OPTIMIZATION OF FIRST PASSAGE TIMES BY MULTIPLE COOPERATING MOBILE TRAPS

A. E. LINDSAY∗, J. C. TZOU†, AND T. KOLOKOLNIKOV‡

Abstract. We study the mean capture time of an unbiased random walker by multiple absorbing mobile traps in bounded domains of one and two spatial dimensions. In one dimension, we consider multiple traps undergoing prescribed oscillatory motion on an interval with reflecting or absorbing boundary conditions. We develop trap co-operation strategies which optimize the mean capture time. We find that as the frequency of oscillation passes through certain fixed values, the optimal trap strategy alternates between oscillating exactly in phase and exactly out-of-phase with neighboring traps. We also demonstrate a scenario in which the optimal configuration is neither in phase nor antiphase. In two dimensions, we consider two small traps rotating with the same angular velocity inside a unit disk, and characterize the optimal positions (radii of rotation and relative phase) of the two traps as a function of ω and trap radius r ≪ 1. We identify several distinguished regimes in ω where the optimal configuration can be distinctly characterized. In particular, in the ω ∼ O(1) regime, the optimal configuration jumps from one in which two traps rotate antipodal and along the same radius to one where the two traps rotate on the same side of the disk but at different radii. In addition, we demonstrate an algebraic approach to obtaining optimal configurations of N rotating traps as ω → ∞.

Key words. mean first passage time, multiple mobile traps, trap cooperation, asymptotic analysis, optimization strategy.

AMS subject classifications. 35B25, 35C20, 35J05, 35J08.

1 Introduction

We study the problem for the mean first passage time (MFPT) of a randomly diffusing particle to multiple absorbing mobile traps which undertake a prescribed motion in bounded regions of one and two spatial dimensions. Random motion is a ubiquitous transport mechanism in many biological, physical and chemical systems. Often, a significant event is triggered when a dispersing particle reaches a particular site, or meets another particle. Consequently, many important processes may be formulated as an MFPT problem for the expected time taken for a particle to hit a trap. One dimensional examples arise in finance, where an investor sells a stock when it reaches a certain threshold, and in sequential analysis and goodness of fit tests in statistics [11].

In two and three dimensions, a special case known as a narrow escape or narrow capture problem (see, e.g., [2, 8, 21, 23, 26–28]) arises when the size of the trap is small in comparison to that of the search domain. For example, intracellular processes require proteins to diffuse in the cytoplasm until they reach the nucleus where they are transported to the interior through nuclear pore complexes distributed on its surface [13, 14, 16, 22]. The cell nucleus is modeled as a small interior trap as its volume is small in comparison to that of the whole cell. Conversely, when ions diffuse in search of an open ion channel located on the cell membrane [6, 18, 23, 26], the traps may be modeled as small absorbing portions of an otherwise reflective boundary. The search for antigen presenting molecules in lymph node tissue by T cells may be modeled as a three dimensional narrow escape problem with interior traps [12] in which MFPT yields insight into immune system recognition. The applications of narrow escape problems are numerous, and we refer to [7, 19, 20] for detailed reviews.

Existing mathematical treatments of these examples predominantly assume that traps occupy a fixed location over time. However, in many applications traps are known to be mobile. In the example of intra-cellular transport, the cell nucleus is in motion before and after mitosis [29]; therefore proteins must diffuse to mobile targets in order to complete their processes. In one dimension, a scenario lending to mobile targets is that of fixation times in population genetics (see [31] and references therein). In this work, we investigate mean survival times of random walkers in the presence of multiple traps undergoing prescribed motion along a constrained path. In particular, we study the question of how multiple mobile searchers should cooperate in order to most quickly locate a diffusing target. We cite as a typical scenario the search of a lost person by a team of rescuers.

MFPT problems involving mobile traps have been gaining attention for their various applications and also because there is not yet a systematic methodology for their analysis as exists for stationary traps. A recent review on MFPT problems in bounded domains [3] cited the generalization to mobile traps as an interesting extension. Many works in this new direction have focused on one dimensional problems, where the mobile trap undergoes either random motion or advances in one direction linearly in time [4, 5, 10, 15, 17, 30].

An overarching question is whether a mobile trap is more or less effective than a stationary one. In [33], it was shown...
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that a single trap undergoing sinusoidal motion in a bounded one-dimensional interval is more effective only when the frequency exceeds a certain threshold. This criticality can be heuristically understood from a balance between two competing factors that contribute to the MFPT. First, the placement of the absorbing trap at the center of the one-dimensional interval results in a lower MFPT. Second, trap mobility allows a trap to explore its space more effectively and so improves its trapping ability. Therefore, a mobile trap is superior to a stationary one only when it moves quickly enough to overcome the detrimental effects of moving away from optimal spatial locations.

A similar two dimensional result was established in [32] for a single trap rotating inside the unit disk. The presence of two variables of motion (frequency and radius of rotation) poses a simple optimization problem: for a given frequency, what is the radius of rotation that would minimize average mean first passage times? In this setting, a similar criticality is observed where the trap must rotate sufficiently quickly to offset the detrimental effect of moving off the origin - the optimal spatial location for the unit disk [21].

In the present work, we analyze MFPT problems in bounded one and two dimensional regions with multiple mobile traps with prescribed trajectories and emphasize the optimization of average (or global) MFPT with respect to the relative motion between the traps. In §2, we consider a diffusing particle on a one-dimensional interval with reflecting or absorbing end points and absorbing internal traps with small amplitude oscillations at common frequency \( \omega \) and centered on fixed points with separation \( \ell \). A schematic of the one dimensional two trap problem is displayed in Fig. 1.1(a). The linearity of the governing equations allows for trivial extension of the present work to trap trajectories with multiple frequency components. However, we focus herein on trajectories described by a single frequency component as the resulting motion minimizes the MFPT under a fixed kinetic energy constraint.

We show in the one dimensional setup of Fig. 1.1(a) that the mean capture time of the particle averaged uniformly over all starting locations (often referred to as global MFPT) is minimized when the two traps oscillate either exactly in phase or exactly antiphase, depending on the sign of a certain quantity \( \chi(\omega \ell^2) \), where

\[
\chi(z) = \frac{\cosh \sqrt{2} \sin \sqrt{2} + \sinh \sqrt{2} \cos \sqrt{2}}{\cos \sqrt{2}z - \cosh \sqrt{2}z},
\]

the trap separation as \( \varepsilon \to 0 \) is \( \ell \), and the common frequency is \( \omega \). The oscillatory nature of \( \chi(z) \) means that the optimal strategy alternates as the frequency of the trap’s motion increases. In §2.1, these results are extended to \( N \) traps oscillating about fixed points \( x_j \) with small amplitude \( \varepsilon \) and common frequency \( \omega \). We determine that the globally optimal cooperation strategy corresponds to neighboring traps oscillating either exactly in phase or exactly out-of-phase depending on the sign of \( \chi(\omega \ell_j^2) \) where \( \ell_j = x_{j+1} - x_j \). We also illustrate a scenario in which the

![Figure 1.1: (a) A schematic of the 1D problem with two traps. Two traps oscillate in time at the same frequency tracing out the paths indicated by the curves. Their relative phase is arbitrary. (b) A schematic of the 2D problem with two traps. In the reference frame rotating clockwise at frequency \( \omega \), the first trap is placed on the horizontal axis (without loss of generality) at a distance \( r_1 \) from the origin. The second trap is phase shifted counterclockwise by angle \( \theta_2 \) and is a distance \( r_2 \) from the origin. Both traps have common radius \( \varepsilon \).](image)
optimizing strategy does not necessarily correspond to being exactly in or out-of-phase with adjacent traps. In §3, we consider $N$ small traps of radius $0 < \varepsilon \ll 1$ rotating clockwise with common frequency $\omega$ at distances $r_j$ from the center of a unit disk with $j = 1, \ldots, N$ (schematic in Fig. 1.1(b)). We use a matched asymptotics approach (e.g., [21, 23, 32]) to compute the global MFPT of a randomly diffusing particle. Our formulation allows for arbitrary phase differences between the traps. For $N = 2$, we perform a numerical optimization of the global MFPT with respect to the two radii of rotation in addition to the relative phase. The results of optimization show that as $\omega$ increases past a critical $\mathcal{O}(1)$ frequency, the optimal configuration of the traps switches from rotating at the same radius but $\pi$-radians out of phase to rotating at different radii but exactly in phase. We also show that in the regime $\mathcal{O}(1) \ll \omega \ll \mathcal{O}(\varepsilon^{-1})$, the optimal radii of $N$ traps divides the unit disk into $N$ annuli of equal area (with the outermost radius approaching the boundary). We further use a hybrid numeric-asymptotic method [9, 32] to interpolate between these two regimes, showing that the transition between the regimes is smooth. In §4, we draw conclusions and list open avenues for further work. For a related problem involving optimizing the fundamental Neumann eigenvalue on a two-dimensional domain with $N$ small Dirichlet holes, see [21] and the references therein.

2 Multiple Traps in 1D

In this section we consider the MFPT problem in a bounded one-dimensional interval with reflecting stationary endpoints, and two mobile internal traps undergoing prescribed oscillatory motion with period $2\pi/\omega$. The main idea in the formulation of these moving domain problems is to project the trap motion in a new direction, orthogonal to the walker’s spatial motion, and coupled to an advection term in that direction (cf. Fig. 2.1).

