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Adaptive Behaviours in Multi-Agent Source Localization using Passive Sensing

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Abstract

In this paper, the role of adaptive group cohesion in a cooperative multi-agent source localization problem is investigated. A distributed source localization algorithm is presented for a homogenous team of simple agents. An agent uses a single sensor to sense the gradient and two sensors to sense its neighbours. The algorithm is a set of individualistic and social behaviours where the individualistic behaviour is as simple as an agent keeping its previous heading and is not self-sufficient in localizing the source. Source localization is achieved as an emergent property through agent's adaptive interactions with the neighbours and the environment. Given a single agent is incapable of localizing the source, maintaining team connectivity at all times is crucial. Two simple temporal sampling behaviours, intensity-based-adaptation and connectivity-based-adaptation, ensure an efficient localization strategy with minimal agent breakaways. The agent behaviours are simultaneously optimized using a two phase evolutionary optimization process. The optimized behaviours are estimated with analytical models and the resulting collective behaviour is validated against agent's sensor and actuator noise, strong multi-path interference due to environment variability, initialization distance sensitivity and loss of source signal.

Keywords

Swarm intelligence, Multi-agent systems, Collective behaviour, Cooperative source localization, Autonomous robots.

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1 Introduction

Over the last decade, swarm robotics has gained significant research momentum owing to its promise in solving real world problems (Blum and Groß, 2015; Brambilla et al., 2013). Swarm robotics can be seen as an approach which studies the emergence of a desired collective behaviour from the local interactions of agents among themselves and with their environment (Şahin, 2005). The agent behaviours may either be individualistic or social. Individualistic behaviors refer to agent's rules that only define interactions with its environment and/or reaction to its internal state. The social behaviours refer to agent's rules of interaction with its neighbours.

In swarm robotics, foraging has been the main testbed application (Brambilla et al., 2013). It has been used for investigating navigational behaviours such as collective exploration (Ferrante et al., 2012), collective transport (Ferrante et al., 2013) and collective decision making (Gutiérrez et al., 2010). Source localization can be thought of as a subproblem of foraging where it benefits from collective exploration and collective decision making behaviours. The recent events of aircraft crashes in the sea (Normile, 2014), algal blooms in water bodies (Michalak et al., 2013) and oil spills undersea (Camilli et al., 2010) have underscored the importance of developing a swarm robotic system which can localize sources of interest in real world.

Practically, there are two main concerns that need to be addressed for a cooperative source localization problem. First, we need to define the method of gradient sensing to acquire information about the gradient, if not known a priori. Second, we need to define the communication methods to achieve cooperation between agents.

Most swarm robotic studies assume a priori knowledge of the source direction relative to all or some of the agents (Mataric, 1992; Çelikkanat and Şahin, 2010; Gökçe and Şahin, 2010; Spears et al., 2004). Such an assumption is viable in case an agent can instantaneously sense the gradient using multiple sensors (Braitenberg, 1986; Grasso et al., 2000; Ishida et al., 2012). However, the ability to sense the gradient instantaneously using multiple sensors is subject to the smoothness of the scalar field, available intensity variations over the body length of an agent and the noise levels of the sensor and the environment. The *size-problem* discussed for the case of a bacterium performing chemotaxis by Macnab and Koshland (1972) relates well with a miniature agent sensing a gradient in real world. In case, an agent cannot detect the gradient instantaneously or is only equipped with one sensor, it resorts to temporal sampling to sense the gradient (Jin, 2013). Another similar technique is an agent undergoing motions based on persistent excitation to localize the source (Dandach et al., 2009). However, such an implementation requires a reliable position estimate of an agent along with an estimate for distance from the source based on the sensed intensity values. Acquiring a reliable position estimate in a GPS-denied environment such as undersea is a hard and an expensive problem to solve (Stojanovic and Preisig, 2009). In most real world scenarios, instantaneous intensity values of the source are corrupted with high levels of ambient noise (Dahl et al., 2007). Especially in

underwater environments, multipath constructive and destructive interference due to variability of the environment makes gradient sensing a hard problem to solve (Stojanovic and Preisig, 2009). It also makes multiple sensor based instantaneous gradient sensing almost impossible to achieve.

The problem of source localization can be solved cooperatively by having a mix of individualistic and social behaviours (Matarić, 1995; Ioannou et al., 2015; Shaukat et al., 2013). An individualistic behaviour may be self-sufficient in localizing the source, i.e., an agent is capable of localizing the source on its own. For example, a biased random walk of a bacterium or a moth is an example of a self-sufficient behaviour (Berg et al., 1972; Kennedy, 1983). However, in some cases, the individualistic behaviour may not be self-sufficient, e.g., an agent changing its speed as a function of instantaneous intensity as proposed by Berdahl et al. (2013) can only localize the source being in a team. In the latter case, source localization is achieved as an emergent property of agent interactions where social behaviours are fundamental to achieve the desired collective behaviour.

Conventional social behaviour models require explicit inter-agent communication (Shaukat and Chitre, 2015b). In this paper, we follow the definition of explicit and implicit communication as given by Balch and Arkin (1994). Explicit-communication is defined as a deliberate act of invoking the signal transmission, whereas in implicit communication there is no such deliberate attempt. For example, an agent sending out its position estimate in form of a data packet to another agent is considered as an act of explicit-communication. Explicit inter-agent communication is especially hard to achieve in environments with considerable delays and limited bandwidth such as undersea (Stojanovic, 2003). Implicit communication can itself be classified into two types. The first one is stigmergy (Grassé, 1959) where the information is acquired through memory of the environment. Pheromone-trail deposition based collective behaviour of ants and termites has been a major inspiration in designing stigmergic multi-agent systems (Beckers et al., 1994; Panait and Luke, 2004; Sugawara et al., 2004). The other implicit communication approach is based on the interaction of an agent with its neighbours without using environment's memory, simply referred to as passive sensing (Shaukat and Chitre, 2015b). Actively leaving a pheromone-like trail or modifying the environment so that other agents can use cues from the environment memory may not be desirable or even possible in many real world environments.

The scope of this paper is to investigate the emergent properties of adaptive agent behaviours from which a robust and a scalable collective behaviour for a source localization problem can be achieved. We consider a realistic underwater acoustic source localization problem where we require all the agents of a multi-agent system to travel from one point to another in a two dimensional space. The two dimensional assumption is practically valid for autonomous vehicles operating on water surface or underwater at a specific depth. Given the motivation of using temporal sampling for gradient sensing and a passive sensing model for agent cooperation, we propose an algorithm, i.e., a set of agent behaviours that requires only one passive sensor for gradient sensing and two

passive sensors for inter-agent cooperation. As for the social behaviours, there are no known strategies except the ones discussed in the following section which can achieve collective behaviour using a passive sensing model without exploiting environment memory. This paper improves the performance of the collective behaviours proposed in the previous studies by proposing an optimized adaptive group cohesion strategy. Simultaneous optimization of the agent behaviours as a function of team size, initialization distance and neighbourhood size allows us to develop analytical models to estimate the underlying correlations. This sets this study apart from most of the behaviour based studies that ignore the behavioural optimization completely or optimize only one parameter at a time with all the other parameters held constant. The performance of the algorithm is statistically tested in a simulated underwater environment in presence of strong multipath interference due to environment variability, sensor noise and actuator noise. The robustness is further validated for sensitivities in initialization distance and loss of source signal. It is shown that the achieved collective behaviour is robust and scalable and achieves source localization without any agent breakaways. The proposed algorithm is also compared against a similar source localization algorithm albeit with a self-sufficient individualistic behaviour and a static group cohesion model.

2 Related Work

The robotic implementations of a single sensor based gradient detection are generally inspired from the biased random walk of a bacterium, *Escherichia coli*, performing chemotaxis (Russell et al., 2003; Maes et al., 1996; Maes, 1996). The bacterium has multiple chemoreceptors over its body, however, insignificant difference between concentration levels over its body length keeps it from instantaneous gradient sensing (Macnab and Koshland, 1972). Hence, it resorts to temporal sampling to sense the gradient (Porter et al., 2011; Jin, 2013). The bacterium swims in a straight path interrupted by abrupt random turns known as tumbles. Increasing concentrations result in decreased frequency of abrupt turns and decreasing concentrations result in increased frequency, i.e., if a bacterium detects increasing concentrations then it swims relatively straight and takes random turns otherwise. However, some studies assume a constant tumbling frequency where the tumbling angle is a function of the chemical gradient. It is claimed by Shklarsh et al. (2011) that both approaches produce the same effect statistically. A similar constant frequency approach was used by Shaukat and Chitre (2016) for localizing an underwater acoustic source and an evolutionary algorithm was used to optimize the tumbling behaviour. An agent kept its heading in case it was travelling in the direction of a positive gradient, however, took a Normally-distributed random turn with some mean and variance otherwise. Interestingly, the optimization data for cooperative teams showed that a deterministic turn (optimal values of variance being zero) is more beneficial. In such a case, randomness in the walk is only a result of a noisy gradient or sensing noise. Note that all these bacterium-inspired individualistic behaviours are self-sufficient in localizing the source, i.e., the individualistic

behaviour can localize the source on its own without being aided by any other individualistic or social behaviour(s).

