depots \((N_d)\) for the MPFA and the MPFA\(_T\). In the MPFA, we distributed depots on each delivery route proportional to the length of that route. Thus, the number of depots for collection zone \(j\) is \(N_j = (d_j/D)N_d\), where \(d_j\) is the distance from the collection zone \(j\) to the central collection zone and \(D\) is the total distance of all collection zone to the central collection zone. The number of searching robots \((N_s)\) is 4 robots per region \((N_s = 4N_r)\). Each experiment runs for 30 simulated minutes, and each configuration is replicated 60 times. Resources are distributed at uniform random and the density of resources is constant across all experiments \((D_t = 1/m^2)\). We include two additional idealized foraging experiments which allow depots to pass through one another without colliding (MPFA* and MPFA\(_T^*\)) in MPFA and MPFA\(_T\).

V. RESULTS

We display and analyze log-transformed data of \(Y = \alpha X^b\) so that the regression between the log\(_2\) \(Y\) and log\(_2\) \(X\) gives the scaling exponent \(b\). In Fig. 2(a), the algorithms with the * illustrate the maximum scaling exponent (0.46 and 0.45) if there were no collisions. However, when we include collisions, the CPFA barely increases the foraging rate. Visual inspection of simulations shows extreme congestion at the collection zone for larger swarms. The scaling exponents of the MPFA and MPFA\(_T\) are closer to, but still lower than the expected 1/2 scaling. Similarly, in Fig. 2(b), the scaling exponents with collisions are lower than predicted, but the collision-free transportation scaling exponents (0.64) are close to the 2/3 scaling. However, in Fig. 2(c), the MPFA\(_T\) results in a much higher scaling exponent 0.95 without collisions and 0.86 with collisions. There is less crowding in the MPFA\(_T\) (compared to the MPFA) because the number of paths to each collection zone equals the branching factor \(b\) regardless of swarm and arena size.

VI. DISCUSSION

Scalability is achieved with a hierarchical branching transpor-
tation network inspired by animal cardiovascular net-
works. This approach essentially aggregates collected re-
sources in larger depots (where depot capacity is set accord-
ing to scaling theory), much the way blood is aggregated in larger vessels like the aorta in cardiovascular networks. However, biological networks face a constraint on the size of blood vessels (their total volume must be equal to a constant fraction of the animal volume [13]). In contrast, depot can increase capacity to accommodate the increase in transport. This work demonstrates the viability of an artificial bio-inspired transportation network in robot swarms.

We predict the required number of robots, and the number and size of depots for a given size arena to achieve scale invariant foraging. We are building a prototype of real depot to test MPFA\(_T\), following the experimental protocol we developed to go from the Autonomous Robots Go Swarming (ARGoS) [14] simulation to a ROS implementation [15].
REFERENCES