For a random walk with Brownian dynamics in the $x$ direction and deterministic transport in the positive $t$ direction, the equation satisfied by the MFPT $u(x,t)$ of a particle initially at $(x, t)$ is derived by first considering discrete jumps of size $\Delta x$ in the time interval $(t, t + \Delta t)$. This yields that,

$$u(x, t) = \Delta t + \frac{1}{2} \left[ u(x + \Delta x, t + \Delta t) + u(x - \Delta x, t + \Delta t) \right]. \quad (2.1)$$

In the limit $\Delta x \rightarrow 0$ and $\Delta t \rightarrow 0$ with $D = \Delta x^2 / (2\Delta t)$ fixed, equation (2.1) reduces to the partial differential equation [5, 25, 33]

$$u_t + Du_{xx} + 1 = 0; \quad 0 < x < 1; \quad 0 < t < \frac{2\pi}{\omega}; \quad u(x, 0) = u \left( x, \frac{2\pi}{\omega} \right), \quad 0 < x < 1; \quad (2.2a)$$

for the MFPT $u(x, t)$, starting from $(x, t)$. This approach is readily applicable to non-stationary boundaries with a variety of boundary conditions. In what follows, we consider the boundary conditions

$$u_x(0, t) = u_x(1, t) = 0, \quad (2.2b)$$

$$u(x_1 + \varepsilon f_1(t)) = u(x_2 + \varepsilon f_2(t)) = 0, \quad (2.2c)$$

so that the domain exterior is reflecting and there are two absorbing interior traps. For convenience, the diffusivity will
be normalized to one for the remainder of the treatment. Each mode in the dynamics of a trap can be considered in isolation due to the linearity of (2.1), so the two absorbing traps (2.2c) are assumed to undergo motion with a common frequency $\omega$, but with a phase shift according to their cooperation strategy,

$$f_1(t) = \sin \omega t, \quad f_2(t) = \sin \omega (t - \phi), \quad \phi \in \left(0, \frac{2\pi}{\omega}\right). \quad (2.2d)$$

In Fig. 2.2, the two extremal cooperation strategies are displayed with $\phi = 0$ and $\phi = \pi/\omega$ indicating in and out of phase cooperation strategies respectively. The main goal is to understand how the relative motion of the traps affects the mean time to capture. In particular, for which values of $\phi$ is the MFPT optimized? To study this we calculate the global MFPT

$$\tau(\omega; \phi) = \frac{\omega}{2\pi} \int_0^{2\pi} \int_{x=0}^{1} u(x, t) \, dx \, dt , \quad (2.3)$$

which gives a measure of the trapping effectiveness of the configuration. From this quantity, optimizing configurations of $\phi$ and $\omega$ can be determined. In the limit $\varepsilon \to 0$, (2.2) admits a regular expansion of form

$$u(x, t) = u_0(x) + \varepsilon u_1(x, t) + \varepsilon^2 u_2(x, t) + O(\varepsilon^3) , \quad (2.4a)$$

with $u_x(0, t) = u_x(1, t) = 0$. Expanding around the trapping boundaries supplements the equations with the internal conditions

$$u_0(x_j) = 0, \quad u_1(x_j) = -u''_0(x_j) f_1, \quad u_2(x_j) = -\frac{u''_0(x_j)}{2} f_1^2 - u'_1(x_j) f_1, \quad j = 1, 2. \quad (2.4b)$$

This subdivides the interval $\Omega = [0, 1]$ into three distinct regions

$$\mathcal{R}_1(t) = \{0, x_1 + \varepsilon f_1(t)\}, \quad \mathcal{R}_2(t) = \{x_1 + \varepsilon f_1(t), x_2 + \varepsilon f_2(t)\}, \quad \mathcal{R}_3(t) = \{x_2 + \varepsilon f_2(t), 1\}. \quad (2.4c)$$

In the analysis that follows, the regular expansion (2.4a) is substituted into equation (2.2) and terms gathered at each order of $\varepsilon$. This generates a sequence of reduced problems for $u_0, u_1, u_2, \ldots$ for which explicit solutions satisfying boundary conditions (2.4b) are obtained. From these solutions, the global MFPT arising from a uniform distribution of initial locations can be obtained by explicit integration of $\tau$ defined in (2.3). Once this explicit expression for $\tau(\phi, \omega)$ is obtained, the role of trap motion can be studied explicitly and cooperation strategies determined.
At the leading order of the expansion, the problem \( u_0(x, t) \) satisfies
\[
\begin{align*}
\frac{\partial u_0}{\partial t} + u_0 + u_{0xx} + 1 &= 0, \quad -1 < x < 1; \quad u_0(x, 0) = u_0(1) = 0, \quad u(x_j) = 0, \quad j = 1, 2,
\end{align*}
\] (2.5)
which corresponds to the stationary solution in the absence of trap motion. The solution is \( t \) independent and given by
\[
\begin{align*}
u_0(x) &= \frac{1}{2} \begin{cases} 
-x^2 + x_1^2, & x \in R_1(t); \\
-x^2 + (x_1 + x_2)x - x_0x_1, & x \in R_2(t); \\
(x_2 - x)(x_2 + x - 2), & x \in R_3(t).
\end{cases}
\end{align*}
\] (2.6)

**Order \( \varepsilon^1 \):** In region \( R_1 \), the boundary conditions on the correction term \( u_1(x, t) \) are \( u_{1x}(0) = 0 \) together with
\[
\begin{align*}
u_1(x_1) &= -u_0'(x_1)f_1 = \frac{x_1}{2i} \left( e^{\omega_1^2 t} - e^{\omega_2^2 t} \right),
\end{align*}
\] (2.7)
which gives rise to a correction equation featuring homogeneous solutions of
\[
\phi_{xx} + \phi_t = 0, \quad \phi(x, 0) = \phi \left( x, \frac{2\pi}{\omega} \right). \tag{2.8a}
\]
The general solution of (2.8a) which matches the boundary conditions (2.7) is
\[
\phi(x, t; \omega) = e^{\omega_1^2 t} \left[ A_1 \cosh \omega_+ x + B_1 \sinh \omega_+ x \right] + e^{\omega_2^2 t} \left[ A_2 \cosh \omega_- x + B_2 \sinh \omega_- x \right], \quad \omega_\pm = \sqrt{\pm i \omega}, \tag{2.8b}
\]
for constants \( A_1, A_2, B_1, B_2 \). It is convenient to work with a complex form of the solution until the final result, at which point the real form is obtained. Fitting the relevant boundary conditions for \( u_1(x_j) \) at \( j = 1, 2 \), gives the solutions in each region to be
\[
\begin{align*}
u_1 &= \frac{x_1}{2i} \left( e^{\omega_1^2 t} \frac{\cosh \omega_- x}{\cosh \omega_- x_1} - e^{\omega_2^2 t} \frac{\cosh \omega_+ x}{\cosh \omega_+ x_1} \right), \quad x \in R_1; \tag{2.9a} \\
u_1 &= \frac{\ell}{4i} \left( \frac{e^{\omega_1^2 t}}{\sinh \omega_- \ell} \left[ \sinh \omega_- (x - x_2) + e^{\omega_2^2 t} \phi \sinh \omega_- (x - x_1) \right] - \frac{e^{\omega_2^2 t}}{\sinh \omega_+ \ell} \left[ \sinh \omega_+ (x - x_2) + e^{\omega_1^2 t} \phi \sinh \omega_+ (x - x_1) \right] \right), \quad x \in R_2; \tag{2.9b} \\
u_1 &= \frac{x_2 - 1}{2i} \left( e^{\omega_1^2 t} \frac{\cosh \omega_- (x - 1)}{\cosh \omega_- (x_2 - 1)} - e^{\omega_2^2 t} \frac{\cosh \omega_+ (x - 1)}{\cosh \omega_+ (x_2 - 1)} \right), \quad x \in R_3, \tag{2.9c}
\end{align*}
\]
where \( \ell = x_2 - x_1 \). As \( u_1(x, t) \) has zero mean over \( t \in (0, \frac{2\pi}{\omega}) \), it does not make a direct contribution to \( \tau \) in (2.3). However, \( u_{1x}(x_j) \) for \( j = 1, 2 \) contributes to \( \tau \) through the boundary conditions on \( u_2(x_j) \) given in (2.4b).

**Order \( \varepsilon^2 \):** Taking the general form \( u_{1x}(x_j) = a_j e^{\omega_1^2 t} + b_j e^{\omega_2^2 t} \) where \( a_j \) and \( b_j \) are coefficients taken from (2.9), the boundary conditions on \( u_2(x_j) \) from (2.4b) are
\[
\begin{align*}
u_2(x_j) &= -\frac{u_0''(x_j)}{2} f_1^2 - u_1'(x_j)f_1 = \frac{1}{2} - \frac{a_j}{2t} + \frac{b_j}{2t} + O(e^{2\omega^2 t}).
\end{align*}
\]
The general solution is therefore of form \( u_2(x, t) = u_{2h}(x) + u_{2p}(x, t) \), where \( u_{2p}(x, t) \) is the periodic component with zero mean over \( t \in (0, \frac{2\pi}{\omega}) \) and makes no contribution to the value of \( \tau \). Therefore only \( u_{2h}(x) \) is required in each of the sub regions. As \( u_{2h} \) satisfies a homogeneous Neumann condition in regions \( R_1, R_3 \), its value is constant.
in those regions while in $\mathcal{R}_2$, Dirichlet conditions are applied at either end of the region resulting in a linear $u_{2h}$:

$$u_{2h} = \frac{1}{2} - \frac{x_1}{4} \left( \omega_+ \tanh \omega_+ x_1 + \omega_- \tanh \omega_- x_1 \right), \quad x \in \mathcal{R}_1,$$

$$u_{2h} = \frac{x - x_1}{4} \left( \frac{\omega_+ \sinh \omega_+ \ell}{\sinh \omega_- \ell} - \frac{\omega_- \sinh \omega_- \ell}{\sinh \omega_+ \ell} \right) \sin \omega \phi + \frac{1}{8} \left( \frac{\omega_+ \cosh \omega_+ \ell}{\cosh \omega_- \ell + e^{\omega \phi}} + \frac{\omega_- \cosh \omega_- \ell}{\cosh \omega_+ \ell + e^{-\omega \phi}} \right), \quad x \in \mathcal{R}_2,$$

$$u_{2h} = \frac{1}{2} - \frac{1 - x_2}{4} \left( \omega_+ \tanh \omega_+ (1 - x_2) + \omega_- \tanh \omega_- (1 - x_2) \right), \quad x \in \mathcal{R}_3.$$  

The value of $\tau$ is calculated by integration in each subregion with application of Leibniz’s rule. This gives

$$\tau = \frac{\omega}{2\pi} \int_0^{2\pi} \left[ \int_{\mathcal{R}_1} u \, dx + \int_{\mathcal{R}_2} u \, dx + \int_{\mathcal{R}_3} u \, dx \right] dt = \tau_0 + \epsilon^2 \tau_2 + \cdots,$$

where, after much algebra and simplification of complex valued expressions, the final result

$$\tau_0 = \frac{x_1^2}{3} + \frac{(1 - x_2)^3}{3} + \frac{\ell^3}{12};$$

$$\tau_2 = \frac{\sqrt{2\omega_0 x_1}}{4} \left( \frac{\sin \sqrt{2\omega_0} x_1 + \sin \sqrt{2\omega_0} x_1}{\cos \sqrt{2\omega_0} x_1 + \sin \sqrt{2\omega_0} x_1} \right) - \frac{\sqrt{2\omega_1(1 - x_2)^2}}{4} \left( \frac{\sin \sqrt{2\omega_1(1 - x_2)} + \sin \sqrt{2\omega_1(1 - x_2)}}{\cos \sqrt{2\omega_1(1 - x_2)} + \sin \sqrt{2\omega_1(1 - x_2)}} \right)$$

$$+ \frac{\ell}{2} + \frac{\sqrt{2\omega_0 \ell}}{8} \left[ \frac{\sin \sqrt{2\omega_0 \ell} + \sin \sqrt{2\omega_0 \ell}}{\cos \sqrt{2\omega_0 \ell} - \cosh \sqrt{2\omega_0 \ell}} + 2 \left( \cosh \frac{\sqrt{2\omega_0 \ell}}{\sqrt{2\omega_0 \ell} \sin \frac{\sqrt{2\omega_0 \ell}}{\sqrt{2\omega_0 \ell} \cos \sqrt{2\omega_0 \ell}} \frac{\sqrt{x_1^2}}{\sqrt{2\omega_0 \ell}} \cos \omega \phi \right) \right].$$

is obtained. Before proceeding to study the local extrema of $\tau$, we first remark that $\tau_0$ and $\tau_2$ each contain three distinct contributions from each of the three intervals. In $\tau_0$ and $\tau_2$, the first two terms are contributions from the intervals $\mathcal{R}_1(t)$ and $\mathcal{R}_3(t)$ respectively, while the final terms are contributions associated with $\mathcal{R}_2(t)$. The local extrema of $\tau = \tau(\phi)$ are $\omega \phi = 0, \pi$ and correspond to the two traps being exactly in or out phase with each other. The nature of these critical points is determined by

$$\frac{d^2 \tau}{d\phi^2} = -\epsilon^2 \frac{\sqrt{2\omega_0 \ell}}{4} \cos \omega \phi, \quad \chi(z) = \left[ \frac{\cosh \sqrt{2\omega_0 \ell} \sin \sqrt{2\omega_0 \ell} + \sin \sqrt{2\omega_0 \ell} \cos \sqrt{2\omega_0 \ell}}{\cos \sqrt{2\omega_0 \ell} - \cosh \sqrt{2\omega_0 \ell}} \right],$$