As far as the cooperative multi-agent source localization approaches are concerned, they are either scaled versions of the individualistic behaviour (Li et al., 2008) or require explicit inter-agent communication for social behaviours (Marjovi et al., 2010) to achieve cooperation. This is also true for the single-sensor based temporal sampling implementations which either require centralized (Ogren et al., 2004) or decentralized explicit inter-agent communication (Bachmayer and Leonard, 2002; Shaukat et al., 2013). Strategies that use implicit communication for social behaviours are inspired from ants' pheromone sensing and hence use stigmergy (Deveza et al., 1994; Russell, 1999; Panait and Luke, 2004; Sugawara et al., 2004).

Implementation of social behaviours using strictly passive sensing, i.e., implicit communication without using stigmergy, is rare in the robotics literature. Even the strategies that assume passive sensing for one social behaviour assume explicit communication for other social behaviours and hence can be categorized as hybrid strategies (Mataric, 1992; Kuniyoshi et al., 1994).

Recently, we proposed a distributed source localization algorithm (Shaukat and Chitre, 2015b) that assumes static temporal sampling approach for gradient sensing, passive sensing based social behaviours and a self-sufficient individualistic behaviour based on a bacterium-inspired random walk. All the agent behaviours were optimized using a Genetic Algorithm (GA) (Man et al., 1999). It was shown that the proposed strategy works at par with the explicit inter-agent communication based counterparts. In a similar study, an adaptive temporal sampling strategy was proposed where sampling time is a function of the sensed intensity values (Shaukat and Chitre, 2015a). The adaptive temporal sampling strategy improved the performance of the earlier localization algorithm. However, both these studies assumed a static group cohesion model.

In this paper, the proposed source localization algorithm is called Adaptive Cohesion based Localization Algorithm (ACLA). The concept of adaptive cohesion presented in ACLA is related the earlier work of Shklarsh et al. (2011). However, Shklarsh et al. (2011) used a bacterium-inspired self-sufficient individualistic behaviour where the parameters of the Normally-distributed random walk, i.e. a zero mean and a variance of π radians, were set arbitrarily. The temporal sampling approach was also static. Also, the adaptable interaction model acted like a switch where the weight of the heading dictated by the individualistic behaviour was either 0 or 1 based on the gradient sensing. An agent used the average of its individualistic heading and the social heading if it was travelling in the direction of increasing concentration, otherwise, it only considered its social heading. Moreover, the presented social behaviours required explicit communication. In ACLA, the individualistic behaviour is as simple as an agent keeping its previous heading. The social behaviours, i.e., Group Cohesion (GC) and Collision Avoidance (CA), are based on the passive sensing model (Shaukat and Chitre, 2015b). The Adaptive Cohesion (AC) behaviour is a weighted average of the GC and the individualistic behaviour where an agent varies its cohesion based on the sensed intensity values. The adaptive temporal

sampling approach is based on two behaviours, i.e., Intensity based Adaptation (IbA) and Connectivity based Adaptation (CbA). IbA varies the sampling times of an agent as a function of the sensed intensity values, whereas CbA varies the sampling times as a function of the sensed number of neighbours. AC and CA with the adaptive temporal sampling approach constitute ACLA.

3 Problem Statement

We assume a team of homogeneous, miniature and simple robots such as shown in Fig. 1(a), called Swarmbots. Each agent is equipped with one sensor to sense the signal of the source and hence conducts temporal sampling to sense the gradient. For the social behaviours, an agent cannot explicitly communicate with other agents. However, it can detect the number of neighbours and the neighbour majority in either its left or right half within some local neighbourhood using two passive sensors.

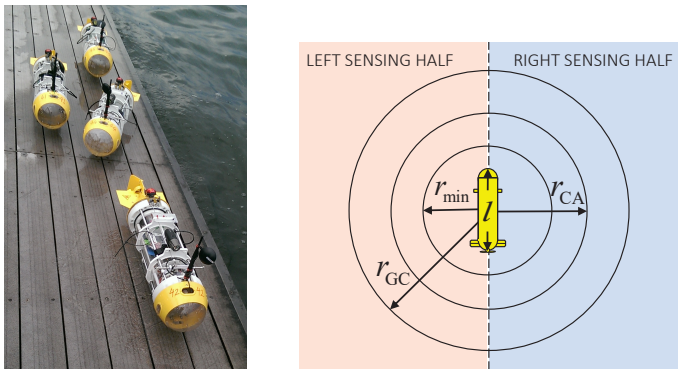
We assume a source localization scenario in which we want to send a team of agents to a target location over a long distance to carry out some desired task. This assumption is especially relevant for applications where want to access targets of interest in areas hit by nuclear radiation or hazardous chemicals. The team needs to travel in an unconstrained search space and arrive at the source location with minimal number of agent breakaways. In Global Positioning System (GPS) denied environments where the robots do not have a sense of their own position or of the source location, this becomes a challenging task. One possibility is sensing the gradient of interest to localize the highest concentration areas or contours. Another possibility is to have a single point-source such as a Radio Frequency (RF) beacon (on land) or an Underwater Locator Beacon (ULB) (in sea) installed at the target of interest, the signal strength of which can help the robots to localize the target. We can also flip the notion. Once the team has completed the given task, we can start the post-mission retrieval using the same method where another beacon can help the agents localize the home position.

In this paper, we consider an underwater source localization scenario where the source is a ULB. The gradient is corrupted with strong constructive and destructive multipath interference due to environment variability and agent's sensor noise.

We define *arrival time* as the time taken by the last agent in a team to enter a success zone of radius, r_s, centered around the point-source where each agent that enters the success zone does not diverge from the source afterwards.

4 Adaptive Cohesion based Localization Algorithm

In this section, we first define the three constituent behaviours of ACLA, i.e., group cohesion, collision avoidance and adaptive cohesion. Each behaviour only desires a certain heading for an agent while all the agents are assumed to maintain a constant speed throughout their mission. Inspired by Couzin et al. (2002), we use unit heading vectors to define each of the behaviours.



(a) (b)

Figure 1. (a) A small team of four Swarmbots at Pandan Reservoir. (b) Passive sensing based interaction zones for CA and GC.

For example, the instantaneous unit heading vector of the n^{th} agent is $\mathbf{d}_n(t) = 1\angle\theta_n(t)$ where $\theta_n(t)$ is the instantaneous heading of the agent. Similarly, $\mathbf{d}_{\text{GC}_n}$, $\mathbf{d}_{\text{CA}_n}$ and $\mathbf{d}_{\text{AC}_n}$ are the agent's heading vectors desired by the group cohesion, collision avoidance and adaptive cohesion behaviours respectively. Following the formal definitions, we present ACLA, i.e., the resultant distributed source localization algorithm from the three fundamental behaviours. Since ACLA is based on adaptive temporal sampling, we conclude this section by discussion on the adaptive sampling techniques used in this paper.

4.1 Group Cohesion

An agent can detect whether the majority of its neighbours are in its left or right half, using two sensors, within some local neighbourhood of radius, r_{GC}, called attraction radius as shown in Fig. 1(b). GC calculates the desired unit heading vector of the n^{th} agent as

$$\mathbf{d}_{\text{GC}_n}(t+\tau_n) = \begin{cases} R_\phi \mathbf{d}_{\text{AC}_n}(t) & \text{if more neighbours on left} \\ R_\phi^- \mathbf{d}_{\text{AC}_n}(t) & \text{if more neighbours on right} \\ \mathbf{d}_{\text{AC}_n}(t) & \text{otherwise} \end{cases} \tag{1}$$

where τ_n is the sampling time, $\mathbf{d}_{\text{AC}_n}(t)$ is the unit directional vector of the agent dictated by AC (see definition in Section 4.3), R_ϕ, R_ϕ^- are the counter clockwise and the clockwise rotation matrices for an angle of $\phi = 90°$. Effectively, an agent turns left if the number of neighbours to its left are more than the number of neighbours on its right and vice versa. In case of the numbers being equal in both the left and the right half, the agent keeps its heading unchanged.

4.2 Collision Avoidance

CA operates at the highest priority. CA has a relatively much smaller sampling time, τ_{CA} set equal to the minimum sampling time, $\tau_{\min}$. In case an agent n of body length, l, detects a neighbour within its repulsion zone of radius, r_{CA} (see Fig. 1(b)), it starts an evasive action and ignores any other behaviours. An agent turns away from the nearest neighbour with a turning rate that is proportional to how close the nearest neighbour is. The turning rate as a function of the estimated distance, $\hat{r}_{n,m}(t)$, between the agent, n, and its nearest neighbour, m, is given as

$$\dot{\theta}_{\text{CA}_n}(t+\tau_{\text{CA}}) = \begin{cases} \text{sgn}(m)\alpha\dot{\theta}_{\max} & \text{if } r_{\min} < \hat{r}_{n,m}(t) \leq r_{\text{CA}} \\ \text{sgn}(m)\dot{\theta}_{\max} & \text{if } \hat{r}_{n,m}(t) \leq r_{\min} \end{cases} \tag{2}$$

where $\text{sgn}(m)$ is 1 if m is in right half and -1 otherwise, positive turning rates being counter clockwise and vice versa, $\alpha = \left(\frac{r_{\text{CA}} - \hat{r}_{n,m}(t)}{r_{\text{CA}} - r_{\min}}\right)$ is the gain which varies linearly as a function of $\hat{r}_{n,m}(t)$ as shown in Fig. 2(a) and $r_{\min} = 2s\tau_{\text{CA}} + \frac{l}{2}$ is the minimum distance (see Fig. 1(b)) where the turning rate is maximum. Note that r_{CA} needs to be greater than $2s\tau_{\text{CA}} + \frac{l}{2}$ for an agent to detect all the potential collisions. The constraint, $r_{\min} = 2s\tau_{\text{CA}} + \frac{l}{2}$, has been calculated assuming the worst case scenario of a head-on collision between two agents travelling at speed, s, where the sensor is assumed to be mounted at the center of each agent's body length, l. Since the formulation for $r_{\min}$ makes sense if both the agents are travelling at the same speed, r_{CA} needs to be sufficiently larger than $r_{\min}$ to compensate for any noise in speed regulation. Then agent, n, assumes heading according to the following direction vector as shown in Fig. 2(b)

$$\mathbf{d}_{\text{CA}_n}(t+\tau_{\text{CA}}) = \frac{\mathbf{\Delta d}_{\text{CA}_n}(t) + \mathbf{d}_n(t)}{\|\mathbf{\Delta d}_{\text{CA}_n}(t) + \mathbf{d}_n(t)\|} \tag{3}$$

where $\mathbf{\Delta d}_{\text{CA}_n}(t) = 1\angle\tau_{\text{CA}} \cdot \dot{\theta}_{\text{CA}_n}(t)$, $\|\cdot\|$ is the Euclidean distance and $\mathbf{d}_n(t)$ being the instantaneous unit directional vector of agent n.

4.3 Adaptive Cohesion

AC varies an agent's group cohesion based on the sensed source-intensity values. The unit direction vector dictated by AC is a weighted average of the GC and the individualistic behaviour as shown in Fig. 3(a) and is given as

$$\mathbf{d}_{\text{AC}_n}(t+\tau_n) = \eta(t+\tau_n)\mathbf{d}_{\text{AC}_n}(t) + (1-\eta(t+\tau_n))\mathbf{d}_{\text{GC}_n}(t+\tau_n), \tag{4}$$

$$\eta(t+\tau_n) = \min\left(1, \max\left(\alpha_I \Delta\hat{I}_n(t+\tau_n) + \frac{1}{2}, 0\right)\right) \tag{5}$$

such that the source bias coefficient, $0 \leq \eta \leq 1$, $\alpha_I \in \mathbb{R}^+$ is the adaptive cohesion coefficient and for the estimated intensity, $\hat{I}_n(t)$, the change in intensity is given

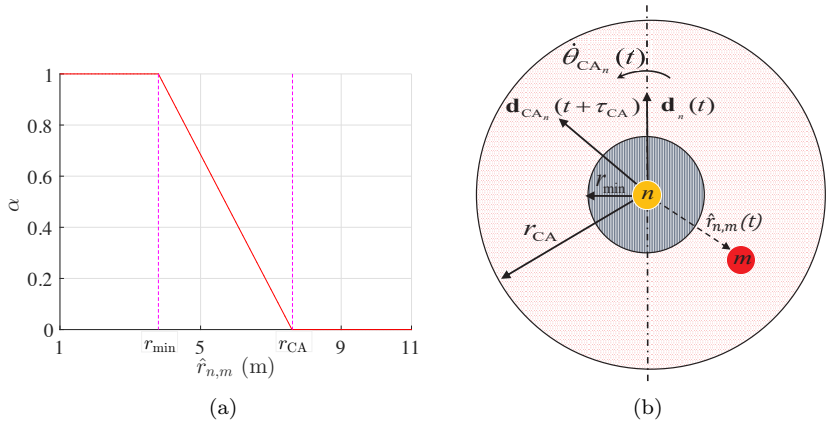


Figure 2. (a) Gain, α, of the turning rate, $\dot{\theta}_{\mathsf{CA}_n}$, in (2) with respect to the estimated inter-agent distance, $\hat{r}_{n,m}$. (b) An agent, n, taking evasive action as given by (eq:CA) for an agent m within its CA zone.

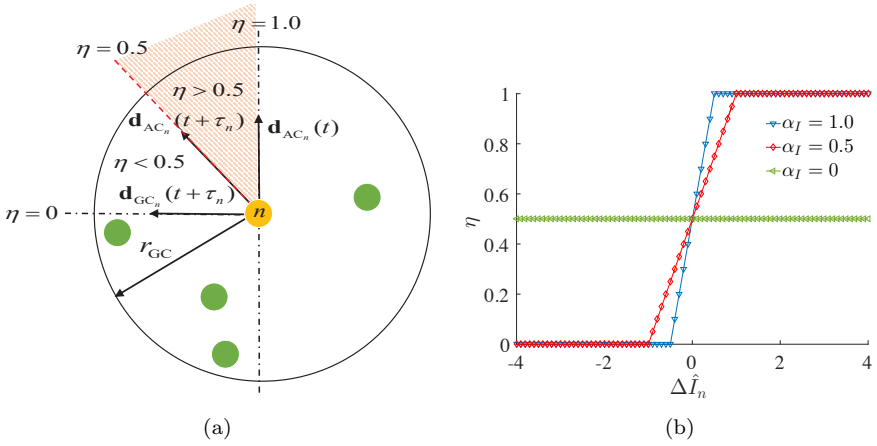


Figure 3. (a) The unit direction vector, $\mathbf{d}_{\mathsf{AC}_n}$, as dictated by AC in (4) and its dependence on the source bias coefficient, η. Green circles depict neighbours inside the GC zone. (b) Source bias coefficient, η as a function of the change in estimated intensity, $\Delta\hat{I}_n$ for varying values of α_I in (5).

as $\Delta\hat{I}_n(t+\tau_n) = \hat{I}_n(t+\tau_n) - \hat{I}_n(t)$. Individualistic behaviour is simply an agent keeping its previous heading. Once an agent loses contact with all the other agents, it will continue to travel in a straight path. Equation (5) varies the source bias coefficient around the nominal value of 0.5 where values, $\eta > 0.5$ bias an agent more towards its previously calculated heading and values, $\eta < 0.5$ bias

an agent more towards the majority of the neighbours. The dependence of η on the change in estimated intensity, $\Delta\hat{I}_n$ is shown in Fig. 3(b) for varying values of α_I. If an agent estimates that it is heading in the direction of decreasing intensity levels ($\Delta\hat{I}_n < 0$), it biases itself more towards its neighbours ($\eta < 0.5$). Otherwise, if an agent estimates it is heading in the direction of increasing intensity levels ($\Delta\hat{I}_n > 0$), it biases itself more towards its previous heading ($\eta > 0.5$).

4.4 ACLA: Resultant Behaviour

Let us write the desired direction of the n^{th} agent, commanded by ACLA as

$$\mathbf{d}_{\text{ACLA}_n}(t) = \begin{cases} \mathbf{d}_{\text{CA}_n}(t) & \text{if } \hat{r}_{n,m}(t) \leq r_{\text{CA}} \\ \mathbf{d}_{\text{AC}_n}(t) & \text{otherwise} \end{cases} \tag{6}$$

where ACLA follows the CA behaviour in case an agent detects neighbour(s) in its repulsion zone, otherwise ACLA follows the adaptive cohesion behaviour.