Therefore, the MFPT is minimized by the traps moving in phase ($\phi = 0$) when $\chi(\omega \ell^2) < 0$ and by out of phase ($\phi = \pi/\omega$) when $\chi(\omega \ell^2) > 0$. The graph of $\chi(z)$ in Fig. 2.3 indicates that its sign changes over certain intervals of $z = \omega \ell^2$. Applying a large argument approximation to $\chi(z_k) = 0$ implies that these thresholds behave asymptotically like

$$z_k \sim \frac{\pi^2}{8} \left( -1 + 4k \right)^2, \quad k = 1, 2, 3, \ldots,$$

which agrees closely with values obtained from numerical solution of $\chi(z_k) = 0$ given in Table 2.1. Therefore, the optimal alignment strategy of the traps alternates as the quantity $\omega \ell^2$ increases. In the fast trap motion limit $\omega \to \infty$, the trap cooperation strategy is of diminished importance since $\chi(\omega \ell^2) \to 0$ as $\omega \to \infty$. In the next section, we extend the analysis to an array of absorbing mobile traps in a bounded 1D interval.

### 2.1 $N$ traps in 1D

The analysis of the previous section can easily be extended to accommodate $N$ traps undergoing motion with relative phases to one another. The 1D domain $(x_1, x_N)$ is expressed as union of $N - 1$ intervals $\bigcup_{j=1}^{N-1} \mathcal{R}_j(t)$ where

$$\mathcal{R}_j(t) = (x_j + \epsilon f_j(t), x_{j+1} + \epsilon f_{j+1}(t)), \quad f_j(t) = \sin \omega (t - \phi_j), \quad \ell_j = x_{j+1} - x_j.$$
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Figure 2.3: Plot of $\chi(z)$ from (2.13) with first three roots indicated. The MFPT is minimized by traps moving in phase when $\chi(\omega\ell^2) < 0$ and out of phase when $\chi(\omega\ell^2) > 0$.

<table>
<thead>
<tr>
<th>$z_1$</th>
<th>$z_2$</th>
<th>$z_3$</th>
</tr>
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<td>60.4513</td>
</tr>
<tr>
<td>Numerical</td>
<td>11.1866</td>
<td>60.4517</td>
</tr>
</tbody>
</table>

Table 2.1: Approximate (2.14) and numerical values for the critical $z = \omega\ell^2$ over which the optimal cooperation strategy changes.

In this case we stipulate that all traps, including the end points, are absorbing so that

$$u(x_j + \varepsilon f_j(t), t) = 0, \quad j = 1, \ldots, N.$$  \hfill (2.15)

We assume the cooperation phases $\phi_j$ are free variables over which to optimize. The process for obtaining the regular expansion solution of (2.1) with trapping conditions (2.15) as $\varepsilon \to 0$ is identical to that of Sec.2. In particular, the solution over each interval $\mathcal{R}_j$ can be solved in terms of the phase difference between the boundary points $x_j, x_{j+1}$. As such, the contributions to the MFPT $\tau$ from each individual cell are exactly analogous to the contribution of the central region $\mathcal{R}_2$ in (2.12). Therefore, the same process yields that as $\varepsilon \to 0$,

$$\tau = \sum_{j=1}^{N-1} \frac{\ell_j^3}{12} + \varepsilon^2 \sum_{j=1}^{N-1} \left[ \frac{\ell_j}{2} + \frac{\sqrt{2\omega\ell_j^2}}{8} \left( \frac{\sin \sqrt{2\omega\ell_j} + \sinh \sqrt{2\omega\ell_j}}{\cos \sqrt{2\omega\ell_j} - \cosh \sqrt{2\omega\ell_j}} + 2\chi(\omega\ell_j^2)\cos \omega(\phi_{j+1} - \phi_j) \right) \right] + O(\varepsilon^2), \hfill (2.16)$$

where $\ell_j = x_{j+1} - x_j$. In Fig. 2.4 we display a numerical comparison of this formula for $N = 2$ with the MFPT obtained from full numerical simulation of (2.2) and observe close agreement. Additionally, we numerically observe the optimal cooperation strategy switching over when $\omega\ell^2 = z_1 \approx 11.1866$ as determined from the roots of $\chi(z)$ in (2.13).

When the intervals have common length, $\ell_j = \ell$ for $j = 1, \ldots, N - 1$, the conclusions are the same as the two trap case, i.e. the MFPT is minimized by moving in phase with the neighboring trap if $\chi(\omega\ell^2) < 0$ and out of phase with neighboring traps if $\chi(\omega\ell^2) > 0$. For non uniform spacing, finding the lowest MFPT is reduces to minimizing $f(s_1, \ldots, s_n) = \sum_{j=1}^n a_j \cos s_j$ for $s_j \in (0, 2\pi)$. The global minimum of this function is $-\sum_{j=1}^n |a_j|$ which is attained when $s_j = 0$ if $a_j < 0$ and $s_j = \pi$ if $a_j > 0$. Consequently, the co-operation strategy of $N$ traps which minimizes the MFPT (2.16) up to $O(\varepsilon^2)$ is

$$\phi_{j+1} - \phi_j = \begin{cases} 0 & \text{if } \chi(\omega\ell_j^2) < 0; \\ \pi & \text{if } \chi(\omega\ell_j^2) > 0, \end{cases} \hfill (2.17)$$
with a corresponding minimum MFPT $\tau_{\text{min}}$

$$\tau_{\text{min}} = \sum_{j=1}^{N-1} \frac{\ell_j^4}{12} + \varepsilon^2 \sum_{j=1}^{N-1} \left[ \frac{\ell_j^2}{2} + \frac{\sqrt{2} \omega \ell_j^2}{8} \left( \sin \frac{\sqrt{2} \omega \ell_j}{\cos \sqrt{2} \omega \ell_j - \cosh \frac{\sqrt{2} \omega \ell_j}{2} | \chi(\omega \ell_j^2) |} \right) \right] + \mathcal{O}(\varepsilon^2). \quad (2.18)$$

as $\varepsilon \to 0$. Similarly, the global MFPT $\tau$ is maximized by adopting the opposite phase cooperation strategy to (2.17).

(a) Numerical solution of (2.2) over two periods with two in phase mobile absorbing boundary traps. Parameters $\ell = 1$, $\omega = 1$, $\varepsilon = 0.2$ and $\phi = 0$.

(b) Numerical solution of (2.2) over two periods with two out of phase mobile absorbing boundary traps. Parameters $\ell = 1$, $\omega = 1$, $\varepsilon = 0.2$ and $\phi = \pi/2$.

(c) $\tau$ against $\omega \phi$ for $N = 2$, $\omega = 1$, $\varepsilon = 0.2$ and $\ell = 1$, ($\omega \ell^2 = 1$). Asymptotic (solid) and numerical solutions (circles).

(d) $\tau$ against $\omega \phi$ for $N = 2$, $\omega = 2$, $\varepsilon = 0.1$, and $\ell = 3$ ($\omega \ell^2 = 18$). Asymptotic (solid) and numerical solutions (circles).

Figure 2.4: Panels (a,b): Numerical solutions of (2.1) for two in phase (top left) and out of phase (top right) traps. Panels (c,d): Agreement of numerical simulations and asymptotic theory as the phase difference between the two traps varies. When $\omega \ell^2 = 1$, the MFPT is minimized at $\phi = 0$ (bottom left) and for $\omega \ell^2 = 18$, an out-of-phase strategy $\omega \phi = \pi$ minimizes the MFPT (bottom right).

2.2 Adaptation to neighboring traps

As a demonstration of this theory in which the optimal strategy is not exactly in phase or out of phase, we suppose a fixed configuration of traps is present with common frequency $\omega$ and individual phases. We then insert an additional trap of frequency $\omega$ at location $x_k$ with phase $\phi_k$. The contribution to the MFPT $\tau$ which depends only on the phase
In particular, we consider the scenario in which the two mobile traps perform a search for a particle diffus-

\[ \phi_k \] of the additional trap is

\[ I_k = \frac{\varepsilon^2}{\sqrt{8\omega}} \left[ z_k \cos \omega(\phi_{k+1} - \phi_k) + z_{k-1} \cos \omega(\phi_k - \phi_{k-1}) \right], \quad z_k = \omega t_k^2 \chi(t_k^2), \tag{2.19} \]

where \( x_{k+1} \) and \( x_{k-1} \) are the locations of the traps adjacent to the inserted one. Assuming \( \phi_{k-1} \) and \( \phi_{k+1} \) are fixed, the local extrema of this interaction function are the two solutions \( \phi_k^\pm \in (0, 2\pi/\omega) \) of the equation

\[ \tan \omega \phi_k^\pm = \frac{z_k \sin \omega \phi_{k+1} + z_{k-1} \sin \omega \phi_{k-1}}{z_k \cos \omega \phi_{k+1} + z_{k-1} \cos \omega \phi_{k-1}}. \tag{2.20} \]

Therefore, the optimal interaction strategies are not simply in or out of phase with the adjacent traps, but determined by a weighted average of their phases. The nature of each local extrema follows from the sign of

\[ \frac{d^2 I_k}{d^2 \phi_k} (\phi_k^\pm) = -\omega^2 I_k (\phi_k^\pm) = -\frac{\varepsilon^2 \omega^3}{\sqrt{8}} \sec \omega \phi_k^\pm \left[ z_k \cos \omega \phi_{k+1} + z_{k-1} \cos \omega \phi_{k-1} \right]. \]

As an example, consider two mobile traps centered at \( x = 0, 1 \) with fixed phases \( \omega \phi = 0, \frac{\pi}{4} \) respectively and common frequency \( \omega \). An additional mobile trap is centered at location \( 0 < s < 1 \) with phase \( \phi_s \) and frequency \( \omega \). From (2.20), the optimizing values of \( \phi_s \) satisfy

\[ \tan \omega \phi_s^\pm = \frac{(1 - s)^2 \chi(\omega(1 - s)^2) \sin \frac{\pi}{4}}{(1 - s)^2 \chi(\omega(1 - s)^2) \cos \frac{\pi}{4} + s^2 \chi(\omega s^2)}. \tag{2.21} \]

In Fig. 2.5, we display the solution of (2.21) for values of \( \omega = 5 \) and \( \omega = 50 \). The optimal adaptation strategy is observed to depend quite sensitively on the frequency \( \omega \) and the spatial placement of the trap.

### 3 \( N \) traps on a unit disk

In this section, we seek optimal cooperation strategies for two small identical mobile traps in a bounded two-dimensional domain. In particular, we consider the scenario in which the two mobile traps perform a search for a particle diffus-
ing inside the reflective unit disk \( \Omega \) by rotating around the center of the disk at a constant angular frequency \( \omega \). We first derive the two-dimensional analog of the one-dimensional MFPT problem (2.2) with a single mobile absorbing trap undergoing \( 2\pi/\omega \)-periodic motion. We let \( \Omega \) be any arbitrary bounded two-dimensional domain over which the search is conducted. The set of points occupied by the trap are denoted \( \Omega_{\text{trap}}(z) \subset \Omega \), which indicates the shape and location of the trap at time \( z \) while satisfying the periodicity condition \( \Omega_{\text{trap}}(z) = \Omega_{\text{trap}}(z + 2\pi/\omega) \). The particle location \( x = (x, y) \) at time \( z \) thus takes on the values \( x \in \Omega \setminus \Omega_{\text{trap}}(z) \). The particle is absorbed at time \( z \) when \( x \in \partial \Omega_{\text{trap}}(z) \). See the left panel in Fig. 3.1. In this way, the particle undergoes a random walk in the \( x \) direction with a deterministic drift in the \( z \) direction. For a particle located at \( x \) at time \( z \), its MFPT \( u(x, z) \) is then an average of the MFPT associated with all the locations it can possibly occupy at time \( z + \Delta z \) plus the \( \Delta z \) time it takes to get there. That is

\[
\begin{align*}
  u(x, y, z) &= \frac{1}{4} \left[ u(x + \Delta x, y, z + \Delta z) + u(x - \Delta x, y, z + \Delta z) 
  + u(x, y + \Delta y, z + \Delta z) + u(x, y - \Delta y, z + \Delta z) \right] + \Delta z; \\
  u &= 0, \quad x \in \Omega_{\text{trap}}(z). 
\end{align*}
\]

(3.1)

Expanding for small \( \Delta x \), \( \Delta y \), and \( \Delta z \), and taking the usual limit \( \Delta x = \Delta y \to 0 \) and \( \Delta z \to 0 \) with \( \Delta z \sim \Delta x^2 = \Delta y^2 \), we obtain the three-dimensional boundary value problem for the MFPT \( u(x, z) \)

\[
\begin{align*}
  \Delta_x u + u_z + 1 &= 0, \quad x = (x, y) \in \Omega \setminus \Omega_{\text{trap}}(z), \quad z \in [0, 2\pi/\omega), \\
  u &= 0, \quad x \in \partial \Omega_{\text{trap}}(z), \quad \partial_n u = 0, \quad x \in \partial \Omega, \quad z \in [0, 2\pi/\omega), \\
  u(x, 0) &= u(x, 2\pi/\omega), \quad x \in \Omega \setminus \Omega_{\text{trap}}(0). 
\end{align*}
\]

(3.2)

In (3.2), \( \Delta_x \equiv \partial^2/\partial x^2 + \partial^2/\partial y^2 \), and we have assumed periodicity of the trap’s motion \( \Omega_{\text{trap}}(z + 2\pi/\omega) = \Omega_{\text{trap}}(z) \). The motion of the random particle is therefore diffusive in the \( x-y \) plane with a deterministic drift in the positive \( z \) direction. The quantity \( u(x, z) \) gives the mean time to capture of a random particle starting from location \( x \) by a mobile trap beginning its periodic motion with configuration \( \Omega_{\text{trap}}(z) \). The schematic of this three-dimensional problem is shown in the right panel of Fig. 3.1. We remark that the derivation generalizes easily to \( N \) mobile traps each undergoing \( 2\pi/\omega \)-periodic motion. Analysis of (3.2) is in general very difficult. We therefore consider the special case in which the \( N \) traps rotate at the same frequency about the center of a unit disk. With this rotational symmetry, the geometry of the corresponding PDE remains two dimensional. A detailed derivation of the PDE for a single rotating trap is given in [32], which we generalize here for \( N \) rotating traps. In the frame of \( N \) traps each rotating clockwise about the center of the disk with common frequency \( \omega \), we obtain the mixed Neumann-Dirichlet boundary value problem

\[
\begin{align*}
  \Delta u + \omega u_\theta + 1 &= 0, \quad x \in \Omega \setminus \bigcup_{j=1}^N \Omega_{\epsilon_j}; \\
  u &= 0, \quad x \in \partial \Omega_a = \bigcup_{j=1}^N \partial \Omega_{\epsilon_j}, \quad j = 1, \ldots, N; \quad \partial_n u = 0, \quad x \in \partial \partial \Omega, 
\end{align*}
\]

(3.3)

where \( u_\theta \) is the derivative of \( u \) with respect to the angular coordinate \( \theta \). In (3.3), \( \Delta \) denotes the Laplacian with respect to the polar coordinates \( (r, \theta) \), \( \partial \Omega_a \) the union of the absorbing boundaries of \( N \) small traps separated by \( \mathcal{O}(1) \) distance, \( \partial \partial \Omega \) the reflective outer boundary of the disk, and \( u(x) \) the nondimensional mean first passage time of a random walker starting from location \( x \) to one of the traps. The \( j \)-th trap \( \Omega_{\epsilon_j} = x_j + \epsilon \Omega_{\epsilon_{0j}} \) is centered at location \( x_j \), where \( \Omega_{\epsilon_{0j}} \) is the \( \mathcal{O}(1) \) geometry of the trap and \( \epsilon \) is its “radius”. The schematic and a typical solution (computed using the finite element software FlexPDE [1]) are shown in Figs. 1.1(b) and 3.2, respectively.

Assuming a uniform distribution of starting locations, the average MFPT (or sometimes referred to as global MFPT) is the quantity

\[
\bar{u} = \frac{1}{|\Omega|} \int_{\Omega} u(x) d\Omega,
\]

(3.4)

where \( |\Omega| \) is the size of the domain. Below, we calculate \( \bar{u} \) in terms of the trap locations \( x_j \). We then optimize \( \bar{u} \) with respect to the locations. To reduce the number of parameters in the optimization problem, we assume that all traps are circular and share a common radius \( \epsilon \); i.e., \( \Omega_{\epsilon_{0j}} \) are disks of unit radius for each \( j = 1, \ldots, N \).
First passage time to multiple mobile traps

3.1 The regime $\omega \sim O(1)$

In the regime $\omega \sim O(1)$, we adopt the method of matched asymptotic expansions [21, 23] to calculate $\bar{u}$ as a function of the relative locations $x_j$ of $N$ traps. In the inner region near the $j$-th trap, we let $y = |x - x_j|/\varepsilon$ and $u(x_j + \varepsilon y) = U_j(y)$ to obtain the leading order inner problem

$$\Delta U_j = 0, \quad y \in \mathbb{R}^2 \setminus \Omega_{0j}, \quad U_j \sim S_j \log |y| - S_j \log d_j \text{ as } |y| \to \infty. \quad (3.5)$$

In (3.5), $d_j$ is the referred to as the logarithmic capacitance of the $j$-th trap, which depends on the geometry $\Omega_{0j}$. A list of numerical and analytic values of $d$ for different shapes are given in [24]. For the case we consider, where $\Omega_{0j}$ is
the unit disk, \( d_j = 1 \) so that \( U_j = S_j \log |y| \) is the exact solution of (3.5). The quantity \( S_j \), the strength of trap \( j \), is to be determined from a system of linear equations obtained by matching inner and outer solutions. In terms of the outer variables, we calculate the matching condition

\[
 u \sim S_j \log |x - x_j| - S_j \log \varepsilon \quad \text{as} \quad x \to x_j .
\]

Since \( u \) is logarithmic near each trap, we may express \( u \) as a sum of Neumann Green’s functions \( G(x, x_0) \) satisfying

\[
\Delta G + \omega G = \frac{1}{|\Omega|} \delta(x - x_0) , \quad x \in \Omega ;
\]

\[
\partial_n G = 0 , \quad x \in \partial \Omega ; \quad \int_{\Omega} G \, d\Omega = 0 ,
\]

\[
 G \sim -\frac{1}{2\pi} \log |x - x_0| + R(x_0, x_0) \quad \text{as} \quad x \to x_0 .
\]

Then in the limit \( \varepsilon \to 0 \), we write

\[
 u = -2\pi \sum_{j=1}^{N} S_j G(x, x_j) + \bar{u} .
\]

In (3.7c), \( R(x_0, x_0) \) is the regular part of \( G \) as \( x \to x_0 \), referred to as the self-interaction term. By the integral condition in (3.7b), which uniquely specifies \( G, \bar{u} \) in (3.8) is the uniform average of \( u \) in (3.4) that we seek to optimize. To obtain the \( N + 1 \) equations for \( S_1, \ldots, S_N \) and \( \bar{u} \), we first compare (3.8) with (3.7) to (3.3) to obtain the solvability condition

\[
 \sum_{j=1}^{N} S_j = \frac{1}{2} .
\]