4.5 Adaptive Temporal Sampling

An adaptive temporal sampling approach is a better alternative to a static temporal sampling approach for the source localization problem considered in this paper as shown by Shaukat and Chitre (2015a). The adaptive temporal sampling is composed of two behaviours. Principal behaviour is IbA, i.e., the sampling time varies as a function of sensed intensity values. Intuition behind using IbA is based on the relationship between the initialization distance and size of the success zone. The radius of the success zone, r_{s}, is generally very small as compared to r_0. Starting hundreds of meters away from the source, an agent thrives on larger sampling time to improve its decision accuracy, i.e., the probability of detecting the correct gradient in presence of noise. However as large a sampling time would be, it will be as difficult to enter inside a success zone with a small radius. The adaptive sampling time, $\tau'_n \coloneqq t_{i+1} - t_i$ for an n^{th} agent, where i^{th} sample is taken at time, t_i, and $(i+1)^{\text{th}}$ sample is taken at time, $t_i + \tau'_n$, is given as follows

$$\tau'_n = \beta_\tau f(\hat{I}_n) + \tau_{\min} \tag{7}$$

where $f(\hat{I}_n) = 3.6 \times 10^6 e^{-0.086\hat{I}_n}$ is the exponential function as shown in Fig. 4(a). The adaptive sampling coefficient, $\beta_\tau \in \mathbb{R}^+$, is optimized via GA. In our earlier work (Shaukat and Chitre, 2015a, p. 2), the sampling time being a negative-sigmoid function of the sensed intensity levels was an arbitrary choice. It is more suitable for a fixed initialization distance scenario where for variable initialization distances, we required to tune three different parameters. Also, we noticed that if we optimize the sampling times for varying initialization distances, the fall-offs of all the negative sigmoid curves are nearly identical as shown in Fig. 4(a) where the blue hexagrams depict the optimized sampling times for the intensity values at these initialization distances. The shape of

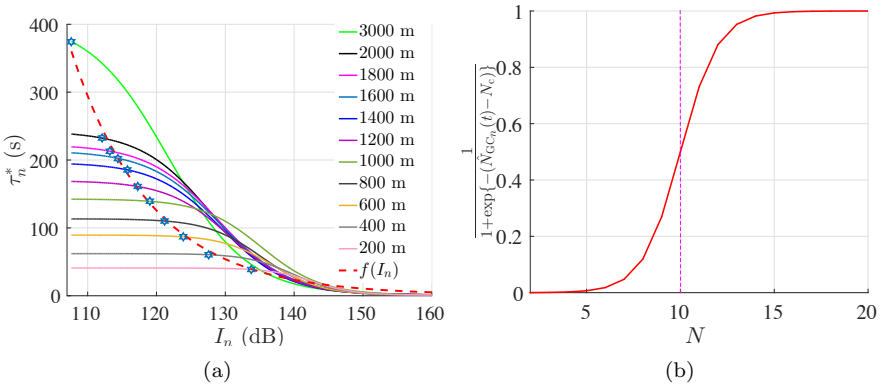


Figure 4. (a) Plotting the optimized adaptive sampling times shown as τ_n^* proposed in Shaukat and Chitre (2015a) for varying initialization distances results in an optimal exponential curve, $f(\hat{I}_n) = 3.6 \times 10^6 e^{-0.086\hat{I}_n}$ shown as red dashed line. (b) CbA's regulation of IbA for the case of critical number of agents, $N_c = 10$.

the negative sigmoid fall-offs is also similar to the shape of the fall-off of the blue hexagrams suggesting an optimal shape which can be approximated by an exponential function, $f(\hat{I}_n)$, as given in (7). This choice enables us to optimize only one parameter, i.e., $\beta_\tau \in \mathbb{R}^+$, for varying initialization distances instead of three for the negative-sigmoid function.

The sampling time calculated by IbA in (7) is further regulated by CbA as

$$\tau_n = \begin{cases} \tau_n' \left(\frac{1}{1+\exp\{-(\hat{N}_{GC_n}(t)-N_c)\}} \right) & \text{if } \hat{N}_{GC_n}(t) > 0 \\ \tau_n' & \text{otherwise} \end{cases} \tag{8}$$

where $\hat{N}_{GC_n}(t)$ is the estimated number of neighbours of agent n within r_{GC} at time t and N_c is the critical number of neighbours. The sigmoid function is CbA which updates the IbA's adaptive sampling time, τ_n'.

Effectively, CbA decreases the originally calculated sampling time by IbA in case an agent's number of neighbours fall around the critical number of agents, N_c as shown in Fig. 4(b) for the case of $N_c = 10$. This is to increase the decision-making frequency to improve the connectivity of the team, i.e., to reduce or ideally eliminate the number of agents breaking away from the team. As large the sampling time, the better an agent's gradient sensing and hence the more an agent travels before making another decision. In the meanwhile an agent may breakaway from the team. If we consider the current heading of an agent, $\mathbf{d}_{AC_n}(t)$, in (4) such that it is travelling in the direction of a potential breakaway, increasing the frequency of updating (4) as the number of neighbours drop biases the agent towards the team.

4.6 Practical Relevance

From the earlier discussion, it is clear that gradient sensing and neighbours' majority detection may require two separate sensing mechanisms. For example, a team of agents localizing a chemical source would require one chemical sensor per agent. For cooperation between agents, i.e., sensing the majority of neighbours, an agent may use two acoustic sensors to sense the noise made by other agents.

In this subsection, we look at some examples of using the two sensors for neighbour detection from the perspective of practical implementation. One of the possibilities is using two microphones or hydrophones per agent where an agent can *listen* for the presence of its neighbours. Generally, the drive or propulsion systems of Unmanned Ground Vehicles (UGVs), Unmanned Aerial Vehicles (UAVs) and Autonomous Underwater Vehicles (AUVs) make significant noise which can be detected within some local neighbourhood. We can use the time-of-arrival analysis on the sensors' data which can help an agent estimate the number of neighbours in its neighbourhood as well as detect whether the majority of its neighbours is located in its right or left half. In harsh environments such as undersea environments where communication bandwidth is severely limited, low frequency sound signals like the thruster noise can travel several hundreds of meters (Dahl et al., 2007; Urick, 1984; Calderon, 1964). A typical AUV has a thruster noise in the range of 120 dB to 160 dB re 1 μPa at 1 m (Griffiths et al., 2001; Cai et al., 2010). Underwater locator beacons can be mounted onto the AUVs which emit an acoustic pulse at a fixed rate in time. For example, a 20 kHz pinger with a source level of 180 dB re 1 μPa at 1 m can be heard over several kilometers undersea. Another option can be two cameras as passive sensors in environments where robots can detect the number of neighbours and the neighbour majority using simple image processing techniques.

Acquiring information of the number of neighbours and neighbour majority completely defines CbA and GC respectively, however, CA requires the range information from the nearest neighbour. Let us think about any other agent within the local neighbourhood as an additional source. Given an agent has some prior knowledge of the source (neighbour in this case) intensity and its propagation model, it can obtain a good estimate of the range in a close proximity. This is especially true for sources which follow the inverse square law, i.e., the intensity is inversely proportional to the distance squared. Since the repulsion radius is generally small, the assumption pertaining to the knowledge of the estimated nearest neighbour distance is practically valid.

5 Experimental Setup

A team of N homogeneous agents is considered. Simulated model of an agent follows the kinematics of Swarmbot where each agent is assumed to be of length, l, has its turning rate, $\dot{\theta}$ and speed, s. A constant speed operation with non-holonomic constraints has been assumed and both the turning rate and the speed have been further corrupted with additive Gaussian noise for each agent

Table 1. Symbols, Description and explored values of the mission variables in simulation.

Sym.	Description	Value(s)
N	Total number of team members	2 to 20
l	Length of an agent	0.8 m
r_0	Initialization distance	$\{600, 1000, 1400\}$ m
r_i	Radius of the initialization zone	$12.5l$
r_s	Radius of the success zone	$62.5l$
r_GC	Attraction radius	$\{0.1r_0, 0.2r_0, \ldots, 0.6r_0, \infty\}$
r_CA	Repulsion radius	7.6 m
τ_min	Minimum sampling time	1 s
τ_CA	CA sampling time	τ_min
r_min	Minimum radius of the repulsion zone	3.8 m
s	Speed of an agent	$\sim \mathcal{N}(1.5, 0.15)$ m s^{-1}
ε_θ	Compass heading error	$\sim \mathcal{N}(0, 1)$ $^\circ$
$\dot{\theta}$	Turning rate of an agent	$\sim \mathcal{N}(35, 3.5)$ $^\circ$ s^{-1}
σ	Noise in received intensity level	$\{1, 6\}$ dB

to simulate the effects of turbulence in the medium. The compass reading, θ, has also been corrupted with additive Gaussian noise, ε_θ. A simplistic motion model is meant to keep the model-specific artifacts, in case of a more realistic dynamical model, from affecting the results of the collective behaviour.

The attraction radius, r_GC, is expressed as a fraction of the initialization distance. Practically, r_GC is limited by the sensing range of an agent. It has been known that the long-range attraction is related with the *expanse* of a school, i.e., the mean distance of all the fish from the school's centroid Lukeman et al. (2010). Larger the r_GC, larger can be the expanse of the team without compromising the team connectivity. A large team expanse also enables the agents to collect spatially uncorrelated samples which improves the collective decision making (Kao and Couzin, 2014). As the initialization distance increases, a team with the same expanse would be collecting more spatially correlated samples. This is why larger initialization distances require larger r_GC for the emergence of a collective behaviour (Shaukat and Chitre, 2016, p. 8). Given the relationship between the initialization distance and r_GC, it is better if r_GC is expressed as a fraction of the initialization distance than r_GC being expressed independently. This helps to develop a more general inference of results for a range of initialization distances. The repulsion neighbourhood radius, r_CA, has been set to twice the minimum distance, $r_\mathrm{min} = 2s\tau_\mathrm{CA} + \frac{l}{2}$, required to avoid collisions.

Each of N agents is assumed to be deployed with a random pose in a circular area of radius, r_i, centered around the initialization point. The initialization distance, r_0, i.e., the distance of the initialization point from the source is varied in a range to simulate different Signal to Noise Ratio (SNR) conditions. The radius of the success zone centered around the source, r_s.

All the values for the variables with their description have been listed in Table 1.

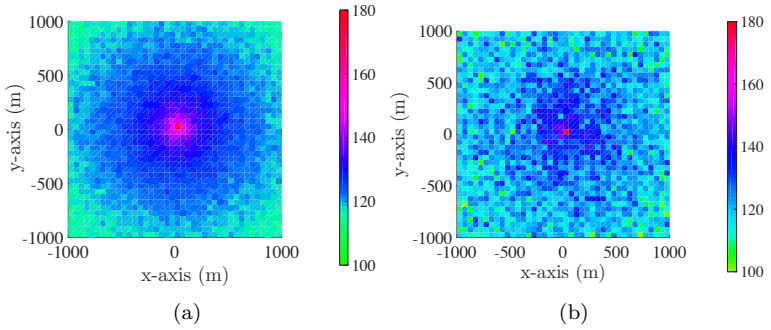


Figure 5. A two dimensional realization of source-intensity spatial profile for: (a) $\sigma = 1$ dB. (b) $\sigma = 6$ dB.

5.1 Sound Propagation

The acoustic source is assumed to be a Dukane DK-180 ULB with a frequency of 8.8 ± 1.0 kHz and an effective bandwidth of 100 Hz. The Source sound-Level, SL, is set to 180 dB re 1 µPa at 1 m. The assumed ambient Noise Level, NL, is set corresponding to the pressure spectral density level of 52 dB re 1 $\mu Pa^2\,Hz^{-1}$ pertaining to sea state 3 (Dahl et al., 2007; Urick, 1984) which is equal to a sound level of 84 dB re 1 µPa in the operating frequency band of the ULB.

We adopt a simple incoherent model for sound propagation taking into account the transmission losses due to spherical spreading and absorption in seawater (Thorp, 1967). Spatial profiles of received source-intensity, I, are shown in Fig. 5. Intensity levels have been corrupted with additive Gaussian noise of zero mean and equivalent dB-scale standard deviation of $\sigma = 1$ dB in Fig. 5(a) and of $\sigma = 6$ dB in Fig. 5(b). Assuming the noise of a typically calibrated sensor, $\sigma = 1$ dB of noise in received intensity levels is a valid assumption given a sufficiently long sampling window. However, in dynamic environments where there is a strong constructive and destructive multipath interference, the variation in received intensity levels can be estimated by setting σ within the range of 3 dB to 6 dB. We will consider the more conservative case of $\sigma = 6$ dB in conjunction with $\sigma = 1$ dB to validate the robustness of the source localization algorithm against noise. For reference, a realization of noise-corrupted source-intensity as a function of distance from the source is shown in Fig. 6 for $\sigma = 1$ dB and $\sigma = 6$ dB.

5.2 Evolutionary Optimization

The parameters of the agent behaviours are optimized using a Genetic Algorithm (GA) (Man et al., 1999). According to the classification given by Brambilla et al. (2013), agent behaviours can be designed by either *behaviour based design* or *automatic design*. Behaviour based design involves manually developing the individual behaviors of the agents which result in a desired collective behavior.

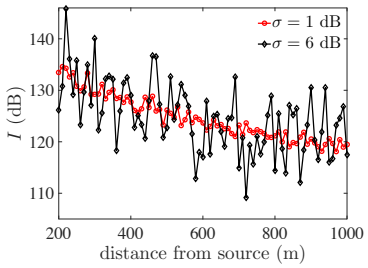


Figure 6. A realization of the noise-corrupted spatial intensity levels.

It is generally a trial and error procedure where iterative tuning of the individual behaviors is carried out until the desired collective behavior is achieved. On the other hand, automatic design for multi-robot systems is mainly based on the evolutionary robotics approach. In evolutionary robotics approach, initially a population of individual behaviors is generated at random. In each iteration, a certain number of experiments or simulations for each individual behavior are conducted. In each iteration, a fitness function is used to evaluate the collective behavior resulting from the individual behavior. Individual behaviors with a good fitness value are modified by genetic operators and then used for the subsequent iterations. Once no improvement is seen in the fitness value of the best individual behaviour for a specific number of iterations, the evolutionary process is ended.

In this paper, we have a fixed general structure of the individualistic and social behaviours. However, the optimal values of the coefficients of the adaptive temporal sampling function and adaptive group cohesion are found through GA. The process is identical to that of the evolutionary robotics approach where each behaviour in a population would be a different set of values of the sampling time and the turn's probability distribution parameters. Our approach differs from a purely evolutionary robotics approach since the search space has been constrained by an already fixed behavioural structure. Hence our approach can be seen as a hybrid of behaviour based design and automatic design. However, note that GA itself is not critical in the design process since any optimization strategy that is suitable for a high-dimensional, nonseparable and nonlinear problem without any guarantees of convexity can be used to find the optimal parameter values.

The GA's fitness function is the mean arrival time (defined in Section 3) over 1024 simulated source localization missions. The number of simulated missions have been calculated using the Vargha Delaney's A-measurement test (Vargha and Delaney, 2000) to ensure similar distributions for the entire GA population.

5.3 Robustness Analysis

We optimize the behaviours for an ambient noise level of 1 dB, followed by estimation of the optimized behaviours with an analytical model. The collective behaviours based on these analytical models are then validated against ambient noise of 1 dB and 6 dB. The validation is mainly based on the statistical analysis of the arrival time distributions via box-plots where each plot represents 5×10^4 simulated experiments, a band represents the median of a distribution, a box delineating the 25th to the 75th percentile, the whiskers show the lowest datum still within 1.5 Inter Quartile Range (IQR) of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile. Wherever comparisons between different localization algorithms have been made, significance of comparative medians has been tested using the Mann-Whitney-Wilcoxon test.

In some instances, analysis of a particular simulated experiment is also undertaken to give a clearer understanding of both the collective behaviour and the agent behaviour. Such analysis is done through examining the team expanse and number of agent breakaways.

6 Optimization Results

The optimization process for ACLA is composed of two phases. First we optimize the algorithm's two key parameters for infinite attraction radius, i.e., adaptive cohesion coefficient, α_I and the adaptive sampling coefficient, β_τ. In the second phase, we optimize the critical number of agents, N_c, for limited attraction radii and show that we can achieve performance at par with the infinite attraction radius beyond a certain finite attraction radius. The explored values of the parameters during the optimization process are given in Table 2. For the constant parameters, refer to the settings given in Table 1.