The other \( N \) equations come from applying the matching condition (3.6) at the \( N \) trap locations \( x_j \). Letting \( x \to x_i \) in (3.8) and using the limiting behavior of \( G \) near \( x_i \), we calculate

\[
 -2\pi S_i \left[ -\frac{1}{2\pi} \log |x - x_i| + R_{ii} \right] - 2\pi \sum_{j \neq i}^{N} G_{ij} S_j + \bar{u} = S_i \log |x - x_i| + \frac{S_i}{\nu} , \quad i = 1, \ldots, N ,
\]

where \( R_{ii} \equiv R(x_i, x_i) \), \( G_{ij} \equiv G(x_i, x_j) \), and \( \nu \equiv -1/\log \varepsilon \ll 1 \). The logarithmic terms in (3.10) match by construction. To write (3.10) in matrix form, we define

\[
 s \equiv \begin{pmatrix} S_1 \\ \vdots \\ S_N \end{pmatrix} , \quad e \equiv \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} , \quad \mathcal{E} \equiv ee^t , \quad \mathcal{G} \equiv \begin{pmatrix} R_{11} & G_{12} & \cdots & G_{1N} \\ G_{21} & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots \\ G_{N1} & \cdots & G_{N,N-1} & R_{NN} \end{pmatrix} ,
\]

where \( t \) denotes the transpose, and \( \mathcal{G} \) in (3.11) is the Green’s interaction matrix, which encodes information on the locations of the \( N \) traps. In contrast to the Green’s matrix in [21], \( \mathcal{G} \) is not symmetric due to the symmetry-breaking rotation of the traps. We rewrite (3.9) and (3.10) in the form

\[
2\pi \mathcal{G}s + \frac{1}{\nu} \mathcal{I} = \bar{u}e , \quad e^ts = \frac{1}{2} ,
\]

where \( \mathcal{I} \) is the \( N \times N \) identity matrix. Multiplying both sides of (3.12) by \( e^t \) and solving for \( \bar{u} \), we obtain the solution for \( \bar{u} \) and the strengths of the traps \( S_1, \ldots, S_N \)

\[
 \bar{u} = \frac{1}{N} \left[ 2\pi e^t \mathcal{G}s + \frac{1}{2\nu} \right] , \quad s = \frac{1}{2\nu N} \left[ 2\pi \left( \mathcal{I} - \frac{1}{N} \mathcal{E} \right) \mathcal{G} + \frac{1}{\nu} \mathcal{I} \right]^{-1} e .
\]
We observe in (3.13) that $S_j = (2N)^{-1}$ to leading order in $\nu^{-1}$ for all $j$, and $\bar{u} = (2\nu N)^{-1}$. That is, all traps share a common strength to leading order, and $\bar{u}$ increases logarithmically as $\varepsilon \to 0$. The effect of trap locations on $\bar{u}$ is therefore a smaller $O(1)$ correction.

To construct the Green’s interaction matrix (3.11) in the case $\omega \neq 0$, we adopt a Fourier series approach where we let $\mathbf{x} = (r \cos \theta, r \sin \theta)$. The Neumann Green’s function satisfying (3.7) is then given by [32]

$$G(\mathbf{x}, \mathbf{x}_0; \omega) = G(r, \theta, r_0, \theta_0; \omega) = R_0(r, r_0) + \sum_{m > 0} e^{im(\theta - \theta_0)} R_m(r, r_0) + c.c.,$$

(3.14a)

where the coefficients $R_0$ and $R_m$ are given by

$$R_0(r, r_0) = \frac{r^2}{4\pi} + \frac{1}{8\pi} [2r^2 - 3] - \frac{1}{2\pi} \begin{cases} \log r_0, & 0 < r < r_0 \\ \log r, & r_0 < r < 1 \end{cases},$$

(3.14b)

$$R_m(r, r_0; \omega) = \frac{1}{2\pi} \begin{cases} \left[ \frac{K_{m+1}(c_m)}{I_{m+1}(c_m)} I_m(c_m r_0) + K_m(c_m r_0) \right] I_m(c_m r), & 0 < r < r_0 \\ \left[ \frac{K_{m+1}(c_m)}{I_{m+1}(c_m)} I_m(c_m r) + K_m(c_m r) \right] I_m(c_m r_0), & r_0 < r < 1 \end{cases},$$

(3.14c)

where $K_m(z)$ and $I_m(z)$ are modified Bessel functions of the first and second kind. The regular part of $G$ is obtained by using the definition in (3.7c) and expressing $\log |\mathbf{x} - \mathbf{x}_0|$ in terms of its Fourier series. This calculation yields

$$R(\mathbf{x}_0; \mathbf{x}_0) = \frac{r_0^2}{2\pi} - \frac{3}{8\pi} + \sum_{m > 0} \left( R_m(r_0, r_0) - \frac{1}{4\pi m} \right) + c.c.$$  

(3.14d)

In (3.14), $c.c.$ refers to the complex conjugate of the term involving the summation. In the case where $\omega, \varepsilon$ are fixed and $N = 2$, we compare in Fig. 3.3 the asymptotic result (3.13) for $\bar{u}$ to full numerical solutions of (3.3) obtained using FlexPDE. In Fig. 3.3(a), we let the polar coordinates of the first trap be $(r_1, \theta_1) = (0.4, 0)$, with the second located at various locations on the ring $r_2 = 0.8$. In Fig. 3.3(b), we fix the angle of the second trap at $\theta_2 = \pi$, and vary $r_2$ between 0 and 1. In both figures, we observe excellent agreement between the asymptotic formula (3.13) and numerical results.

Figure 3.3: Comparison of the asymptotic formula for $\bar{u}$ (3.13) (solid curve) versus numerical results obtained from a finite elements solution of (3.3) (circles) with parameter values $\omega = 5$ and $\varepsilon = 0.01$. In both figures, the first trap is located at $(r_1, \theta_1) = (0.4, 0)$ while the location of the second $(r_2, \theta_2)$ is varied. In (a), $r_2 = 0.8$ while $\theta_2$ is varied. In (b), $\theta_2 = \pi$ while $r_2$ is varied.

Using MATLAB’s global optimization algorithm GlobalSearch with fmincon(), we optimize $\bar{u}$ in (3.13) over
Optimal radii of rotation (a) along with relative phase and minimum well-separated.

With open circles in Fig. 3.4(b) (not shown). For to avoid clutter.

Figure 3.4: Optimal radii of rotation (a) along with relative phase and minimum \( \bar{u} \) (b) obtained from optimizing (3.13) for a range of \( \omega \) using MATLAB’s global optimization algorithm GlobalSearch with fmincon() (solid). Here, \( \varepsilon = 1 \times 10^{-4} \). Open circles indicate optimal results obtained from an exhaustive search over the entire (discretized) parameter space \((r_1, r_2, \theta_2)\). For \( \omega \lesssim 14 \), the optimal configuration consists of two traps rotating \( \pi \)-phase apart at the same radius. For \( 14 \lesssim \omega \lesssim 160 \), the optimal configuration has the traps rotating exactly in phase but on two different rings. The dashed lines in (a) represent the limiting behavior in the subregime \( O(1) \ll \omega \ll O(\varepsilon^{-1}) \). In (b), we observe that for \( \omega \gtrsim 160 \), the phase difference becomes nonzero while the traps remain on two different rings. With the dashed line on the right axis, we plot by how much the average MFPT increases (as a fraction of its optimal value) when \( \bar{u} \) is chosen to be \( \pi (\pi - 0.1) \) when \( \omega \lesssim 14 \) radians from its optimizing value. The inset plots the suboptimality on a log-log scale, showing that it decreases rapidly as \( \omega \) becomes large. The favorably similar results of the exhaustive search have been excluded in (b) to avoid clutter.

For large \( \omega \), the optimal phase difference again becomes nonzero, but the two traps remain on different rings.

With the dashed line in Fig. 3.4(b), we plot by how much the average MFPT increases (as a fraction of its optimal value) when the relative phase is chosen to be \( \pi (\pi - 0.1) \) radians from its optimal value. The inset plots the suboptimality on a log-log scale, showing that it decreases rapidly as \( \omega \) becomes large, as expected. We remark that the leading order value of \( \bar{u} \) as given by (3.4) is \( \bar{u} \sim (2\pi \nu N)^{-1} \), while its dependence on \( r_1, r_2, \) and the phase \( \theta_2 \) appears at \( O(1) \). As such, the fraction by which a suboptimal MFPT exceeds the optimal value is of order \( O(\nu) \). However, since \( \nu = -1/\log \varepsilon \) can be rather large even when \( \varepsilon \) is small, the improvement of choosing an optimal over suboptimal configuration can be nontrivial. For example, with \( \varepsilon = 1 \times 10^{-4} \) in Fig. 3.4(b), choosing a suboptimal phase increased the MFPT by \( \sim 11\% \) when \( \omega = 10 \).

We note that, in the small \( \omega \to 0 \) limit of Fig. 3.4(a), the result is the same as that obtained from optimizing \( \bar{u} \) with the Neumann Green’s function and its particular part (3.14) replaced by their \( \omega = 0 \) variants [21]. For large \( \omega \), the optimal radii approach \( r_1 = 1/\sqrt{2} \) and \( r_2 = 1 \), represented by the dashed lines. In this limit, the accuracy of the truncated sum of (3.14d) is diminished due to numerical under- and overflow. In §3.2, we adopt a different approach for calculating \( \bar{u} \) in this particular large \( \omega \) regime that does not involve a infinite sum. We use it to demonstrate the result suggested by the dashed lines in Fig. 3.4(a), and extend it to \( N \) traps.
From a separately constructed inner solution, the limiting behavior of
locations near boundaries. However, it was shown also in the same subregime
we make three remarks. The first is that result (3.20) is rather counterintuitive given the suboptimal nature of search
order formula for two rings of rotation divide the unit disk into two regions of equal area. In fact, it can be easily shown using (3.18)
that the optimal radii of rotation for
where
symmetry in constructing
is the Heaviside step function and
From a separately constructed inner solution, the limiting behavior of \( G \)
\[ G(r, r_0) \sim \frac{1}{2\pi} \left[ -\log|x - x_0| - \log \left( \frac{\nu \omega}{4} \right) - \gamma \right] + \hat{H}(r_0), \quad \text{as} \quad x \to x_0, \quad (3.16) \]
yields the leading order regular part of \( G \)
\[ R(r_0) \sim \frac{1}{2\pi} \left[ -\log \left( \frac{\nu \omega}{4} \right) - \gamma \right] + \hat{H}(r_0). \quad (3.17) \]
In (3.16), \( \gamma \) is Euler’s constant. Recalling that \( s = (2N)^{-1}e \) to leading order in \( \nu \), we calculate the simplified leading
order formula for \( \bar{u} \)
\[ \bar{u} = \frac{1}{2\nu \pi} + \frac{1}{N^2} \sum_{ij} G_{ij} + O(\nu), \quad (3.18) \]
where \( G_{ij} \) is the \( ij \)-th entry of the matrix \( G \) defined in (3.11). For \( N = 2 \), assuming \( r_1 < r_2 \), we use (3.15) to calculate
\[ \bar{u} = 1 - \frac{1}{2\nu} + \frac{1}{8} \left[ \log \left( \frac{16}{\omega^2} \right) - 2\gamma - 3 + 2(\nu_1^2 + \nu_2^2) - 2 \log r_1 - 4 \log r_2 \right] + O(\nu). \quad (3.19) \]
Finding the critical points of (3.19) by solving \( \partial_{r_1} \bar{u} = \partial_{r_2} \bar{u} = 0 \) leads to two uncoupled equations for \( r_1 \) and \( r_2 \). The
result is that \( \bar{u} \) is minimized to leading order when \( r_1 \) and \( r_2 \) are given by
\[ r_1 \sim \frac{1}{\sqrt{2}}, \quad r_2 \sim 1, \quad \text{as} \quad \omega \to \infty \text{ with } \omega \ll O(\varepsilon^{-1}). \quad (3.20) \]