6.1 Optimization for Infinite Attraction Radius

For the infinite attraction radius and varying initialization distances in the range of 600 m to 1400 m, the results for the optimized α_I and β_τ are shown in Fig. 7(a) and Fig. 7(b) respectively. It can be seen that the values of α_I^* are nearly identical for the considered initialization distances in Fig. 7(a). The average behaviour of α_I^* over the initialization distances, $\bar{\alpha}_I(N) = \frac{1}{3}\sum_{r_0} \alpha_I^*(r_0, N)$, is shown as a red-dashed line in Fig. 7(a) which we approximate as

$$\hat{\alpha}_I^*(N) = a_\alpha N^{b_\alpha} + c_\alpha \tag{9}$$

as shown in Fig. 8(a) and the values of the parameters are given in Table 3.

The values of β_τ^* vary significantly in initialization distance. We choose to approximate β_τ^* by its average response over the team sizes in the range of 2 to 20 agents, $\bar{\beta}_\tau(r_0) = 0.1\sum_N \beta_\tau^*(r_0, N)$, shown as dashed lines in Fig. 7(b), as

$$\hat{\beta}_\tau^*(r_0) = a_\beta r_0^{b_\beta} + c_\beta \tag{10}$$

as shown in Fig. 8(b) and the values of the parameters are given in Table 3.

Table 2. Explored values of the parameters during the optimization process

Param.	Description	Bounds
α_I	Adaptive cohesion coefficient	$[0, 2]$
β_τ	Adaptive sampling coefficient	$[0, 2]$
N_c	Critical number of neighbours	$[0, 20]$

Table 3. Parameter and Root Mean Square Error (RMSE) values for respective equations

Eq.	Parameter Values	RMSE
(9)	$a_\alpha = 1.661$, $b_\alpha = -1.935$, $c_\alpha = 0.3588$	0.003
(10)	$a_\beta = 2.247 \times 10^{-5}$, $b_\beta = 1.175$, $c_\beta = 0.7379$	2.66×10^{-5}
(11)	$a_N = 0.716$	0.5957

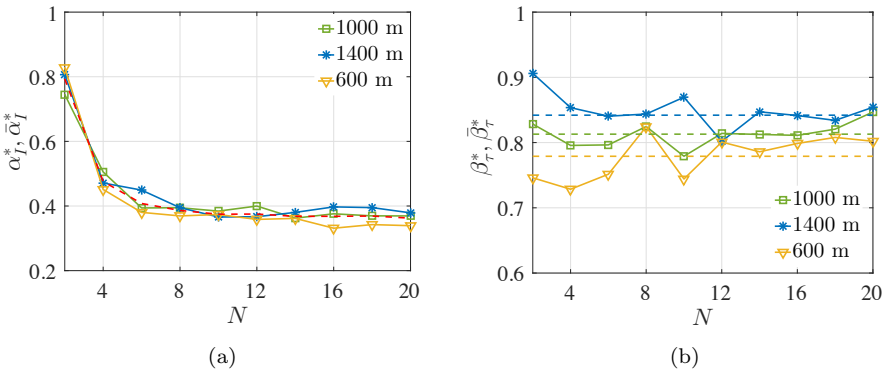


Figure 7. Optimization results for infinite attraction radius and varying initialization distances and team sizes (a) Optimized α_I where the red dashed-line shows the average response over the considered initialization distances. (b) Optimized β_τ where the dashed lines for each initialization distance are the average response over the team sizes in the range of 2 to 20 agents.

6.2 Optimization for Limited Attraction Radius

Now, let us optimize the critical number of agents, N_c, for limited attraction radii. Objective is to see if we can achieve performance for a certain limited attraction radius at par with the infinite attraction radius just by controlling the sampling times through CbA. This would mean that we do not need to optimize the other two parameters, i.e., the adaptive cohesion coefficient and the adaptive sampling coefficient, separately for each limited attraction radius.

The optimized critical number of agents as a function of team size is shown in Fig. 9(a) along with the optimized mean arrival times in Fig. 9(b) for limited attraction radii in the range of 10 % to 60 % of the initialization distance. It can be seen that for limited attraction radii, more than or equal to 30 % of the

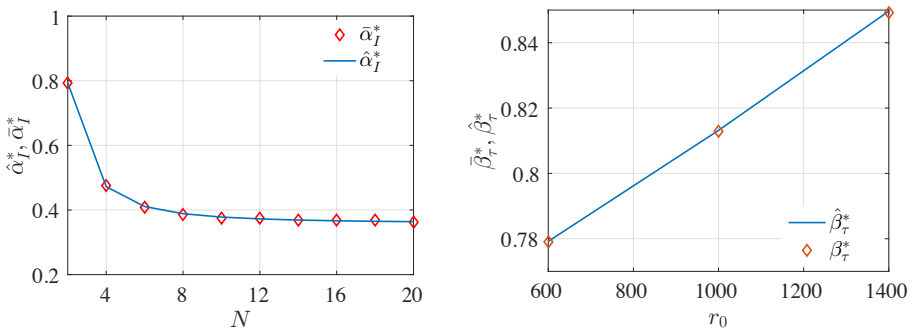


Figure 8. For infinite attraction radius, estimates for: (a) $\bar{\alpha}_I^*$. (b) $\bar{\beta}_\tau^*$.

attraction radius, the arrival performance is almost identical with the infinite attraction radius for team sizes of $N = 8$ and above.

As far as the optimization data for the critical number of agents is concerned in Fig. 9(a), it increases almost linearly in N for team sizes less than or equal to 16 agents for all the attraction radii. However, as the attraction radii increase, e.g., $r_{\mathrm{GC}} = 0.6r_0$, the N_{c}^* becomes saturated beyond a certain team size. Also, note that larger the number of N_{c}, the more conservative the CbA regulation as shown in Fig. 10. For attraction radii greater than or equal to $r_{\mathrm{GC}} = 0.3r_0$ where the performance is almost identical, we can see that the most conservative curve is for $r_{\mathrm{GC}} = 0.3r_0$ and hence we may assume that as a general estimate for all the attraction radii given the choice does not significantly degrade the performance of other attraction radii.

The estimate for the optimized critical number of neighbours can be written simply as a linear function in N as follows

$$\hat{N}_{\mathrm{c}}^*(N) = a_N N \tag{11}$$

and is shown as a solid line in Fig. 11(a) and the value of the parameter is given in Table 3. The associated mean arrival times have been shown in Fig. 11(b) where we can see that the choice of $\hat{N}_{\mathrm{c}}^*$ has worked well for all the limited attraction radii except $r_{\mathrm{GC}} = 0.1r_0$ if we compare the results of Fig. 11(b) with the results of Fig. 9(b).

7 Robustness Analysis

In this section, the robustness of the resulting collective behaviour from the estimated models of the optimized ACLA is validated against noise levels of $\sigma = 1$ dB and $\sigma = 6$ dB. Also, the performance of the collective behaviour is validated against initialization distance sensitivity, loss of source signal and

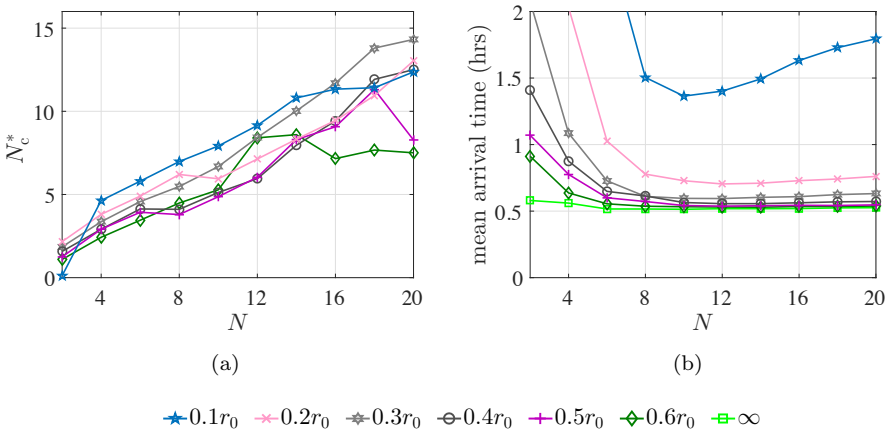


Figure 9. Optimization for limited attraction radius (see legend at the bottom): (a) Optimized critical number of agents. (b) Mean arrival times.

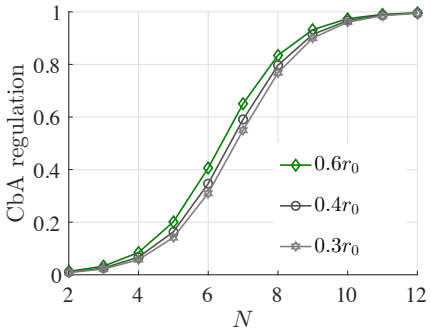


Figure 10. Optimized CbA regulation for a team size of 10 agents and various limited attraction radii in the range of $0.3r_0$ to $0.6r_0$.

neighbour detection noise in presence of $\sigma = 1$ dB and $\sigma = 6$ dB. For all the considered scenarios, the arrival time performance of the collective behaviour is robust and improves with the increasing team size.

The arrival time performance is either shown by using box-plots following the details given in Section 5.3 or by analyzing the team expanse of a single localization mission. Team expanse, e, is defined as the average distance of all the agents from the team's centroid, i.e.,

$$e = \frac{1}{N}\sum_{i}^{N}\|\mathbf{x}_c(t) - \mathbf{x}_i(t)\| \tag{12}$$

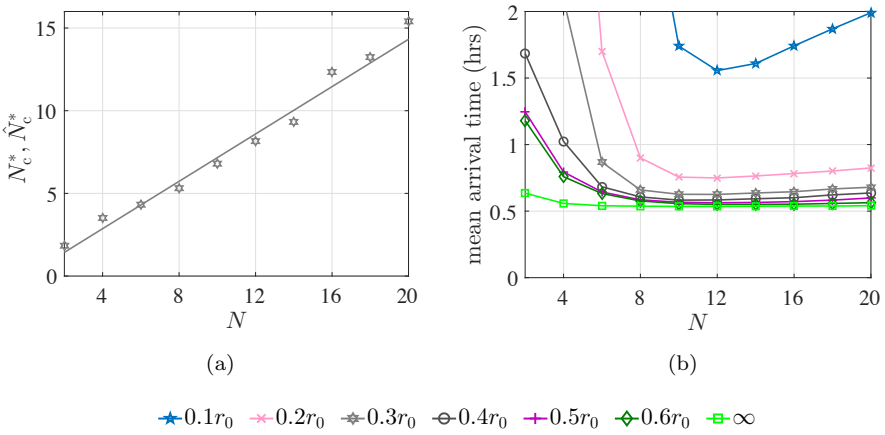


Figure 11. (a) Estimate for critical number of agents in limited attraction radii where solid line is the estimate for the data points. (b) Mean arrival times for the estimated model (see legend at the bottom for different attraction radii in the range of $0.1r_0$ to $0.6r_0$).

where $\mathbf{x}_c(t) = \frac{1}{N}\sum_i^N \mathbf{x}_i(t)$ is the team centroid at time t. Keeping in mind, the problem statement in Section 3, it is of interest to see if the expanse remains bounded. An agent breakaway is directly related to the team expanse. Since in ACLA, if an agent breaks away from the team, it will travel in a straight line and hence the the team expanse will continue to increase without bound.

7.1 Multipath Interference

The box-plots for ACLA's arrival time performance are shown in Fig. 12(a) and Fig. 12(b) for noise levels of 1 dB and 6 dB respectively. It can be seen that for both the plots, the variance as well as the median of the arrival time distributions improves as N is increased. Also the difference between the arrival time distribution of infinite attraction radius and $r_{GC} = 0.6r_0$ reduces as the team size increases and for $N > 12$, arrival time distributions are almost identical for both the noise levels of 1 dB and 6 dB.

The number of failed missions in a total number of 5×10^4 missions is equivalent to the number of events in which one or more agent breakaways occurred. The plots for failure rate are given in Fig. 13(a) for different attraction radii. It can be seen that for N_c^*, the failure rate has been less than 0.5 % for $r_{GC} \geq 0.6r_0$ for the entire range of team sizes and for $r_{GC} = 0.3r_0$, for $N > 6$ agents. However, for N_c^*, it is also seen that the failure rate starts increasing as the number of agents increase. There are two points that need to be noted. First, the optimization process has a single objective function, i.e., the mean arrival time. Second, more conservative CbA regulation, i.e., $N_c > N_c^*$, may

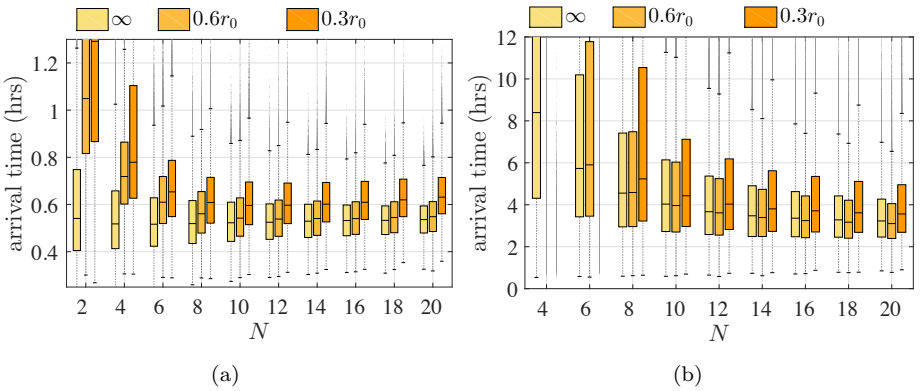


Figure 12. Arrival time performance for varying attraction radii (see legend) and varying levels of ambient noise for the analytical model estimated for the optimized ACLA: (a) $\sigma = 1$ dB. (b) $\sigma = 6$ dB.

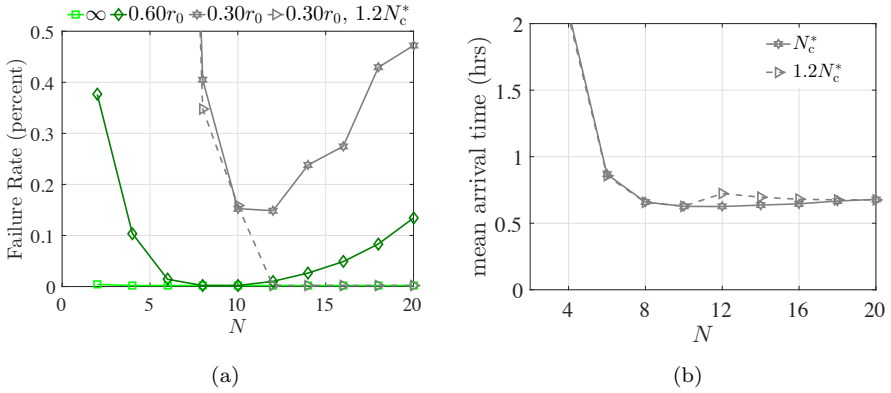


Figure 13. (a) Failure rate for varying attraction radii with optimal CbA and a more conservative CbA, i.e., 1.2 times the optimal N_c^*. (b) Mean arrival time comparison for $r_{GC} = 0.3r_0$ with optimal N_c^* against $r_{GC} = 0.3r_0$ with $1.2N_c^*$.

result in a lower failure rate but at the same time affect the mean arrival time performance. To substantiate this, we increase the critical number of agents such that $N_c = 1.2N_c^*$ and show in Fig. 13(a) that the failure rate goes to zero for $r_{GC} = 0.3r_0$ as N increases beyond 10 agents. However, it is shown in Fig. 13(b) that a more conservative strategy has a slightly degraded mean arrival time. The phenomenon highlights the need of a carefully thought multi-objective optimization setup which penalises the fitness of an individual in case there are any failures.

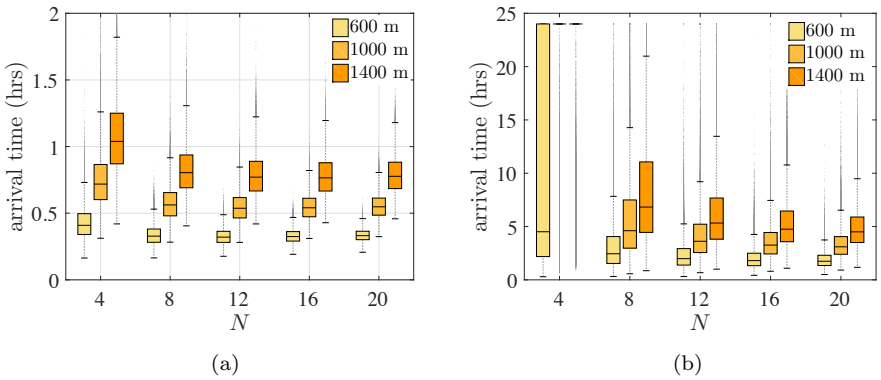


Figure 14. Initialization distance sensitivity analysis for optimized solution for $r_0 = 1000$ m and $r_{GC} = 0.6r_0$ and noise levels: (a) $\sigma = 1$ dB. (b) $\sigma = 6$ dB.