We make three remarks. The first is that result (3.20) is rather counterintuitive given the suboptimal nature of search
locations near boundaries. However, it was shown also in the same subregime \( O(1) \ll \omega \ll O(\varepsilon^{-1}) \) that a single
rotating trap is best placed asymptotically close to the boundary of the unit disk [32]. Second, in assuming radial
symmetry in constructing \( G \) in (3.16), we have lost resolution on \( \theta_2 \), the relative phase between the two traps. Because
the radial symmetry of \( \bar{u} \) increases with increasing \( \omega \), the effect of relative phase diminishes in this regime. Lastly, the
two rings of rotation divide the unit disk into two regions of equal area. In fact, it can be easily shown using (3.18)
that the optimal radii of rotation for \( N \) traps are
\[ r_j = \sqrt{\frac{j}{N}}, \quad j = 1, \ldots, N. \quad (3.21) \]
The results of [21, 32] show that a single Dirichlet ring on which \( u = 0 \) is best placed at \( r = 1/\sqrt{2} \), which divides the unit disk into two equal areas. In [32], this occurred in the \( \omega \to \infty \) regime with \( \omega \gg \mathcal{O}(\varepsilon^{-1}) \) regime. The result (3.21), showing that the equal division of area in fact occurs in the \( \mathcal{O}(1) \ll \omega \ll \mathcal{O}(\varepsilon^{-1}) \) subregime, is thus unexpected. In Fig. 3.5, with \( r_1 = 1/\sqrt{2} \) fixed, we verify the formula (3.19) with full numerical solutions of (3.3) for various \( r_2 \). We observe that \( \bar{u} \) is minimized very near \( r_2 = 1 \), consistent with (3.20). In Fig. 3.5, with \( r_1 = 1/\sqrt{2} \) fixed, we verify the formula (3.19) with full numerical solutions of (3.3) for various \( r_2 \). We observe that \( \bar{u} \) is minimized very near \( r_2 = 1 \), consistent with (3.20). Here, \( \omega = 500 \) and \( \varepsilon = 1 \times 10^{-4} \). The circles (stars) are for \( \theta_2 = 0 \) (\( \theta_2 = \pi \)), their similarity showing that the relative phase of the traps has little effect on \( \bar{u} \).

**Figure 3.5:** Comparison in the regime \( \mathcal{O}(1) \ll \omega \ll \mathcal{O}(\varepsilon^{-1}) \) of \( \bar{u} \) from (3.19) (solid) with that from full numerical solutions of (3.3) (circles and stars). One radius of rotation is fixed at \( r_1 = 1/\sqrt{2} \), while the second \( (r_2) \) is varied. We observe that \( \bar{u} \) is minimized very near \( r_2 = 1 \), consistent with (3.20). Here, \( \omega = 500 \) and \( \varepsilon = 1 \times 10^{-4} \). The circles (stars) are for \( \theta_2 = 0 \) (\( \theta_2 = \pi \)), showing that the relative phase of the traps has little effect on \( \bar{u} \).

### 3.3 The regime \( \omega \to \infty \) with \( \omega \gg \mathcal{O}(\varepsilon^{-1}) \)

In this regime the MFPT \( u \) is radially symmetric and satisfies

\[
\frac{1}{r} u_r + u_r + 1 = 0, \quad u(r_j) = 0 \text{ and } u'(0) = u'(1) = 0, \quad 0 \leq r_1, \ldots, r_N \leq 1. \tag{3.22}
\]

The solution to (3.22) can be obtained in piecewise fashion. The optimal radii are then found by optimizing \( \int_0^1 u(r)rdr \) with respect to \( N \) variables \( r_1, \ldots, r_N \).

We now show how this \( N \)--dimensional optimization problem can be reduced to a sequence of \( N - 1 \) algebraic equations whose solution yields the optimal radii. We first define two functions: let \( r_2 = F(r_1, r_3) \) be the optimal ring location \( r_2 \) for the MFPT problem on an annulus with Dirichlet boundary conditions on \( r = r_1 \) and \( r_3 \), and with a ring trap at location \( r_2 \in (r_1, r_3) \). That is, let

\[
r_2 = F(r_1, r_3) = \min_{r_2 \in (r_1, r_3)} \int_{r_1}^{r_3} u(r)rdr,
\]

where \( u(r) \) solves

\[
\frac{1}{r} u_r + u_r + 1 = 0, \quad u(r_1) = u(r_2) = u(r_3) = 0. \tag{3.23b}
\]

Similarly, let \( r_1 = G(r_2) \) be the optimal location of the ring trap of radius \( r_1 \) inside a Dirichlet disk of radius \( r_2 \):

\[
r_1 = G(r_2) = \min_{r_1 \in (0, r_2)} \int_0^{r_2} u(r)rdr. \tag{3.24a}
\]
where \( u(r) \) solves

\[
ur + \frac{1}{r} ur + 1 = 0, \quad u(r_1) = u(r_2) = 0, \quad u'(0) = 0.
\] (3.24b)

The following are three key observations that allow us to “decouple” the problem.

- **Observation 1:** For an optimal configuration \( r_1, \ldots, r_N \) which minimizes
  \[
  \min_{r_1, \ldots, r_N} \int_0^1 ur(r) dr
  \]
  of problem (3.22), one has that \( r_1 = G(r_2), \ r_2 = F(r_3), \ldots, r_{N-1} = F(r_{N-2}, r_N) \). In other words, \( r_2 \) is optimal for the MFPT with Dirichlet boundary conditions of an annulus of radii \( r_1 \) and \( r_3 \), and so on.

- **Observation 2:** If \( r_2 = F(r_1, r_3) \) then \( \frac{r_2}{r_3} = F(\frac{z_2}{z_3}, 1) \) and similarly, \( r_1 = G(r_2) \iff \frac{r_1}{r_2} = G(1) \). This is a simple consequence of the geometric invariance under the scaling of space.

- **Observation 3:** Let \( A_1, \ldots, A_{N+1} \) be the areas of the regions that are obtained by cutting the disk along the radii \( r_1, \ldots, r_N \). Then the sum of even areas is equal to the sum of odd areas. We show below that this condition may be written as
  \[
  r_1^2 - r_2^2 + r_3^2 - \ldots - (-1)^N r_N^2 - (-1)^N \frac{1}{2} = 0.
  \] (3.25)

The first two observations yield the following algorithm to compute the optimal radii of rotation \( r_1, \ldots, r_N \). First, define:

\[
 z_i = \frac{r_i}{r_{i+1}}, \quad i = 1, \ldots, N - 1.
\] (3.26)

Then from Observation 2, we have that \( z_1 \) satisfies \( z_1 = G(1) \), while \( z_i \) for \( i > 1 \) may be found sequentially by solving

\[
 z_2 = F(z_1 z_2, 1), \quad \ldots, z_{N-1} = F(z_{N-1} z_N, 1).
\]

Once we determine \( z_1, \ldots, z_{N-1} \), the radii \( r_1, \ldots, r_N \) are found by simultaneously solving (3.25) and (3.26).

Explicit solutions of (3.23) and (3.24) show, respectively, that \( z_1 \) satisfies

\[
 4 - \frac{z_1^2 - 1}{z_1 \ln(z_1)} = 0,
\] (3.27)

while \( z_{i+1} \) is related to \( z_i \) through

\[
 4 - \frac{z_{i+1}^2 - 1}{z_{i+1} \ln(z_{i+1})} = \frac{z_i^2 - 1}{\ln(z_i)}, \quad i \geq 1.
\] (3.28)

Note that the values of \( z_i \) are universal and do not depend on \( N \). The first seven values of \( z_i \) are approximately:

<table>
<thead>
<tr>
<th>( k )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( z_k )</td>
<td>0.533543</td>
<td>0.712445</td>
<td>0.792159</td>
<td>0.837265</td>
<td>0.866283</td>
<td>0.886517</td>
<td>0.901433</td>
</tr>
</tbody>
</table>

To illustrate this method, we consider the case of \( N = 3 \) rings. Then we have

\[
 r_1 = z_1 z_2 r_3, \quad r_2 = z_2 r_3, \quad r_3 = \sqrt{\frac{1}{2}(z_1 z_2)^2 - (z_2)^2 + 1},
\] (3.29)

which yields the optimal radii of rotation for the three traps \( r_1 = 0.33679, \ r_2 = 0.63124, \ r_3 = 0.886022 \). We observe that these radii satisfy (3.25) of Observation 3, which we show here. First, consider the following problem:

\[
 r_m = \min_{r_m \in (r_1, r_a)} \int_{r_i}^{r_a} u(r) r dr,
\] (3.30a)

where \( u(r) \) solves

\[
 u_{rr} + \frac{1}{r} u_r + 1 = 0, \quad u'(r_i) = u'(r_a) = 0, \quad u(r_m) = 0.
\] (3.30b)
For a fixed $r_m$, $u(r)$ is given by

$$u = \begin{cases} 
\frac{r_m^2 - r^2}{4} + \frac{r_i^2}{2} \ln \left( \frac{r}{r_m} \right), & r_i < r < r_m; \\
\frac{r_m^2 - r^2}{4} + \frac{r_o^2}{2} \ln \left( \frac{r}{r_m} \right), & r_m < r < r_o.
\end{cases}$$

To find $r_m$ which minimizes (3.30), we compute

$$\frac{\partial}{\partial r_m} \int_{r_i}^{r_o} u(r) r dr = \int_{r_i}^{r_o} \left( \frac{\partial}{\partial r_m} u \right) r dr = \frac{1}{4r_m} \left( r_m^2 - r_i^2 \right)^2 - \frac{1}{4r_m} \left( r_m^2 - r_o^2 \right)^2 = 0.$$ 

It follows that the minimizing $r_m$ satisfies

$$r_m^2 - r_i^2 = r_o^2 - r_m^2.$$  

(3.31)

We conclude that for the problem (3.30), the optimal $r_m$ divides the annulus into two regions of equal area. Now consider the optimal solution to (3.22). As an example of this theory, the case $N = 3$ is considered and the optimal solution $u(r)$ shown in Fig. 3.6. The solution $u(r)$ is plotting along with the interior maximizers of $u$ by $r_{12}$ and $r_{23}$ and the areas between maxima and zeros of $u$ as shown. By the property (3.31), we have:

$$A_1 = A_{21}, \quad A_{22} = A_{31}, \quad A_{32} = A_4.$$  

(3.32)

Moreover, we have

$$A_2 = A_{21} + A_{22}, \quad A_3 = A_{31} + A_{32},$$  

(3.33)

where $A_1, \ldots, A_4$ are the areas of the regions that are obtained by cutting the disk along the radii $r_1, \ldots, r_3$. It follows from (3.32) and (3.33) that $A_1 + A_3 = A_2 + A_4$. This is equivalent to (3.29).

![Figure 3.6: Plot of the solution $u(r)$ to (3.22) for $N = 3$ with traps located at the optimal radii.](image)

In Fig. 3.7, we compare the optimal radii in this $\omega \to \infty$ with $\omega \gg O(\varepsilon^{-1})$ regime (top row) against those in the $O(1) \ll \omega \ll O(\varepsilon^{-1})$ regime (bottom row). In the top row, we observe that as $N$ increases, the outer rings appear to be equally spaced. By contrast, in the bottom row, the rings locations have an explicit formula $r_i = \sqrt{i/N}$ for $i = 1, \ldots, N$, and tend to concentrate nearer to the boundary.

### 3.4 The regime $\omega \sim O(\varepsilon^{-1})$

The distinguished regime $\omega \sim \omega_0 = O(1)$ marks the transition between the $1 \ll \omega \ll O(\varepsilon^{-1})$ regime of §3.2 and the $\omega \to \infty$ regime with $\omega \gg O(\varepsilon^{-1})$ analyzed in §3.3. In this regime, the equation in the $O(\varepsilon)$ j-
With the mean of \(\theta\) obtained from computing the mean of the solution of (3.34c), which yields

\[
\Delta \theta_{j0} + \omega_0 r_j \frac{\partial}{\partial y_2} \theta_{j0} = 0, \quad |y| > 1, \quad \theta_{j0} = 0, \quad |y| = 1, \quad \theta_{j0} \sim u_{j0}(\omega_0 r_j) \quad \text{as} \quad |y| \to \infty; \quad y = (y_1, y_2),
\]

(3.34a)

where \(u_{j0}(\omega_0 r_j)\) is a constant to be found. This inner solution and the outer solution is mediated through an intermediate parabolic layer with scaling \(\hat{r} = \sqrt{\omega_0(r - r_j)}/\sqrt{\omega}\) and \(\hat{\theta} = 2\pi - \theta\), forming an \(O(\sqrt{\varepsilon})\) layer around the ring \(r = r_j\). In this layer, we expand \(u = \hat{u}_{j0} + O(\sqrt{\varepsilon})\) so that at the leading order, we obtain the parabolic equation for \(\hat{u}_{j0}\)

\[
\hat{u}_{j0,\hat{r}} - \hat{u}_{j0,\hat{\theta}} = 0, \quad \hat{u}_{j0}(\hat{r}, 0) = u_{0j} + O(\sqrt{\varepsilon}), \quad \hat{u}_{j0} \sim \text{constant as} \quad \hat{r} \to \pm\infty,
\]

(3.34b)

where \(u_{j0}\) is an \(O(1)\) constant. The solution of (3.34b) is simply \(\hat{u}_{j0} = u_{j0}\) so that \(u\) in the outer region is approximately constant on the ring \(r = r_j\).

In the outer region, we expand the solution as \(u = u_0 + \sqrt{\varepsilon} u_1\). Substituting this expansion into (3.3) with \(\omega = \varepsilon^{-1} \omega_0\), we obtain at \(O(\varepsilon^{-1})\) and \(O(\varepsilon^{-1/2})\) that \(u_{0\theta} = u_{1\theta} = 0\). That is, the outer solution is radially symmetric to \(O(\sqrt{\varepsilon})\).

At \(O(1)\) with \(u_{0\theta} = 0\), we obtain the radially symmetric ODE for \(u_0\)

\[
u_{0rr} + \frac{1}{r}u_{0r} + 1 = 0, \quad u_0 = u_{0j}, \quad r = r_j, \quad u_0(0) = u_0(1) = 0,
\]

(3.34c)

where the constants \(u_{0j}\) are to be found by matching fluxes in the outer and elliptic regions. The solution to (3.34) was found in [32] for a single rotating trap using a hybrid numerically-asymptotic technique similar to that employed in [9]. Here, we extend the method to the case of two traps, noting that extension to \(N\) traps follows in the same manner. Using a hybrid asymptotic-numerical method detailed in Appendix A, we calculate that \(u_{01}\) and \(u_{02}\) are given by

\[
u_{01} = \frac{1}{2} \frac{u_{c1}(r_2^2 - r_1^2 - 4u_{c2})}{\log \frac{r_2^2 - 4u_{c1} - 2u_{c2}}{r_2^2}}, \quad u_{02} = \frac{1}{2} \frac{u_{c2} \left(2\log \frac{r_2}{r_1} - r_2^2 + r_1^2 - 4u_{c1}\right)}{\log \frac{r_2}{r_1} - 2u_{c1} - 2u_{c2}}, \quad r_1 < r_2,
\]

(3.35)

where the constants \(u_{c1}\) and \(u_{c2}\) are obtained numerically from a canonical elliptic problem. The mean of \(u\) is then obtained from computing the mean of the solution of (3.34c), which yields

\[
\bar{\bar{u}} = \frac{1}{8 \log \frac{r_1}{r_2}} \left[\left(r_2^2 - r_1^2\right)r_2^2 + 4(u_2 - u_1) + \left(4r_2^2 + 8u_2 - 3 - 4 \log r_2\right) \log \frac{r_1}{r_2}\right] + O(\sqrt{\varepsilon}), \quad r_1 < r_2.
\]

(3.36)
In Fig. 3.8(a), with $\omega_0 = 10$, $\varepsilon = 0.001$ and $r_2 = 0.95$, we compare (3.36) (solid) with full numerical solutions of (3.3) (circles) for a range of $r_1$. We observe good agreement not only in the value of $\bar{u}$, but in where the minimum occurs. Further confirmation of the analysis (not shown) comes from the agreement of $u_1$ and $u_2$ given asymptotically by (3.35) with that obtained from numerical solutions of (3.3). In Fig. 3.8(b), we show the optimal radii of rotation obtained from optimizing (3.36) with respect to $r_1$ and $r_2$.

**Figure 3.8:** In (a), with $\omega_0 = 10$, $\varepsilon = 0.001$, and $r_2 = 0.95$, we compare $\bar{u}$ in (3.36) for a range of $r_1$ (solid) against full numerical results of (3.3) (circles). The asymptotic result (3.36) correctly predicts the location of the minimum. In (b), we show optimal radii $r_1$ and $r_2$ that minimize $\bar{u}$. The dashed lines are the optimal radii $r_1 = 1/\sqrt{2}$ and $r_2 = 1$ in the limit $\omega_0 \to 0$. The dotted lines represent the limit in which $\omega_0 \to \infty$, discussed in §3.3.

We recall that this regime interpolates between the results of the $O(1) \ll \omega \ll O(\varepsilon^{-1})$ subregime ($\omega_0 \to 0$) and the $\omega \to \infty$ regime with $\omega \gg O(\varepsilon^{-1})$ ($\omega_0 \to \infty$). Indeed, taking the latter limit in (3.34a), it is simple to see that, since $\partial_{y_2} U_j = 0$ and $U_j = 0$ on $\partial \Omega$, we must have $u_j = 0$. This corresponds to the case in which $u = 0$ on the ring $r = r_j$, which occurs in the limit of infinitely fast trap rotation. This limit was discussed in detail in §3.3, the two-trap result of which is represented by the dotted lines in Fig. 3.8(b). Analysis of the former limit $\omega_0 \to 0$ (dashed lines in Fig. 3.8(b)) in Appendix A shows that the transition between the optimal configurations of the regimes $O(1) \ll \omega \ll O(\varepsilon^{-1})$ and $\omega \sim O(\varepsilon^{-1})$ is smooth.

We make as a final remark that to calculate the $O(\sqrt{\varepsilon})$ correction to (3.36), we must calculate the solution of the $O(\sqrt{\varepsilon})$ outer problem

$$u_{rr} + \frac{1}{r} u_r + 0, \quad u_1 = u_{1j}, \quad r = r_j, \quad u_1^r(0) = u_1^r(1) = 0. \quad (3.37)$$

The constants $u_{1j}$ in (3.37) uniquely determine $u_1$, and may be calculated by employing a higher-order matching between the three regions. In particular, the far-field conditions of the elliptic layer must be matched to the “initial conditions” of the parabolic layer, while the far-field conditions of the parabolic layer must be matched to the local gradient of $u_0$ near $r = r_j$. By imposing periodicity in the parabolic layer along with a higher order matching between the parabolic and elliptic layers, a certain terminal value problem can be formulated for which a numerical solution yields $u_{1j}$. This is a lengthy analysis that we omit for brevity.

**4 Discussion**

We have used the techniques from [21, 32, 33] to study the MFPT in the presence of multiple mobile traps in one and two dimensions. Very surprising and intricate behaviour is observed even in a one dimensional setting, where we find an infinite sequence of bifurcations (two oscillating traps switch from an in-phase to antiphase configuration infinitely many times) as the oscillation frequency $\omega$ is increased. When a trap is forced to adapt to two neighbors whose dynamics are predetermined, its optimal strategy may be neither in-phase nor antiphase with either neighbor.

In two dimensions, the presence of multiple distinguished regimes allows for the characterization of distinct optimal configurations. The simplest of these regimes is $\omega \gg O(\varepsilon^{-1})$, in which case each rotating trap becomes a Dirichlet
ring inside a disk. It is interesting to contrast this to the regime $O(1) \ll \omega \ll O(\epsilon^{-1})$, for which each trap becomes a “ring” but instead of a pure Dirichlet condition on a ring, it is more “porous”, yielding different optimal radii. For both of these regimes, the relative phase between the two traps is insignificant to leading order, and it is an open question to find the optimal phase. In the $\omega \sim O(1)$ regime, we observe a bifurcation in which the optimal configuration changes from antiphase rotation with a common radius to an in-phase rotation on well-separated rings.

While our analysis of all regimes is valid for three or more traps, the complexity of the numerical optimizations quickly increases with the number of traps. However, we expect that some behavior observed in the two-trap scenario would extend to the $N > 2$ case. For example, if three traps rotate slowly, we expect that they rotate with the same radius separated by a $2\pi/3$ phase, and that a similar bifurcation occurs as the rotation rate increases. On the other hand it is unclear what the resulting phase difference (if any) will result on the other side of the bifurcation. For seven or more traps, where the optimal stationary configuration may be a ring of six traps with one at the origin [21], the bifurcation may be more complex.