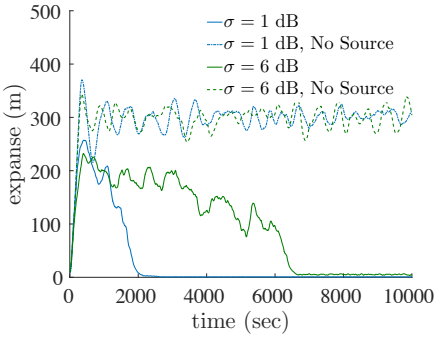


Figure 15. Comparative team expanse for source signal vs. loss of source signal for $r_0 = 1000$ m and $r_{GC} = 0.6r_0$.

7.2 Initialization Distance Sensitivity

As far as the problem statement discussed in this paper is concerned, the initialization distance can be controlled within a tight uncertainty range. However, it is desired that the optimized solution for a specific distance scales well for a wide range of distances. We conduct sensitivity analysis for an optimized solution for $r_0 = 1000$ m and $r_{GC} = 0.6r_0$ for a change of ± 400 m in Fig. 14(a) and Fig. 14(b) for $\sigma = 1$ dB and $\sigma = 6$ dB respectively. We can see that the optimized solution scales well with the change in distance for all the team sizes.

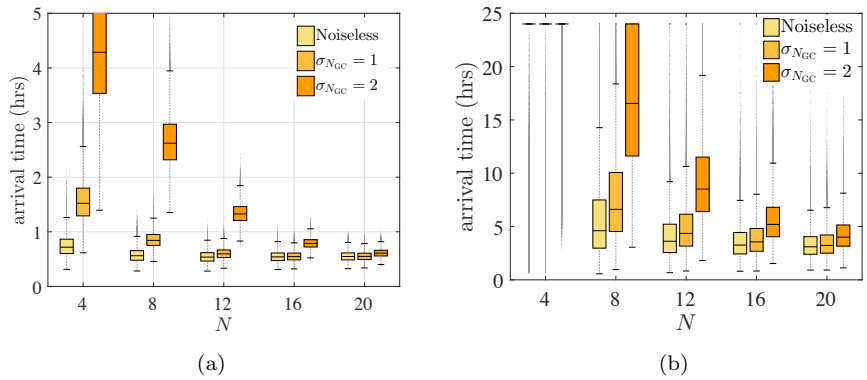


Figure 16. Neighbour detection noise analysis for optimized solution for $r_0 = 1000$ m and $r_{GC} = 0.6r_0$ and noise levels: (a) $\sigma = 1$ dB. (b) $\sigma = 6$ dB.

7.3 Loss of Source Signal

It is of interest to see how a cooperative team behaves in case the source signal disappears for some time. The primary concern in such a case is agents breaking away from the team. We conduct the analysis for a single localization mission for $\sigma = 1$ dB and $\sigma = 6$ dB. Figure 15 shows that the team expanse for the case of loss of source signal during a 2.8 h interval remains well regulated at approximately 300 m for $N = 20$ agents, $r_0 = 1000$ m and $r_{GC} = 0.6r_0$. We also explicitly checked for the number of agent breakaways during the mission and found no agent breakaways for all the four scenarios considered.

7.4 Neighbour Detection Noise

Since the proposed algorithm depends on the passive neighbourhood sensing, we conduct comparative analysis for performance degradation in case of different noise levels. Since we have two sensors, one on the right and one on the left, we corrupt the number of neighbours estimation on both sides by an additive Gaussian noise with zero mean and variance, $\sigma_{N_{GC}} = \{1, 2\}$. The output of the estimated neighbours is then truncated to the nearest integer value.

The arrival time performance for $\sigma = 1$ dB and $\sigma = 6$ dB is shown in Fig. 16(a) and Fig. 16(b) respectively for $r_0 = 1000$ m and $r_{GC} = 0.6r_0$. It can be seen that the relative degradation in performance with respect to a noiseless neighbourhood detection decreases as the team size increases.

8 Comparative Analysis

In this section, let us compare the performance of ACLA against our earlier work which builds on a self-sufficient individualistic model inspired by the biased random walk of a bacterium performing chemotaxis and a static group

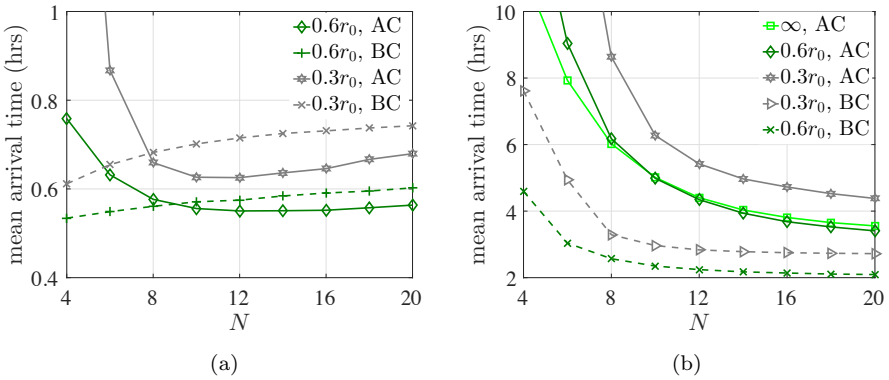


Figure 17. (a) Mean arrival time comparison for ACLA (AC in legend) versus Bio-CAST (BC in legend) for varying attraction radii and noise levels: (a) $\sigma = 1$ dB. (b) $\sigma = 6$ dB.

cohesion model (Shaukat and Chitre, 2016), referred to as Bio-inspired Control Algorithm for Small Teams (Bio-CAST). The optimized Bio-CAST used here for comparison is based on the same adaptive temporal sampling strategy as ACLA. In Fig. 17(a), the mean arrival times are shown for a noise level of 1 dB where ACLA is referred to as AC and Bio-CAST as BC in the legend. For both the cases of limited attraction radii, ACLA performs better than Bio-CAST for team sizes greater than 8 agents. However, if we increase the noise to 6 dB for the algorithms optimized for a noise level of 1 dB, we see that Bio-CAST is more robust to the ambient noise than ACLA. We can also see that ACLA is still in the process of improving its performance as N increases within the considered range of 1 to 20 agents while Bio-CAST is able to achieve its maximum performance at about a team size of 16 agents.

The comparative analysis shows that fusing ACLA and Bio-CAST in a more generic optimization setup may result in a more robust and a better performing localization algorithm. The fusion would assume an adaptive biased random walk which is a function of sensed number of neighbours. As the number of neighbours decrease, an agent would assume a more bacterium-like response to the changing intensity levels whereas it may let go off the self-sufficient individualistic behaviour completely when with a large number of neighbours. It will also be interesting to investigate how these behaviours evolve once optimized explicitly for a higher ambient noise scenario.

9 Conclusion

In this paper, a source localization algorithm based on adaptive group cohesion was presented. The proposed algorithm, called ACLA, achieves source localization as an emergent property through agent interactions. An agent does

not have a self-sufficient individualistic behaviour and hence is incapable of localizing the source on its own.

For optimizing the behaviours of ACLA, a two phase optimization strategy was introduced. In the first phase, IbA and the adaptive cohesion were optimized for infinite attraction radius and in the second phase CbA was optimized to minimize agent breakaways for limited attraction radii. It was shown that by only having an optimized CbA, the performance of finite attraction radii above a certain threshold can be made identical to the performance of an infinite attraction radius.

The optimized behaviours were then approximated with analytical models which were validated against sensor and actuator noise, strong multipath interference due to environment variability, sensitivities in initialization distance and loss of source signal. The statistical analysis of the arrival time distributions shows robustness of the collective behaviour for all the considered scenarios. The localization failure rate was also studied which shows that by selecting a slightly more conservative CbA, a more robust collective behaviour can be achieved with a zero failure rate.

ACLA was further compared against Bio-CAST, a source localization algorithm with a self-sufficient individualistic behaviour. It was shown that for low ambient noise levels, ACLA performs significantly better than Bio-CAST. However, for strong multipath interference, Bio-CAST is more robust than ACLA and performs significantly better. A fusion of the two algorithms which would result in an adaptive turning behaviour as a function of team size was also proposed as future work. The fusion approach may lead to a better performing and a more robust source localization algorithm.

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