Our analysis of the two dimensional problem was greatly simplified by the rotational symmetry. It would be very interesting to solve (3.2) either numerically or asymptotically to understand the effects on MFPT of more general trap motion. Within the same rotational framework, one could use (3.2) to investigate whether it is more optimal for two traps to rotate in the same or opposite direction, and whether the result depends on rotation rate in a similar way to what was found in §2 for one dimension.

Another open question is to determine an “optimal” path of the trap. Here, the key issue is to find the right “constraint” on the type of admissible motion. This problem may require an energy constraint, as otherwise one can allow the trap to travel with infinite speed on a space-filling curve. Whether an energy constraint leads to a well-posed optimization problem, and if other or additional constraints may be more appropriate are interesting modeling question.

The question of proper constraints also arises in the analogous one-dimensional problem, where one seeks an optimal periodic path of $O(1)$ amplitude. The problem (2.2) for the MFPT would need to be solved numerically for an arbitrary periodic path expressed in terms of Fourier coefficients, which would then be optimized subject to constraints. For example, one may require a fixed energy output over one period, while also penalizing mean square displacement from a certain fixed point.

An overarching theme of this work has been to investigate configurations that result from multiple mobile traps co-operating to optimize a global quantity. It may be interesting to ask what happens when each trap adjusts its motion locally in order to increase its own rate of capturing the Brownian particles, and whether this algorithm leads to any stable configurations.

Acknowledgements

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References

[1] FlexPDE is a general-purpose commercial package to solve PDEs, see www.pdesolutions.com.
Appendix A. Analysis of the $\omega \sim O(\varepsilon^{-1})$ regime.
We demonstrate here how to compute the quantity \( u_{0j} \) in (3.34c). We begin by letting \( \Omega_{j0} = u_{0j}(\mu_j + 1) \). Substituting into (3.34a), we obtain for \( \mu_j \)

\[
\Delta \mu_j + q_j \frac{\partial \mu_j}{\partial y_2} = 0, \quad |y| > 1, \quad \mu_j = -1, \quad |y| = 1, \quad \mu_j \sim 0 \text{ as } |y| \to \infty; \quad q_j \equiv \omega_0 r_j. \tag{A.1}
\]

The quantity we seek is the flux of \( \mu_j \) on the boundary of the unit disk \( \Omega_0 \),

\[
\Phi_j \equiv \int_{\partial \Omega_0} \frac{\partial \mu_j}{\partial n} \, dS, \tag{A.2}
\]

where \( \partial / \partial n \) denotes the outward normal derivative on \( \Omega_0 \). The flux may be extracted numerically as follows [9, 32]. We first consider the adjoint Green’s function satisfying

\[
\Delta \tilde{G} - q_j \frac{\partial \tilde{G}}{\partial \xi_2} = \delta(\xi - z), \quad \tilde{G} \to 0 \text{ as } |\xi| \to \infty, \tag{A.3}
\]

which may be solved to give

\[
\tilde{G}(\xi; z) = -\frac{1}{2\pi} e^{\frac{1}{2}(\eta - z\xi)} K_0 \left( \frac{q_j}{2} |\xi - z| \right) ; \quad \xi = (\xi_1, \xi_2), \quad z = (z_1, z_2). \tag{A.4}
\]

In polar coordinates \((\xi, \xi_2) \to (\tilde{r} \cos \tilde{\theta}, \tilde{r} \sin \tilde{\theta})\) and \((z_1, z_2) \to (\rho \cos \phi, \rho \sin \phi)\), the solution to (A.1) can then be expressed in terms of \( \tilde{G} \) in (A.4) as

\[
\mu_j(\rho \cos \phi, \rho \sin \phi) = \int_0^{2\pi} \frac{\partial \tilde{G}}{\partial \tilde{r}} \bigg|_{\tilde{r}=1} \, d\tilde{\theta} + \int_0^{2\pi} \left( \tilde{G} \frac{\partial \tilde{\mu}_j}{\partial \tilde{r}} \right) \bigg|_{\tilde{r}=1} \, d\tilde{\theta} - q_j \int_0^{2\pi} \tilde{G} \bigg|_{\tilde{r}=1} \sin \tilde{\theta} \, d\tilde{\theta}. \tag{A.5}
\]

Note that all integrals in (A.5) are over the boundary of the unit disk \( \partial \Omega_0 \). To extract the flux \( \frac{\partial \mu_j}{\partial \tilde{r}} \bigg|_{\tilde{r}=1} \), we impose the boundary condition \( \mu_j = -1 \) on \( \rho = 1 \), yielding

\[
- \int_0^{2\pi} \left. \frac{\partial \tilde{G}}{\partial \tilde{r}} \right|_{\tilde{r}=1} \, d\tilde{\theta} = -\frac{1}{2} \int_0^{2\pi} \left. \frac{\partial \tilde{\mu}_j}{\partial \tilde{r}} \right|_{\tilde{r}=1} \sin \tilde{\theta} \, d\tilde{\theta}. \tag{A.6}
\]

In (A.7), the 1/2 term is a result of evaluating \( \mu_j \) on \( \partial \Omega_0 \) and thus integrating over only half of the delta function in its Green’s function representation. The second term may be computed from integrating by parts the equation for the adjoint Green’s function (A.3) over \( |\xi| > 1 \), which finally yields

\[
\int_0^{2\pi} \left. \frac{\partial \tilde{G}}{\partial \tilde{r}} \right|_{\tilde{r}=1} \, d\tilde{\theta} = -1. \tag{A.7}
\]

The integral equation (A.7) may then be solved numerically for \( \frac{\partial \mu_j}{\partial \tilde{r}} \bigg|_{\tilde{r}=1} \) by expressing the latter as a Fourier series and solving a system of equations for the coefficients.

To express \( \Phi_j \) in terms of the flux \( f_j \) of \( u_0 \), we recall that \( u_0 \sim u_{0j}(\mu_j + 1) \) near \( x = x_j \). Substituting into (A.2), we obtain

\[
u_{0j} = \frac{f_j}{\int_{\partial \Omega_0} \frac{\partial \mu_j}{\partial n} \, dS} = \frac{f_j}{\pi} \frac{-\pi}{\int_{\partial \Omega_0} \frac{\partial \mu_j}{\partial n} \, dS}. \tag{A.8}
\]

where \( f_j \) is the flux of \( u \) on the \( j \)-th trap. We rewrite (A.8) as

\[
\nu_{0j} = -\frac{f_j}{\pi} u_{e_j}, \quad u_{e_j} \equiv \frac{-\pi}{\Phi_j}, \tag{A.9}
\]

where \( \Phi_j \) is defined in (A.2). The quantity \( u_{e_j}(q_j) \), whose dependence on \( q_j \equiv \omega_0 r_j \) is through that of \( \mu_j \), was
computed in [32] and reproduced in Fig. A.1. To find $u_{0j}$ in (A.9), we require $N$ equations for $f_j$. We demonstrate this for two traps. In the three distinct regions, we compute $u_r$ as

$$u_r = -r + \begin{cases} 0, & 0 < r < r_1; \\ \frac{c}{r}, & r_1 < r < r_2; \\ \frac{1}{2r_1}, & r_2 < r < 1, \end{cases}$$ (A.10)

The total fluxes on the rings $r = r_1$ and $r = r_2$ must, respectively, be $f_1$ and $f_2$. We calculate that

$$f_1 = -2\pi c, \quad f_2 = 2\pi c - \pi.$$ (A.11)

We remark that $f_1 + f_2 = -\pi$, as expected from applying the divergence theorem to (3.3). Finally, with $c$ defined in (A.10), we obtain $u_{01}$ and $u_{02}$ as given in (3.35).

To analyze the limit $\omega_0 \to 0$ (dashed lines in Fig. 3.8(b)), we must look at the corresponding limit $q_j \to 0$ in (A.4) and (A.7). From the asymptotics of modified Bessel functions, we calculate the leading order behavior of $\tilde{G}$ and $\frac{\partial \tilde{G}}{\partial \tilde{r}}_{\tilde{r}=\rho=1}$

$$\tilde{G} \sim \frac{1}{2\pi} \left[ \log q_j + \log |\xi - z| - \log 4 + \gamma \right] + \mathcal{O}(q_j \log q_j), \quad \left. \frac{\partial \tilde{G}}{\partial \tilde{r}} \right|_{\tilde{r}=\rho=1} \sim \frac{1}{4\pi} + \mathcal{O}(q_j), \quad \text{as } q_j \to 0,$$ (A.12)

where $\gamma$ is Euler’s constant. With (A.12) in (A.7), we have to leading order that

$$-\frac{1}{2\pi} \left[ \log q_j - \log 4 + \gamma \right] \int_{0}^{2\pi} \frac{\partial \mu_j}{\partial \tilde{r}} \bigg|_{\tilde{r}=1} d\tilde{\theta} - \frac{1}{4\pi} \int_{0}^{2\pi} \log \left[ (\cos \tilde{\theta} - \cos \phi)^2 + (\sin \tilde{\theta} - \sin \phi)^2 \right] \frac{\partial \mu_j}{\partial \tilde{r}} \bigg|_{\tilde{r}=1} d\tilde{\theta} = 1.$$ (A.13)

Since the limit $\omega_0 \to 0$ in (A.1) corresponds to $\mu_j$ approaching a radially symmetric solution, we assume that $\partial_{\tilde{r}} \mu_j$ is uniform on $\partial \Omega_0$. The second term in (A.13) consequently integrates to zero, leaving

$$\int_{0}^{2\pi} \frac{\partial \mu_j}{\partial \tilde{r}} \bigg|_{\tilde{r}=1} d\tilde{\theta} \sim -\frac{2\pi}{\log q_j - \log 4 + \gamma}.$$ (A.14)

Using (A.14) in (A.9), and noting that $\partial_n = -\partial_{\tilde{r}}$, we obtain the asymptotic behavior of $u_{cj}$ in the limit of small $q_j$

$$u_{cj} \sim -\frac{1}{2} \left[ \log q_j - \log 4 + \gamma \right] .$$ (A.15)
With $q_j = \omega_0 r_j$, substituting (A.15) for $u_{c1}$ and $u_{c2}$ into (3.36) and discarding terms of $\mathcal{O}(1/\log \omega_0)$ results in precisely (3.19). The optimal radii of rotation then, as depicted in Fig. 3.8(b), approach $r_1 = 1/\sqrt{2}$ and $r_2 = 1$ (dashed lines) as $\omega_0 \to 0$. As such, the transition between the results of the regimes $\mathcal{O}(1) \ll \omega \ll \mathcal{O}(\epsilon^{-1})$ and $\omega \sim \mathcal{O}(\epsilon^{-1})$ is smooth.